The 4th Industrial Revolution

AI, IoT, Big Data and Disruptive Innovations

Contents

Chapter 1

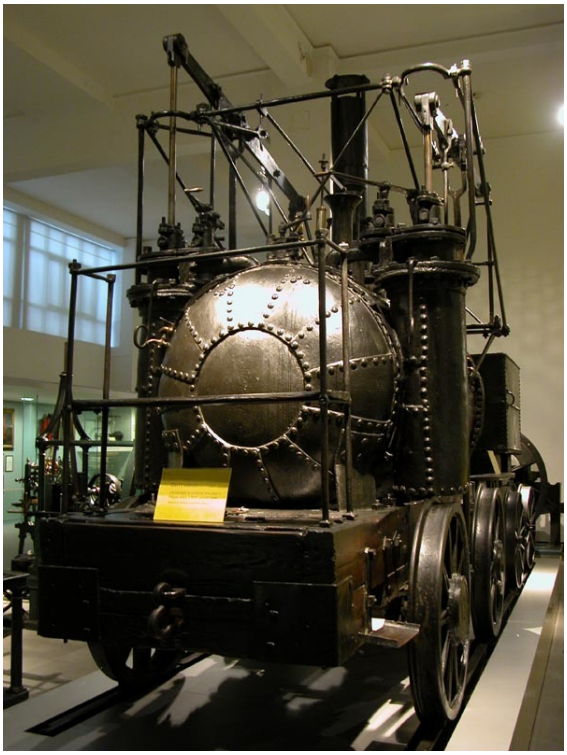
Fourth Industrial Revolution

The **Fourth Industrial Revolution**, or 4IR, is the fourth major industrial era since the initial Industrial Revolution of the 18th century. The Fourth Industrial Revolution can be described as a range of new technologies that are fusing the physical, digital and biological worlds, and impacting all disciplines, economies and industries.[1]

Central to this revolution are emerging technology breakthroughs in fields such as artificial intelligence, robotics, the Internet of Things, autonomous vehicles, 3D printing and nanotechnology.[2]

1.1 Industrial revolutions

1.1.1 First Industrial Revolution



Picture of the "Puffing Billy" steam engine taken in the Science Museum in London.

The First Industrial Revolution took place from the 18th to 19th centuries in Europe and America. It was a period when mostly agrarian, rural societies became industrial and urban.[3] The iron and textile industries, along with the development of the steam engine, played central roles in the Industrial Revolution.[3]

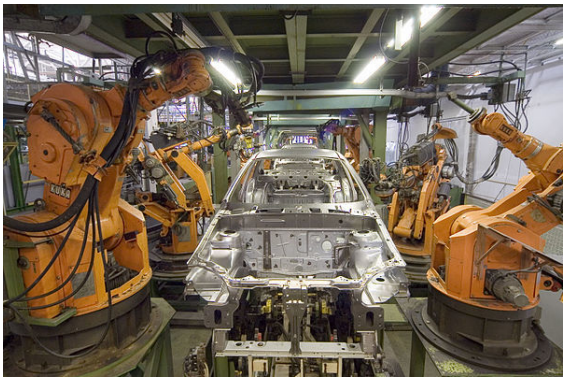
1.1.2 Second Industrial Revolution

The Second Industrial Revolution took place between 1870 and 1914, just before World War I.[4] It was a period of growth for pre-existing industries and expansion of new ones, such as steel, oil and electricity, and used electric power to create mass production. Major technological advances during this period included the telephone, light bulb, phonograph and the internal combustion engine.[5]

1.1.3 Third Industrial Revolution

The Third Industrial Revolution, or the Digital Revolution, refers to the advancement of technology from analog electronic and mechanical devices to the digital technology available today. The era started during the 1980s and is ongoing.[6] Advancements during the Third Industrial Revolution include the personal computer, the internet, and information and communications technology (ICT).

1.1.4 Fourth Industrial Revolution



1983 Industrial Robots KUKA IR160/60, 601/60

The Fourth Industrial Revolution builds on the Digital Revolution, representing new ways in which technology becomes embedded within societies and even the human body.[7] The Fourth Industrial Revolution is marked by emerging technology breakthroughs in a number of fields, including robotics, artificial intelligence, nanotechnology, biotechnology, The Internet of Things, 3D printing and autonomous vehicles.

In his book, *The Fourth Industrial Revolution*, Professor Klaus Schwab, Founder and Executive Chairman of the World Economic Forum, describes how this fourth revolution is fundamentally different from the previous three, which were characterized mainly by advances in technology. These technologies have great potential to continue to connect billions more people to the web, drastically improve the efficiency of business and organizations and help regenerate the natural environment through better asset management.[8]

"Mastering the Fourth Industrial Revolution" was the theme of the World Economic Forum Annual Meeting 2016 in Davos-Klosters, Switzerland.

1.2 See also

- Industry 4.0

1.3 References

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Chapter 2

Artificial intelligence

"AI" redirects here. For other uses, see AI and Artificial intelligence (disambiguation).

Artificial intelligence (**AI**) is intelligence exhibited by machines. In computer science, the field of AI research defines itself as the study of "intelligent agents": any device that perceives its environment and takes actions that maximize its chance of success at some goal.[1] Colloquially, the term "artificial intelligence" is applied when a machine mimics "cognitive" functions that humans associate with other human minds, such as "learning" and "problem solving" (known as Machine Learning).[2] As machines become increasingly capable, mental facilities once thought to require intelligence are removed from the definition. For instance, optical character recognition is no longer perceived as an example of "artificial intelligence", having become a routine technology.[3] Capabilities currently classified as AI include successfully understanding human speech,[4] competing at a high level in strategic game systems (such as Chess and Go[5]), self-driving cars, intelligent routing in content delivery networks, and interpreting complex data.

AI research is divided into subfields[6] that focus on specific problems or on specific approaches or on the use of a particular tool or towards satisfying particular applications.

The central problems (or goals) of AI research include reasoning, knowledge, planning, learning, natural language processing (communication), perception and the ability to move and manipulate objects.[7] General intelligence is among the field's long-term goals.[8] Approaches include statistical methods, computational intelligence, and traditional symbolic AI. Many tools are used in AI, including versions of search and mathematical optimization, logic, methods based on probability and economics. The AI field draws upon computer science, mathematics, psychology, linguistics, philosophy, neuroscience and artificial psychology.

The field was founded on the claim that human intelligence "can be so precisely described that a machine can be made to simulate it".[9] This raises philosophical arguments about the nature of the mind and the ethics of creating artificial beings endowed with human-like intelligence, issues which have been explored by myth, fiction and philosophy since antiquity.[10] Some people also consider AI a danger to humanity if it progresses unabatedly.[11] Attempts to create artificial intelligence have experienced many setbacks, including the ALPAC report of 1966, the abandonment of perceptrons in 1970, the Lighthill Report of 1973, the second AI winter 1987–1993 and the collapse of the Lisp machine market in 1987.

In the twenty-first century, AI techniques, both "hard" and "soft", have experienced a resurgence following concurrent advances in computer power, sizes of training sets, and theoretical understanding, and AI techniques have become an essential part of the technology industry, helping to solve many challenging problems in computer science.[12]. Recent advancements in AI, and specifically in machine learning, have contributed to the growth of Autonomous Things such as drones and self-driving cars, becoming the main driver of innovation in the automotive industry.

2.1 History

Main articles: History of artificial intelligence and Timeline of artificial intelligence

While thought-capable artificial beings appeared as storytelling devices in antiquity,[13] the idea of actually trying to build a machine to perform useful reasoning may have begun with Ramon Llull (c. 1300 CE). With his Calculus ratiocinator, Gottfried Leibniz extended the concept of the calculating machine (Wilhelm Schickard engineered the first one around 1623), intending to perform operations on concepts rather than numbers.[14] Since the 19th century, artificial beings are common in fiction, as in Mary Shelley's *Frankenstein* or Karel Čapek's *R.U.R. (Rossum's Universal Robots)*.[15]

The study of mechanical or "formal" reasoning began with philosophers and mathematicians in antiquity. In the 19th century, George Boole refined those ideas into propositional logic and Gottlob Frege developed a notational system for mechanical reasoning (a *"predicate cal-*

culus").[16] Around the 1940s, Alan Turing's theory of computation suggested that a machine, by shuffling symbols as simple as "0" and "1", could simulate any conceivable act of mathematical deduction. This insight, that digital computers can simulate any process of formal reasoning, is known as the Church–Turing thesis.[17] Along with concurrent discoveries in neurology, information theory and cybernetics, this led researchers to consider the possibility of building an electronic brain.[18] The first work that is now generally recognized as AI was McCullouch and Pitts' 1943 formal design for Turing-complete "artificial neurons".[14]

The field of AI research was "born"[19] at a conference at Dartmouth College in 1956.[20] Attendees Allen Newell (CMU), Herbert Simon (CMU), John McCarthy (MIT), Marvin Minsky (MIT) and Arthur Samuel (IBM) became the founders and leaders of AI research.[21] At the conference, Newell and Simon, together with programmer J. C. Shaw (RAND), presented the first true artificial intelligence program, the Logic Theorist. This spurred tremendous research in the domain:[22] computers were winning at checkers, solving word problems in algebra, proving logical theorems and speaking English.[23] By the middle of the 1960s, research in the U.S. was heavily funded by the Department of Defense[24] and laboratories had been established around the world.[25] AI's founders were optimistic about the future: Herbert Simon predicted, "machines will be capable, within twenty years, of doing any work a man can do." Marvin Minsky agreed, writing, "within a generation ... the problem of creating 'artificial intelligence' will substantially be solved."[26]

They failed to recognize the difficulty of some of the remaining tasks. Progress slowed and in 1974, in response to the criticism of Sir James Lighthill[27] and ongoing pressure from the US Congress to fund more productive projects, both the U.S. and British governments cut off exploratory research in AI. The next few years would later be called an "AI winter",[28] a period when funding for AI projects was hard to find.

In the early 1980s, AI research was revived by the commercial success of expert systems,[29] a form of AI program that simulated the knowledge and analytical skills of human experts. By 1985 the market for AI had reached over a billion dollars. At the same time, Japan's fifth generation computer project inspired the U.S and British governments to restore funding for academic research.[30] However, beginning with the collapse of the Lisp Machine market in 1987, AI once again fell into disrepute, and a second, longer-lasting hiatus began.[31]

In the late 1990s and early 21st century, AI began to be used for logistics, data mining, medical diagnosis and other areas.[12] The success was due to increasing computational power (see Moore's law), greater emphasis on solving specific problems, new ties between AI and other fields and a commitment by researchers to mathematical methods and scientific standards.[32] Deep Blue became the first computer chess-playing system to beat a reigning world chess champion, Garry Kasparov on 11 May 1997.[33]

Advanced statistical techniques (loosely known as deep learning), access to large amounts of data and faster computers enabled advances in machine learning and perception.[34] By the mid 2010s, machine learning applications were used throughout the world.[35] In a *Jeopardy!* quiz show exhibition match, IBM's question answering system, Watson, defeated the two greatest Jeopardy champions, Brad Rutter and Ken Jennings, by a significant margin.[36] The Kinect, which provides a 3D body–motion interface for the Xbox 360 and the Xbox One use algorithms that emerged from lengthy AI research[37] as do intelligent personal assistants in smartphones.[38] In March 2016, AlphaGo won 4 out of 5 games of Go in a match with Go champion Lee Sedol, becoming the first computer Go-playing system to beat a professional Go player without handicaps.[5][39]

According to Bloomberg's Jack Clark, 2015 was a landmark year for artificial intelligence, with the number of software projects that use AI within Google increasing from a "sporadic usage" in 2012 to more than 2,700 projects. Clark also presents factual data indicating that error rates in image processing tasks have fallen significantly since 2011.[40] He attributes this to an increase in affordable neural networks, due to a rise in cloud computing infrastructure and to an increase in research tools and datasets. Other cited examples include Microsoft's development of a Skype system that can automatically translate from one language to another and Facebook's system that can describe images to blind people.[40]

2.2 Goals

The overall research goal of artificial intelligence is to create technology that allows computers and machines to function in an intelligent manner. The general problem of simulating (or creating) intelligence has been broken down into sub-problems. These consist of particular traits or capabilities that researchers expect an intelligent system to display. The traits described below have received the most attention.[7]

Erik Sandwell emphasizes planning and learning that is relevant and applicable to the given situation.[41]

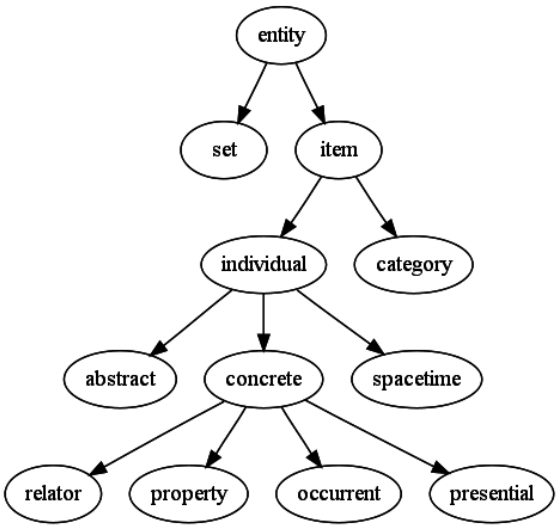
2.2.1 Reasoning, problem solving

Early researchers developed algorithms that imitated step-by-step reasoning that humans use when they solve puzzles or make logical deductions (reason).[42] By the late 1980s and 1990s, AI research had developed methods for dealing with uncertain or incomplete information, employing concepts from probability and economics.[43]

For difficult problems, algorithms can require enormous computational resources—most experience a "combinatorial explosion": the amount of memory or computer time required becomes astronomical for problems of a certain size. The search for more efficient problem-solving algorithms is a high priority.[44]

Human beings ordinarily use fast, intuitive judgments rather than step-by-step deduction that early AI research was able to model.[45] AI has progressed using "sub-symbolic" problem solving: embodied agent approaches emphasize the importance of sensorimotor skills to higher reasoning; neural net research attempts to simulate the structures inside the brain that give rise to this skill; statistical approaches to AI mimic the human ability.

2.2.2 Knowledge representation



An ontology represents knowledge as a set of concepts within a domain and the relationships between those concepts.

Main articles: Knowledge representation and Commonsense knowledge

Knowledge representation[46] and knowledge engineering[47] are central to AI research. Many of the problems machines are expected to solve will require extensive knowledge about the world. Among the things that AI needs to represent are: objects, properties, categories and relations between objects;[48] situations, events, states and time;[49] causes and effects;[50] knowledge about knowledge (what we know about what other people know);[51] and many other, less well researched domains. A representation of "what exists" is an ontology: the set of objects, relations, concepts and so on that the machine knows about. The most general are called upper ontologies, which attempt to provide a foundation for all other knowledge.[52]

Among the most difficult problems in knowledge representation are:

Default reasoning and the qualification problem
Many of the things people know take the form of "working assumptions". For example, if a bird comes up in conversation, people typically picture an animal that is fist sized, sings, and flies. None of these things are true about all birds. John McCarthy identified this problem in 1969[53] as the qualification problem: for any commonsense rule that AI researchers care to represent, there tend to be a huge number of exceptions. Almost nothing is simply true or false in the way that abstract logic requires. AI research has explored a number of solutions to this problem.[54]

The breadth of commonsense knowledge The number of atomic facts that the average person knows is very large. Research projects that attempt to build a complete knowledge base of commonsense knowledge (e.g., Cyc) require enormous amounts of laborious ontological engineering—they must be built, by hand, one complicated concept at a time.[55] A major goal is to have the computer understand enough concepts to be able to learn by reading from sources like the Internet, and thus be able to add to its own ontology.

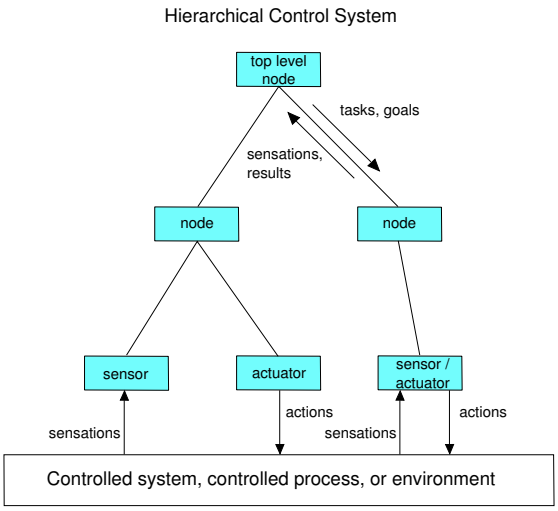
The subsymbolic form of some commonsense knowledge
Much of what people know is not represented as "facts" or "statements" that they could express verbally. For example, a chess master will avoid a particular chess position because it "feels too exposed"[56] or an art critic can take one look at a statue and realize that it is a fake.[57] These are intuitions or tendencies that are represented in the brain non-consciously and sub-symbolically.[58] Knowledge like this informs, supports and provides a context for symbolic, conscious knowledge. As with the related problem of sub-symbolic reasoning, it is hoped that situated AI, computational intelligence, or statistical AI will provide ways to represent this kind of knowledge.[58]

2.2.3 Planning

Main article: Automated planning and scheduling

Intelligent agents must be able to set goals and achieve them.[59] They need a way to visualize the future (they must have a representation of the state of the world and be able to make predictions about how their actions will change it) and be able to make choices that maximize the utility (or "value") of the available choices.[60]

In classical planning problems, the agent can assume that it is the only thing acting on the world and it can be certain



A hierarchical control system is a form of control system in which a set of devices and governing software is arranged in a hierarchy.

what the consequences of its actions may be.[61] However, if the agent is not the only actor, it must periodically ascertain whether the world matches its predictions and it must change its plan as this becomes necessary, requiring the agent to reason under uncertainty.[62]

Multi-agent planning uses the cooperation and competition of many agents to achieve a given goal. Emergent behavior such as this is used by evolutionary algorithms and swarm intelligence.[63]

2.2.4 Learning

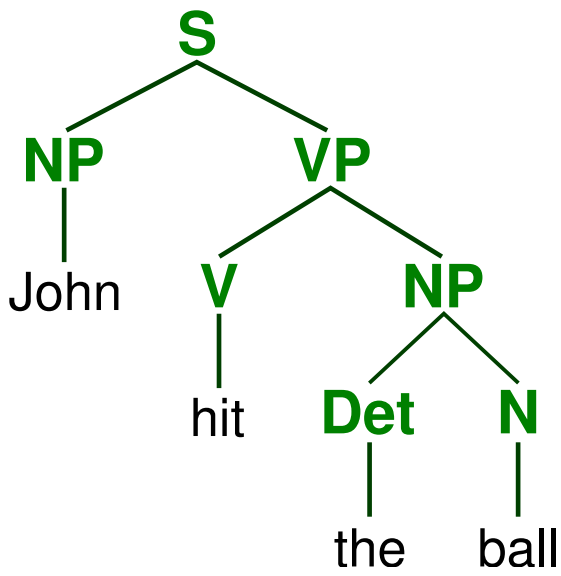
Main article: Machine learning

Machine learning is the study of computer algorithms that improve automatically through experience[64][65] and has been central to AI research since the field's inception.[66]

Unsupervised learning is the ability to find patterns in a stream of input. Supervised learning includes both classification and numerical regression. Classification is used to determine what category something belongs in, after seeing a number of examples of things from several categories. Regression is the attempt to produce a function that describes the relationship between inputs and outputs and predicts how the outputs should change as the inputs change. In reinforcement learning[67] the agent is rewarded for good responses and punished for bad ones. The agent uses this sequence of rewards and punishments to form a strategy for operating in its problem space. These three types of learning can be analyzed in terms of decision theory, using concepts like utility. The mathematical analysis of machine learning algorithms and their performance is a branch of theoretical computer science known as computational learning theory.[68]

Within developmental robotics, developmental learning approaches were elaborated for lifelong cumulative acquisition of repertoires of novel skills by a robot, through autonomous self-exploration and social interaction with human teachers, and using guidance mechanisms such as active learning, maturation, motor synergies, and imitation.[69][70][71][72]

2.2.5 Natural language processing



A parse tree represents the syntactic structure of a sentence according to some formal grammar.

Main article: Natural language processing

Natural language processing[73] gives machines the ability to read and understand the languages that humans speak. A sufficiently powerful natural language processing system would enable natural language user interfaces and the acquisition of knowledge directly from human-written sources, such as newswire texts. Some straightforward applications of natural language processing include information retrieval, text mining, question answering[74] and machine translation.[75]

A common method of processing and extracting meaning from natural language is through semantic indexing. Increases in processing speeds and the drop in the cost of data storage makes indexing large volumes of abstractions of the user's input much more efficient.

2.2.6 Perception

Main articles: Machine perception, Computer vision, and Speech recognition

Machine perception[76] is the ability to use input from sensors (such as cameras, microphones, tactile sensors,

sonar and others more exotic) to deduce aspects of the world. Computer vision[77] is the ability to analyze visual input. A few selected subproblems are speech recognition,[78] facial recognition and object recognition.[79]

2.2.7 Motion and manipulation

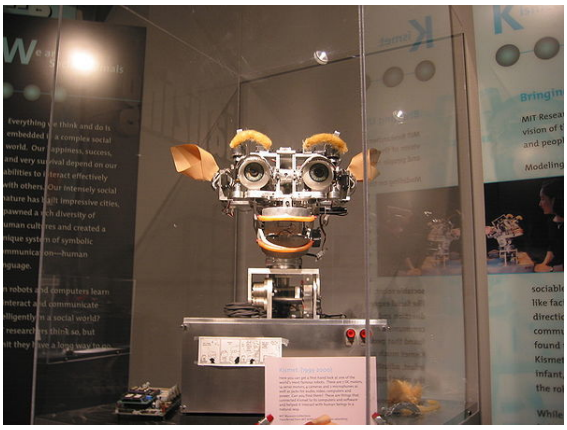
Main article: Robotics

The field of robotics[80] is closely related to AI. Intelligence is required for robots to be able to handle such tasks as object manipulation[81] and navigation, with subproblems of localization (knowing where you are, or finding out where other things are), mapping (learning what is around you, building a map of the environment), and motion planning (figuring out how to get there) or path planning (going from one point in space to another point, which may involve compliant motion – where the robot moves while maintaining physical contact with an object).[82][83]

2.2.8 Social intelligence

Main article: Affective computing

Affective computing is the study and development of



Kismet, a robot with rudimentary social skills[84]

systems and devices that can recognize, interpret, process, and simulate human affects.[85][86] It is an interdisciplinary field spanning computer sciences, psychology, and cognitive science.[87] While the origins of the field may be traced as far back as to early philosophical inquiries into emotion,[88] the more modern branch of computer science originated with Rosalind Picard's 1995 paper[89] on affective computing.[90][91] A motivation for the research is the ability to simulate empathy. The machine should interpret the emotional state of humans and adapt its behaviour to them, giving an appropriate response for those emotions.

Emotion and social skills[92] play two roles for an intelligent agent. First, it must be able to predict the actions of others, by understanding their motives and emotional states. (This involves elements of game theory, decision theory, as well as the ability to model human emotions and the perceptual skills to detect emotions.) Also, in an effort to facilitate human-computer interaction, an intelligent machine might want to be able to *display* emotions—even if it does not actually experience them itself—in order to appear sensitive to the emotional dynamics of human interaction.

2.2.9 Creativity

Main article: Computational creativity

A sub-field of AI addresses creativity both theoretically (from a philosophical and psychological perspective) and practically (via specific implementations of systems that generate outputs that can be considered creative, or systems that identify and assess creativity). Related areas of computational research are Artificial intuition and Artificial thinking.

2.2.10 General intelligence

Main articles: Artificial general intelligence and AI-complete

Many researchers think that their work will eventually be incorporated into a machine with artificial general intelligence, combining all the skills above and exceeding human abilities at most or all of them.[8][93] A few believe that anthropomorphic features like artificial consciousness or an artificial brain may be required for such a project.[94][95]

Many of the problems above may require general intelligence to be considered solved. For example, even a straightforward, specific task like machine translation requires that the machine read and write in both languages (NLP), follow the author's argument (reason), know what is being talked about (knowledge), and faithfully reproduce the author's intention (social intelligence). A problem like machine translation is considered "AI-complete". In order to reach human-level performance for machines, one must solve all the problems.[96]

2.3 Approaches

There is no established unifying theory or paradigm that guides AI research. Researchers disagree about many issues.[97] A few of the most long standing questions that have remained unanswered are these: should artificial intelligence simulate natural intelligence by studying psychology or neurology? Or is human biology as irrelevant to AI research as bird biology is to aeronautical engi-

neering?[98] Can intelligent behavior be described using simple, elegant principles (such as logic or optimization)? Or does it necessarily require solving a large number of completely unrelated problems?[99] Can intelligence be reproduced using high-level symbols, similar to words and ideas? Or does it require "sub-symbolic" processing?[100] John Haugeland, who coined the term GOFAI (Good Old-Fashioned Artificial Intelligence), also proposed that AI should more properly be referred to as synthetic intelligence,[101] a term which has since been adopted by some non-GOFAI researchers.[102][103]

Stuart Shapiro divides AI research into three approaches, which he calls computational psychology, computational philosophy, and computer science. Computational psychology is used to make computer programs that mimic human behavior.[104] Computational philosophy, is used to develop an adaptive, free-flowing computer mind.[104] Implementing computer science serves the goal of creating computers that can perform tasks that only people could previously accomplish.[104] Together, the humanesque behavior, mind, and actions make up artificial intelligence.

2.3.1 Cybernetics and brain simulation

Main articles: Cybernetics and Computational neuroscience

In the 1940s and 1950s, a number of researchers explored the connection between neurology, information theory, and cybernetics. Some of them built machines that used electronic networks to exhibit rudimentary intelligence, such as W. Grey Walter's turtles and the Johns Hopkins Beast. Many of these researchers gathered for meetings of the Teleological Society at Princeton University and the Ratio Club in England.[18] By 1960, this approach was largely abandoned, although elements of it would be revived in the 1980s.

2.3.2 Symbolic

Main article: Symbolic AI

When access to digital computers became possible in the middle 1950s, AI research began to explore the possibility that human intelligence could be reduced to symbol manipulation. The research was centered in three institutions: Carnegie Mellon University, Stanford and MIT, and each one developed its own style of research. John Haugeland named these approaches to AI "good old fashioned AI" or "GOFAI".[105] During the 1960s, symbolic approaches had achieved great success at simulating high-level thinking in small demonstration programs. Approaches based on cybernetics or neural networks were abandoned or pushed into the background.[106] Researchers in the 1960s and the 1970s were convinced that symbolic approaches would eventually succeed in creating a machine with artificial general intelligence and considered this the goal of their field.

Cognitive simulation Economist Herbert Simon and Allen Newell studied human problem-solving skills and attempted to formalize them, and their work laid the foundations of the field of artificial intelligence, as well as cognitive science, operations research and management science. Their research team used the results of psychological experiments to develop programs that simulated the techniques that people used to solve problems. This tradition, centered at Carnegie Mellon University would eventually culminate in the development of the Soar architecture in the middle 1980s.[107][108]

Logic-based Unlike Newell and Simon, John McCarthy felt that machines did not need to simulate human thought, but should instead try to find the essence of abstract reasoning and problem solving, regardless of whether people used the same algorithms.[98] His laboratory at Stanford (SAIL) focused on using formal logic to solve a wide variety of problems, including knowledge representation, planning and learning.[109] Logic was also the focus of the work at the University of Edinburgh and elsewhere in Europe which led to the development of the programming language Prolog and the science of logic programming.[110]

"Anti-logic" or "scruffy" Researchers at MIT (such as Marvin Minsky and Seymour Papert)[111] found that solving difficult problems in vision and natural language processing required ad-hoc solutions – they argued that there was no simple and general principle (like logic) that would capture all the aspects of intelligent behavior. Roger Schank described their "anti-logic" approaches as "scruffy" (as opposed to the "neat" paradigms at CMU and Stanford).[99] Commonsense knowledge bases (such as Doug Lenat's Cyc) are an example of "scruffy" AI, since they must be built by hand, one complicated concept at a time.[112]

Knowledge-based When computers with large memories became available around 1970, researchers from all three traditions began to build knowledge into AI applications.[113] This "knowledge revolution" led to the development and deployment of expert systems (introduced by Edward Feigenbaum), the first truly successful form of AI software.[29] The knowledge revolution was also driven by the realization that enormous amounts of knowledge would be required by many simple AI applications.

2.3.3 Sub-symbolic

By the 1980s progress in symbolic AI seemed to stall and many believed that symbolic systems would never be able to imitate all the processes of human cognition, especially perception, robotics, learning and pattern recognition. A number of researchers began to look into "sub-symbolic" approaches to specific AI problems.[100] Sub-symbolic methods manage to approach intelligence without specific representations of knowledge.

Bottom-up, embodied, situated, behavior-based or nouvelle AI
Researchers from the related field of robotics, such as Rodney Brooks, rejected symbolic AI and focused on the basic engineering problems that would allow robots to move and survive.[114] Their work revived the non-symbolic viewpoint of the early cybernetics researchers of the 1950s and reintroduced the use of control theory in AI. This coincided with the development of the embodied mind thesis in the related field of cognitive science: the idea that aspects of the body (such as movement, perception and visualization) are required for higher intelligence.

Computational intelligence and soft computing
Interest in neural networks and "connectionism" was revived by David Rumelhart and others in the middle of 1980s.[115] Neural networks are an example of soft computing --- they are solutions to problems which cannot be solved with complete logical certainty, and where an approximate solution is often sufficient. Other soft computing approaches to AI include fuzzy systems, evolutionary computation and many statistical tools. The application of soft computing to AI is studied collectively by the emerging discipline of computational intelligence.[116]

2.3.4 Statistical

In the 1990s, AI researchers developed sophisticated mathematical tools to solve specific subproblems. These tools are truly scientific, in the sense that their results are both measurable and verifiable, and they have been responsible for many of AI's recent successes. The shared mathematical language has also permitted a high level of collaboration with more established fields (like mathematics, economics or operations research). Stuart Russell and Peter Norvig describe this movement as nothing less than a "revolution" and "the victory of the neats".[32] Critics argue that these techniques (with few exceptions[117]) are too focused on particular problems and have failed to address the long-term goal of general intelligence.[118] There is an ongoing debate about the relevance and validity of statistical approaches in AI, exemplified in part by exchanges between Peter Norvig and Noam Chomsky.[119][120]

2.3.5 Integrating the approaches

Intelligent agent paradigm An intelligent agent is a system that perceives its environment and takes actions which maximize its chances of success. The simplest intelligent agents are programs that solve specific problems. More complicated agents include human beings and organizations of human beings (such as firms). The paradigm gives researchers license to study isolated problems and find solutions that are both verifiable and useful, without agreeing on one single approach. An agent that solves a specific problem can use any approach that works – some agents are symbolic and logical, some are sub-symbolic neural networks and others may use new approaches. The paradigm also gives researchers a common language to communicate with other fields—such as decision theory and economics—that also use concepts of abstract agents. The intelligent agent paradigm became widely accepted during the 1990s.[1]

Agent architectures and cognitive architectures
Researchers have designed systems to build intelligent systems out of interacting intelligent agents in a multi-agent system.[121] A system with both symbolic and sub-symbolic components is a hybrid intelligent system, and the study of such systems is artificial intelligence systems integration. A hierarchical control system provides a bridge between sub-symbolic AI at its lowest, reactive levels and traditional symbolic AI at its highest levels, where relaxed time constraints permit planning and world modelling.[122] Rodney Brooks' subsumption architecture was an early proposal for such a hierarchical system.[123]

2.4 Tools

In the course of 50 years of research, AI has developed a large number of tools to solve the most difficult problems in computer science. A few of the most general of these methods are discussed below.

2.4.1 Search and optimization

Main articles: Search algorithm, Mathematical optimization, and Evolutionary computation

Many problems in AI can be solved in theory by intelligently searching through many possible solutions:[124] Reasoning can be reduced to performing a search. For

example, logical proof can be viewed as searching for a path that leads from premises to conclusions, where each step is the application of an inference rule.[125] Planning algorithms search through trees of goals and subgoals, attempting to find a path to a target goal, a process called means-ends analysis.[126] Robotics algorithms for moving limbs and grasping objects use local searches in configuration space.[81] Many learning algorithms use search algorithms based on optimization.

Simple exhaustive searches[127] are rarely sufficient for most real world problems: the search space (the number of places to search) quickly grows to astronomical numbers. The result is a search that is too slow or never completes. The solution, for many problems, is to use "heuristics" or "rules of thumb" that eliminate choices that are unlikely to lead to the goal (called "pruning the search tree"). Heuristics supply the program with a "best guess" for the path on which the solution lies.[128] Heuristics limit the search for solutions into a smaller sample size.[82]

A very different kind of search came to prominence in the 1990s, based on the mathematical theory of optimization. For many problems, it is possible to begin the search with some form of a guess and then refine the guess incrementally until no more refinements can be made. These algorithms can be visualized as blind hill climbing: we begin the search at a random point on the landscape, and then, by jumps or steps, we keep moving our guess uphill, until we reach the top. Other optimization algorithms are simulated annealing, beam search and random optimization.[129]

Evolutionary computation uses a form of optimization search. For example, they may begin with a population of organisms (the guesses) and then allow them to mutate and recombine, selecting only the fittest to survive each generation (refining the guesses). Forms of evolutionary computation include swarm intelligence algorithms (such as ant colony or particle swarm optimization)[130] and evolutionary algorithms (such as genetic algorithms, gene expression programming, and genetic programming).[131]

2.4.2 Logic

Main articles: Logic programming and Automated reasoning

Logic[132] is used for knowledge representation and problem solving, but it can be applied to other problems as well. For example, the satplan algorithm uses logic for planning[133] and inductive logic programming is a method for learning.[134]

Several different forms of logic are used in AI research. Propositional or sentential logic[135] is the logic of statements which can be true or false. First-order logic[136] also allows the use of quantifiers and predicates, and can express facts about objects, their properties, and their relations with each other. Fuzzy logic,[137] is a version of first-order logic which allows the truth of a statement to be represented as a value between 0 and 1, rather than simply True (1) or False (0). Fuzzy systems can be used for uncertain reasoning and have been widely used in modern industrial and consumer product control systems. Subjective logic[138] models uncertainty in a different and more explicit manner than fuzzy-logic: a given binomial opinion satisfies belief + disbelief + uncertainty = 1 within a Beta distribution. By this method, ignorance can be distinguished from probabilistic statements that an agent makes with high confidence.

Default logics, non-monotonic logics and circumscription[54] are forms of logic designed to help with default reasoning and the qualification problem. Several extensions of logic have been designed to handle specific domains of knowledge, such as: description logics;[48] situation calculus, event calculus and fluent calculus (for representing events and time);[49] causal calculus;[50] belief calculus;[139] and modal logics.[51]

2.4.3 Probabilistic methods for uncertain reasoning

Main articles: Bayesian network, Hidden Markov model, Kalman filter, Decision theory, and Utility theory

Many problems in AI (in reasoning, planning, learning, perception and robotics) require the agent to operate with incomplete or uncertain information. AI researchers have devised a number of powerful tools to solve these problems using methods from probability theory and economics.[140]

Bayesian networks[141] are a very general tool that can be used for a large number of problems: reasoning (using the Bayesian inference algorithm),[142] learning (using the expectation-maximization algorithm),[143] planning (using decision networks)[144] and perception (using dynamic Bayesian networks).[145] Probabilistic algorithms can also be used for filtering, prediction, smoothing and finding explanations for streams of data, helping perception systems to analyze processes that occur over time (e.g., hidden Markov models or Kalman filters).[145]

A key concept from the science of economics is "utility": a measure of how valuable something is to an intelligent agent. Precise mathematical tools have been developed that analyze how an agent can make choices and plan, using decision theory, decision analysis,[146] and information value theory.[60] These tools include models such as Markov decision processes,[147] dynamic decision networks,[145] game theory and mechanism design.[148]

2.4.4 Classifiers and statistical learning methods

Main articles: Classifier (mathematics), Statistical classification, and Machine learning

The simplest AI applications can be divided into two types: classifiers ("if shiny then diamond") and controllers ("if shiny then pick up"). Controllers do, however, also classify conditions before inferring actions, and therefore classification forms a central part of many AI systems. Classifiers are functions that use pattern matching to determine a closest match. They can be tuned according to examples, making them very attractive for use in AI. These examples are known as observations or patterns. In supervised learning, each pattern belongs to a certain predefined class. A class can be seen as a decision that has to be made. All the observations combined with their class labels are known as a data set. When a new observation is received, that observation is classified based on previous experience.[149]

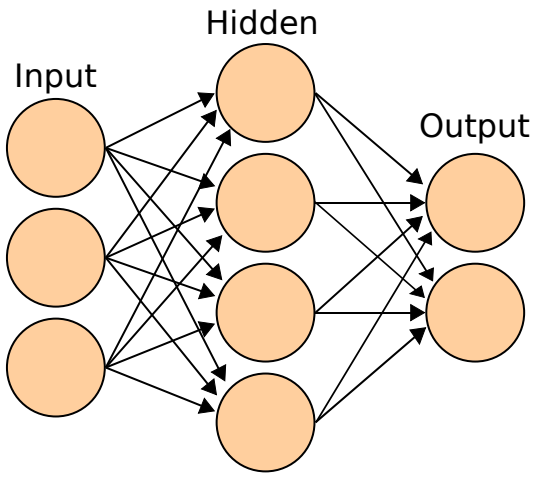
A classifier can be trained in various ways; there are many statistical and machine learning approaches. The most widely used classifiers are the neural network,[150] kernel methods such as the support vector machine,[151] k-nearest neighbor algorithm,[152] Gaussian mixture model,[153] naive Bayes classifier,[154] and decision tree.[155] The performance of these classifiers have been compared over a wide range of tasks. Classifier performance depends greatly on the characteristics of the data to be classified. There is no single classifier that works best on all given problems; this is also referred to as the "no free lunch" theorem. Determining a suitable classifier for a given problem is still more an art than science.[156]

2.4.5 Neural networks

Main articles: Artificial neural network and Connectionism

The study of non-learning artificial neural networks[150] began in the decade before the field of AI research was founded, in the work of Walter Pitts and Warren McCullouch. Frank Rosenblatt invented the perceptron, a learning network with a single layer, similar to the old concept of linear regression. Early pioneers also include Alexey Grigorevich Ivakhnenko, Teuvo Kohonen, Stephen Grossberg, Kunihiko Fukushima, Christoph von der Malsburg, David Willshaw, Shun-Ichi Amari, Bernard Widrow, John Hopfield, Eduardo R. Caianiello, and others.

The main categories of networks are acyclic or feedforward neural networks (where the signal passes in only one direction) and recurrent neural networks (which allow feedback and short-term memories of previous input events). Among the most popular feedforward networks are perceptrons, multi-layer perceptrons and radial basis networks.[157] Neural networks can be applied to the problem of intelligent control (for robotics) or learning, using such techniques as Hebbian learning, GMDH or competitive learning.[158]



A neural network is an interconnected group of nodes, akin to the vast network of neurons in the human brain.

Today, neural networks are often trained by the backpropagation algorithm, which had been around since 1970 as the reverse mode of automatic differentiation published by Seppo Linnainmaa,[159][160] and was introduced to neural networks by Paul Werbos.[161][162][163]

Hierarchical temporal memory is an approach that models some of the structural and algorithmic properties of the neocortex.[164]

2.4.6 Deep feedforward neural networks

Main article: Deep learning

Deep learning in artificial neural networks with many layers has transformed many important subfields of artificial intelligence, including computer vision, speech recognition, natural language processing and others.[165][166][167]

According to a survey,[168] the expression "Deep Learning" was introduced to the Machine Learning community by Rina Dechter in 1986[169] and gained traction after Igor Aizenberg and colleagues introduced it to Artificial Neural Networks in 2000.[170] The first functional Deep Learning networks were published by Alexey Grigorevich Ivakhnenko and V. G. Lapa in 1965.[171] These networks are trained one layer at a time. Ivakhnenko's 1971 paper[172] describes the learning of a deep feedforward multilayer perceptron with eight layers, already much deeper than many later networks. In 2006, a publication by Geoffrey Hinton and Ruslan Salakhutdinov introduced another way of pre-training many-layered feedforward neural networks (FNNs) one layer at a time, treating each

layer in turn as an unsupervised restricted Boltzmann machine, then using supervised backpropagation for fine-tuning.[173] Similar to shallow artificial neural networks, deep neural networks can model complex non-linear relationships. Over the last few years, advances in both machine learning algorithms and computer hardware have led to more efficient methods for training deep neural networks that contain many layers of non-linear hidden units and a very large output layer.[174]

Deep learning often uses convolutional neural networks (CNNs), whose origins can be traced back to the Neocognitron introduced by Kunihiko Fukushima in 1980.[175] In 1989, Yann LeCun and colleagues applied backpropagation to such an architecture. In the early 2000s, in an industrial application CNNs already processed an estimated 10% to 20% of all the checks written in the US.[176] Since 2011, fast implementations of CNNs on GPUs have won many visual pattern recognition competitions.[167]

Deep feedforward neural networks were used in conjunction with reinforcement learning by AlphaGo, Google Deepmind's program that was the first to beat a professional human player.[177]

2.4.7 Deep recurrent neural networks

Main article: Recurrent neural networks

Early on, deep learning was also applied to sequence learning with recurrent neural networks (RNNs)[178] which are general computers and can run arbitrary programs to process arbitrary sequences of inputs. The depth of an RNN is unlimited and depends on the length of its input sequence.[167] RNNs can be trained by gradient descent[179][180][181] but suffer from the vanishing gradient problem.[165][182] In 1992, it was shown that unsupervised pre-training of a stack of recurrent neural networks can speed up subsequent supervised learning of deep sequential problems.[183]

Numerous researchers now use variants of a deep learning recurrent NN called the long short-term memory (LSTM) network published by Hochreiter & Schmidhuber in 1997.[184] LSTM is often trained by Connectionist Temporal Classification (CTC).[185] At Google, Microsoft and Baidu this approach has revolutionised speech recognition.[186][187][188] For example, in 2015, Google's speech recognition experienced a dramatic performance jump of 49% through CTC-trained LSTM, which is now available through Google Voice to billions of smartphone users.[189] Google also used LSTM to improve machine translation,[190] Language Modeling[191] and Multilingual Language Processing.[192] LSTM combined with CNNs also improved automatic image captioning[193] and a plethora of other applications.

2.4.8 Control theory

Main article: Intelligent control

Control theory, the grandchild of cybernetics, has many important applications, especially in robotics.[194]

2.4.9 Languages

Main article: List of programming languages for artificial intelligence

AI researchers have developed several specialized languages for AI research, including Lisp[195] and Prolog.[196]

2.4.10 Evaluating progress

Main article: Progress in artificial intelligence

In 1950, Alan Turing proposed a general procedure to test the intelligence of an agent now known as the Turing test. This procedure allows almost all the major problems of artificial intelligence to be tested. However, it is a very difficult challenge and at present all agents fail.[197]

Artificial intelligence can also be evaluated on specific problems such as small problems in chemistry, handwriting recognition and game-playing. Such tests have been termed subject matter expert Turing tests. Smaller problems provide more achievable goals and there are an ever-increasing number of positive results.[198]

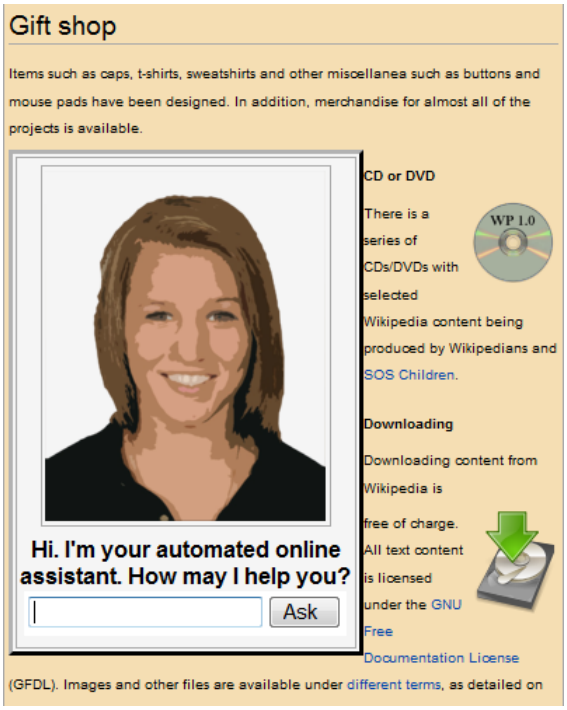
For example, performance at draughts (i.e. checkers) is optimal,[199] performance at chess is high-human and nearing super-human (see computer chess: computers versus human) and performance at many everyday tasks (such as recognizing a face or crossing a room without bumping into something) is sub-human.

A quite different approach measures machine intelligence through tests which are developed from *mathematical* definitions of intelligence. Examples of these kinds of tests start in the late nineties devising intelligence tests using notions from Kolmogorov complexity and data compression.[200] Two major advantages of mathematical definitions are their applicability to nonhuman intelligences and their absence of a requirement for human testers.

A derivative of the Turing test is the Completely Automated Public Turing test to tell Computers and Humans Apart (CAPTCHA). As the name implies, this helps to determine that a user is an actual person and not a computer posing as a human. In contrast to the standard Turing test, CAPTCHA administered by a machine and targeted to a human as opposed to being administered by a human and targeted to a machine. A computer asks a

user to complete a simple test then generates a grade for that test. Computers are unable to solve the problem, so correct solutions are deemed to be the result of a person taking the test. A common type of CAPTCHA is the test that requires the typing of distorted letters, numbers or symbols that appear in an image undecipherable by a computer.[201]

2.5 Applications



An automated online assistant providing customer service on a web page – one of many very primitive applications of artificial intelligence.

Main article: Applications of artificial intelligence

AI is relevant to any intellectual task.[202] Modern artificial intelligence techniques are pervasive and are too numerous to list here. Frequently, when a technique reaches mainstream use, it is no longer considered artificial intelligence; this phenomenon is described as the AI effect.[203]

High-profile examples of AI include autonomous vehicles (such as drones and self-driving cars), medical diagnosis, creating art (such as poetry), proving mathematical theorems, playing games (such as Chess or Go), search engines (such as Google search), online assistants (such as Siri), image recognition in photographs, spam filtering, prediction of judicial decisions[204] and targeting online advertisements.[202][205][206]

With social media sites overtaking TV as a source for news for young people and news organisations increasingly reliant on social media platforms for generating distribution,[207] major publishers now use artificial intelligence (AI) technology to post stories more effectively and generate higher volumes of traffic.[208]

2.5.1 Competitions and prizes

Main article: Competitions and prizes in artificial intelligence

There are a number of competitions and prizes to promote research in artificial intelligence. The main areas promoted are: general machine intelligence, conversational behavior, data-mining, robotic cars, robot soccer and games.

2.5.2 Healthcare

Artificial intelligence is breaking into the healthcare industry by assisting doctors. According to Bloomberg Technology, Microsoft has developed AI to help doctors find the right treatments for cancer.[209] There is a great amount of research and drugs developed relating to cancer. In detail, there are more than 800 medicines and vaccines to treat cancer. This negatively affects the doctors, because there are way too many options to choose from, making it more difficult to choose the right drugs for the patients. Microsoft is working on a project to develop a machine called "Hanover". Its goal is to memorize all the papers necessary to cancer and help predict which combinations of drugs will be most effective for each patient. One project that is being worked on at the moment is fighting myeloid leukemia, a fatal cancer where the treatment has not improved in decades. Another study was reported to have found that artificial intelligence was as good as trained doctors in identifying skin cancers.[210] Another study is using artificial intelligence to try and monitor multiple high-risk patients, and this is done by asking each patient numerous questions based on data acquired from live doctor to patient interactions.[211]

According to CNN, there was a recent study by surgeons at the Children's National Medical Center in Washington which successfully demonstrated surgery with an autonomous robot. The team supervised the robot while it performed soft-tissue surgery, stitching together a pig's bowel during open surgery, and doing so better than a human surgeon, the team claimed.[212]

2.5.3 Automotive industry

Advancements in AI have contributed to the growth of the automotive industry through the creation and evolution of self-driving vehicles. As of 2016, there are over 30 companies utilizing AI into the creation of driverless cars. A few companies involved with AI include Tesla, Google, and Apple.[213]

Many components contribute to the functioning of self-driving cars. These vehicles incorporate systems such as braking, lane changing, collision prevention, navigation and mapping. Together, these systems, as well as high performance computers are integrated into one complex vehicle.[214]

One main factor that influences the ability for a driverless car to function is mapping. In general, the vehicle would be pre-programmed with a map of the area being driven. This map would include data on the approximations of street light and curb heights in order for the vehicle to be aware of its surroundings. However, Google has been working on an algorithm with the purpose of eliminating the need for pre-programmed maps and instead, creating a device that would be able to adjust to a variety of new surroundings.[215] Some self-driving cars are not equipped with steering wheels or brakes, so there has also been research focused on creating an algorithm that is capable of maintaining a safe environment for the passengers in the vehicle through awareness of speed and driving conditions.[216]

2.5.4 Finance

Financial institutions have long used artificial neural network systems to detect charges or claims outside of the norm, flagging these for human investigation.

Use of AI in banking can be tracked back to 1987 when Security Pacific National Bank in USA set-up a Fraud Prevention Task force to counter the unauthorised use of debit cards. Apps like Kasisito and Moneystream are using AI in financial services

Banks use artificial intelligence systems to organize operations, maintain book-keeping, invest in stocks, and manage properties. AI can react to changes overnight or when business is not taking place.[217] In August 2001, robots beat humans in a simulated financial trading competition.[218]

AI has also reduced fraud and crime by monitoring behavioral patterns of users for any changes or anomalies.[219]

2.6 Platforms

A platform (or "computing platform") is defined as "some sort of hardware architecture or software framework (including application frameworks), that allows software to run". As Rodney Brooks pointed out many years ago,[220] it is not just the artificial intelligence software that defines the AI features of the platform, but rather the actual platform itself that affects the AI that results, i.e., there needs to be work in AI problems on real-world platforms rather than in isolation.

A wide variety of platforms has allowed different aspects of AI to develop, ranging from expert systems such as Cyc to deep-learning frameworks to robot platforms such as the Roomba with open interface.[221] Recent advances in deep artificial neural networks and distributed computing have led to a proliferation of software libraries, including Deeplearning4j, TensorFlow, Theano and Torch.

2.6.1 Partnership on AI

Amazon, Google, Facebook, IBM, and Microsoft have established a non-profit partnership to formulate best practices on artificial intelligence technologies, advance the public's understanding, and to serve as a platform about artificial intelligence.[222] They stated: "This partnership on AI will conduct research, organize discussions, provide thought leadership, consult with relevant third parties, respond to questions from the public and media, and create educational material that advance the understanding of AI technologies including machine perception, learning, and automated reasoning."[222] Apple joined other tech companies as a founding member of the Partnership on AI in January 2017. The corporate members will make financial and research contributions to the group, while engaging with the scientific community to bring academics onto the board.[223]

2.7 Philosophy and ethics

Main articles: Philosophy of artificial intelligence and Ethics of artificial intelligence

There are three philosophical questions related to AI:

1. Is artificial general intelligence possible? Can a machine solve any problem that a human being can solve using intelligence? Or are there hard limits to what a machine can accomplish?

2. Are intelligent machines dangerous? How can we ensure that machines behave ethically and that they are used ethically?

3. Can a machine have a mind, consciousness and mental states in exactly the same sense that human beings do? Can a machine be sentient, and thus deserve certain rights? Can a machine intentionally cause harm?

2.7.1 The limits of artificial general intelligence

Main articles: philosophy of AI, Turing test, Physical symbol systems hypothesis, Dreyfus' critique of AI, The Emperor's New Mind, and AI effect

Can a machine be intelligent? Can it "think"?

Turing's "polite convention" We need not decide if a machine can "think"; we need only decide if a machine can act as intelligently as a human being. This approach to the philosophical problems associated with artificial intelligence forms the basis of the Turing test.[197]

The Dartmouth proposal "Every aspect of learning or any other feature of intelligence can be so precisely described that a machine can be made to simulate it." This conjecture was printed in the proposal for the Dartmouth Conference of 1956, and represents the position of most working AI researchers.[224]

Newell and Simon's physical symbol system hypothesis "A physical symbol system has the necessary and sufficient means of general intelligent action." Newell and Simon argue that intelligence consists of formal operations on symbols.[225] Hubert Dreyfus argued that, on the contrary, human expertise depends on unconscious instinct rather than conscious symbol manipulation and on having a "feel" for the situation rather than explicit symbolic knowledge. (See Dreyfus' critique of AI.)[226][227]

Gödelian arguments Gödel himself,[228] John Lucas (in 1961) and Roger Penrose (in a more detailed argument from 1989 onwards) made highly technical arguments that human mathematicians can consistently see the truth of their own "Gödel statements" and therefore have computational abilities beyond that of mechanical Turing machines.[229] However, the modern consensus in the scientific and mathematical community is that these "Gödelian arguments" fail.[230][231][232]

The artificial brain argument The brain can be simulated by machines and because brains are intelligent, simulated brains must also be intelligent; thus machines can be intelligent. Hans Moravec, Ray Kurzweil and others have argued that it is technologically feasible to copy the brain directly into hardware and software, and that such a simulation will be essentially identical to the original.[95]

The AI effect Machines are *already* intelligent, but observers have failed to recognize it. When Deep Blue beat Garry Kasparov in chess, the machine was acting intelligently. However, onlookers commonly discount the behavior of an artificial intelligence program by arguing that it is not "real" intelligence after all; thus "real" intelligence is whatever intelligent behavior people can do that machines still can not. This is known as the AI Effect: "AI is whatever hasn't been done yet."

2.7.2 Potential risks and moral reasoning

Widespread use of artificial intelligence could have unintended consequences that are dangerous or undesirable. Scientists from the Future of Life Institute, among others, described some short-term research goals to be how AI influences the economy, the laws and ethics that are involved with AI and how to minimize AI security risks. In the long-term, the scientists have proposed to continue optimizing function while minimizing possible security risks that come along with new technologies.[233]

Machines with intelligence have the potential to use their intelligence to make ethical decisions. Research in this area includes "machine ethics", "artificial moral agents", and the study of "malevolent vs. friendly AI".

Existential risk

Main article: Existential risk from advanced artificial intelligence

> The development of full artificial intelligence could spell the end of the human race. Once humans develop artificial intelligence, it will take off on its own and redesign itself at an ever-increasing rate. Humans, who are limited by slow biological evolution, couldn't compete and would be superseded.
> — Stephen Hawking[234]

A common concern about the development of artificial intelligence is the potential threat it could pose to mankind. This concern has recently gained attention after mentions by celebrities including Stephen Hawking, Bill Gates,[235] and Elon Musk.[236] A group of prominent tech titans including Peter Thiel, Amazon Web Services and Musk have committed $1billion to OpenAI a nonprofit company aimed at championing responsible AI development.[237] The opinion of experts within the field of artificial intelligence is mixed, with sizable fractions both concerned and unconcerned by risk from eventual superhumanly-capable AI.[238]

In his book *Superintelligence*, Nick Bostrom provides an argument that artificial intelligence will pose a threat to mankind. He argues that sufficiently intelligent AI, if it chooses actions based on achieving some goal, will exhibit convergent behavior such as acquiring resources or protecting itself from being shut down. If this AI's goals do not reflect humanity's - one example is an AI told to compute as many digits of pi as possible - it might harm humanity in order to acquire more resources or prevent itself from being shut down, ultimately to better achieve its goal.

For this danger to be realized, the hypothetical AI would have to overpower or out-think all of humanity, which a

minority of experts argue is a possibility far enough in the future to not be worth researching.[239][240] Other counterarguments revolve around humans being either intrinsically or convergently valuable from the perspective of an artificial intelligence.[241]

Concern over risk from artificial intelligence has led to some high-profile donations and investments. In January 2015, Elon Musk donated ten million dollars to the Future of Life Institute to fund research on understanding AI decision making. The goal of the institute is to "grow wisdom with which we manage" the growing power of technology. Musk also funds companies developing artificial intelligence such as Google DeepMind and Vicarious to "just keep an eye on what's going on with artificial intelligence.[242] I think there is potentially a dangerous outcome there."[243][244]

Development of militarized artificial intelligence is a related concern. Currently, 50+ countries are researching battlefield robots, including the United States, China, Russia, and the United Kingdom. Many people concerned about risk from superintelligent AI also want to limit the use of artificial soldiers.[245]

Devaluation of humanity

Main article: Computer Power and Human Reason

Joseph Weizenbaum wrote that AI applications can not, by definition, successfully simulate genuine human empathy and that the use of AI technology in fields such as customer service or psychotherapy[246] was deeply misguided. Weizenbaum was also bothered that AI researchers (and some philosophers) were willing to view the human mind as nothing more than a computer program (a position now known as computationalism). To Weizenbaum these points suggest that AI research devalues human life.[247]

Decrease in demand for human labor

Martin Ford, author of *The Lights in the Tunnel: Automation, Accelerating Technology and the Economy of the Future*,[248] and others argue that specialized artificial intelligence applications, robotics and other forms of automation will ultimately result in significant unemployment as machines begin to match and exceed the capability of workers to perform most routine and repetitive jobs. Ford predicts that many knowledge-based occupations—and in particular entry level jobs—will be increasingly susceptible to automation via expert systems, machine learning[249] and other AI-enhanced applications. AI-based applications may also be used to amplify the capabilities of low-wage offshore workers, making it more feasible to outsource knowledge work.[250]

Artificial moral agents

This raises the issue of how ethically the machine should behave towards both humans and other AI agents. This issue was addressed by Wendell Wallach in his book titled *Moral Machines* in which he introduced the concept of artificial moral agents (AMA).[251] For Wallach, AMAs have become a part of the research landscape of artificial intelligence as guided by its two central questions which he identifies as "Does Humanity Want Computers Making Moral Decisions"[252] and "Can (Ro)bots Really Be Moral".[253] For Wallach the question is not centered on the issue of *whether* machines can demonstrate the equivalent of moral behavior in contrast to the *constraints* which society may place on the development of AMAs.[254]

Machine ethics

Main article: Machine ethics

The field of machine ethics is concerned with giving machines ethical principles, or a procedure for discovering a way to resolve the ethical dilemmas they might encounter, enabling them to function in an ethically responsible manner through their own ethical decision making.[255] The field was delineated in the AAAI Fall 2005 Symposium on Machine Ethics: "Past research concerning the relationship between technology and ethics has largely focused on responsible and irresponsible use of technology by human beings, with a few people being interested in how human beings ought to treat machines. In all cases, only human beings have engaged in ethical reasoning. The time has come for adding an ethical dimension to at least some machines. Recognition of the ethical ramifications of behavior involving machines, as well as recent and potential developments in machine autonomy, necessitate this. In contrast to computer hacking, software property issues, privacy issues and other topics normally ascribed to computer ethics, machine ethics is concerned with the behavior of machines towards human users and other machines. Research in machine ethics is key to alleviating concerns with autonomous systems—it could be argued that the notion of autonomous machines without such a dimension is at the root of all fear concerning machine intelligence. Further, investigation of machine ethics could enable the discovery of problems with current ethical theories, advancing our thinking about Ethics."[256] Machine ethics is sometimes referred to as machine morality, computational ethics or computational morality. A variety of perspectives of this nascent field can be found in the collected edition "Machine Ethics"[255] that stems from the AAAI Fall 2005 Symposium on Machine Ethics.[256]

Malevolent and friendly AI

Main article: Friendly AI

Political scientist Charles T. Rubin believes that AI can be neither designed nor guaranteed to be benevolent.[257] He argues that "any sufficiently advanced benevolence may be indistinguishable from malevolence." Humans should not assume machines or robots would treat us favorably, because there is no *a priori* reason to believe that they would be sympathetic to our system of morality, which has evolved along with our particular biology (which AIs would not share). Hyper-intelligent software may not necessarily decide to support the continued existence of mankind, and would be extremely difficult to stop. This topic has also recently begun to be discussed in academic publications as a real source of risks to civilization, humans, and planet Earth.

Physicist Stephen Hawking, Microsoft founder Bill Gates and SpaceX founder Elon Musk have expressed concerns about the possibility that AI could evolve to the point that humans could not control it, with Hawking theorizing that this could "spell the end of the human race".[258]

One proposal to deal with this is to ensure that the first generally intelligent AI is 'Friendly AI', and will then be able to control subsequently developed AIs. Some question whether this kind of check could really remain in place.

Leading AI researcher Rodney Brooks writes, "I think it is a mistake to be worrying about us developing malevolent AI anytime in the next few hundred years. I think the worry stems from a fundamental error in not distinguishing the difference between the very real recent advances in a particular aspect of AI, and the enormity and complexity of building sentient volitional intelligence."[259]

2.7.3 Machine consciousness, sentience and mind

Main article: Artificial consciousness

If an AI system replicates all key aspects of human intelligence, will that system also be sentient – will it have a mind which has conscious experiences? This question is closely related to the philosophical problem as to the nature of human consciousness, generally referred to as the hard problem of consciousness.

Consciousness

Main articles: Hard problem of consciousness and Theory of mind

Computationalism and functionalism

Main articles: Computationalism and Functionalism (philosophy of mind)

Computationalism is the position in the philosophy of mind that the human mind or the human brain (or both) is an information processing system and that thinking is a form of computing.[260] Computationalism argues that the relationship between mind and body is similar or identical to the relationship between software and hardware and thus may be a solution to the mind-body problem. This philosophical position was inspired by the work of AI researchers and cognitive scientists in the 1960s and was originally proposed by philosophers Jerry Fodor and Hilary Putnam.

Strong AI hypothesis

Main article: Chinese room

The philosophical position that John Searle has named "strong AI" states: "The appropriately programmed computer with the right inputs and outputs would thereby have a mind in exactly the same sense human beings have minds."[261] Searle counters this assertion with his Chinese room argument, which asks us to look *inside* the computer and try to find where the "mind" might be.[262]

Robot rights

Main article: Robot rights

Mary Shelley's *Frankenstein* considers a key issue in the ethics of artificial intelligence: if a machine can be created that has intelligence, could it also *feel*? If it can feel, does it have the same rights as a human? The idea also appears in modern science fiction, such as the film *A.I.: Artificial Intelligence*, in which humanoid machines have the ability to feel emotions. This issue, now known as "robot rights", is currently being considered by, for example, California's Institute for the Future, although many critics believe that the discussion is premature.[263] The subject is profoundly discussed in the 2010 documentary film *Plug & Pray*.[264]

2.7.4 Superintelligence

Main article: Superintelligence

Are there limits to how intelligent machines – or human-machine hybrids – can be? A superintelligence, hyperintelligence, or superhuman intelligence is a hypothetical agent that would possess intelligence far surpassing that

of the brightest and most gifted human mind. "Superintelligence" may also refer to the form or degree of intelligence possessed by such an agent.[93]

Technological singularity

Main articles: Technological singularity and Moore's law

If research into Strong AI produced sufficiently intelligent software, it might be able to reprogram and improve itself. The improved software would be even better at improving itself, leading to recursive self-improvement.[265] The new intelligence could thus increase exponentially and dramatically surpass humans. Science fiction writer Vernor Vinge named this scenario "singularity".[266] Technological singularity is when accelerating progress in technologies will cause a runaway effect wherein artificial intelligence will exceed human intellectual capacity and control, thus radically changing or even ending civilization. Because the capabilities of such an intelligence may be impossible to comprehend, the technological singularity is an occurrence beyond which events are unpredictable or even unfathomable.[266][93]

Ray Kurzweil has used Moore's law (which describes the relentless exponential improvement in digital technology) to calculate that desktop computers will have the same processing power as human brains by the year 2029, and predicts that the singularity will occur in 2045.[266]

Transhumanism

Main article: Transhumanism

> You awake one morning to find your brain has another lobe functioning. Invisible, this auxiliary lobe answers your questions with information beyond the realm of your own memory, suggests plausible courses of action, and asks questions that help bring out relevant facts. You quickly come to rely on the new lobe so much that you stop wondering how it works. You just use it. This is the dream of artificial intelligence.
> — *Byte*, April 1985[267]

Robot designer Hans Moravec, cyberneticist Kevin Warwick and inventor Ray Kurzweil have predicted that humans and machines will merge in the future into cyborgs that are more capable and powerful than either.[268] This idea, called transhumanism, which has roots in Aldous Huxley and Robert Ettinger, has been illustrated in fiction as well, for example in the manga *Ghost in the Shell* and the science-fiction series *Dune*.

In the 1980s artist Hajime Sorayama's Sexy Robots series were painted and published in Japan depicting the actual organic human form with lifelike muscular metallic skins and later "the Gynoids" book followed that was used by or influenced movie makers including George Lucas and other creatives. Sorayama never considered these organic robots to be real part of nature but always unnatural product of the human mind, a fantasy existing in the mind even when realized in actual form.

Edward Fredkin argues that "artificial intelligence is the next stage in evolution", an idea first proposed by Samuel Butler's "Darwin among the Machines" (1863), and expanded upon by George Dyson in his book of the same name in 1998.[269]

2.8 In fiction

Main article: Artificial intelligence in fiction

Thought-capable artificial beings have appeared as storytelling devices since antiquity.[13]

The implications of a constructed machine exhibiting artificial intelligence have been a persistent theme in science fiction since the twentieth century. Early stories typically revolved around intelligent robots. The word "robot" itself was coined by Karel Čapek in his 1921 play *R.U.R.*, the title standing for "Rossum's Universal Robots". Later, the SF writer Isaac Asimov developed the Three Laws of Robotics which he subsequently explored in a long series of robot stories. Asimov's laws are often brought up during layman discussions of machine ethics;[270] while almost all artificial intelligence researchers are familiar with Asimov's laws through popular culture, they generally consider the laws useless for many reasons, one of which is their ambiguity.[271]

The novel *Do Androids Dream of Electric Sheep?*, by Philip K. Dick, tells a science fiction story about Androids and humans clashing in a futuristic world. Elements of artificial intelligence include the empathy box, mood organ, and the androids themselves. Throughout the novel, Dick portrays the idea that human subjectivity is altered by technology created with artificial intelligence.[272]

Nowadays AI is firmly rooted in popular culture; intelligent robots appear in innumerable works. HAL, the murderous computer in charge of the spaceship in *2001: A Space Odyssey* (1968), is an example of the common "robotic rampage" archetype in science fiction movies. *The Terminator* (1984) and *The Matrix* (1999) provide additional widely familiar examples. In contrast, the rare loyal robots such as Gort from *The Day the Earth Stood Still* (1951) and Bishop from *Aliens* (1986) are less prominent in popular culture.[273]

2.9 See also

- Abductive reasoning
- Case-based reasoning
- Commonsense reasoning
- Emergent algorithm
- Evolutionary computing
- Glossary of artificial intelligence
- Machine learning
- Mathematical optimization
- Soft computing
- Swarm intelligence

2.10 Notes

[1] The intelligent agent paradigm:

- Russell & Norvig 2003, pp. 27, 32–58, 968–972
- Poole, Mackworth & Goebel 1998, pp. 7–21
- Luger & Stubblefield 2004, pp. 235–240
- Hutter 2005, pp. 125–126

The definition used in this article, in terms of goals, actions, perception and environment, is due to Russell & Norvig (2003). Other definitions also include knowledge and learning as additional criteria.

[2] Russell & Norvig 2009, p. 2.

[3] Schank, Roger C. (1991). "Where's the AI". *AI magazine*. Vol. 12 no. 4. p. 38.

[4] Russell & Norvig 2009.

[5] "AlphaGo - Google DeepMind".

[6] Pamela McCorduck (2004, pp. 424) writes of "the rough shattering of AI in subfields—vision, natural language, decision theory, genetic algorithms, robotics ... and these with own sub-subfield—that would hardly have anything to say to each other."

[7] This list of intelligent traits is based on the topics covered by the major AI textbooks, including:

- Russell & Norvig 2003
- Luger & Stubblefield 2004
- Poole, Mackworth & Goebel 1998
- Nilsson 1998

[8] General intelligence (strong AI) is discussed in popular introductions to AI:

- Kurzweil 1999 and Kurzweil 2005

[9] See the Dartmouth proposal, under Philosophy, below.

[10] This is a central idea of Pamela McCorduck's *Machines Who Think*. She writes: "I like to think of artificial intelligence as the scientific apotheosis of a venerable cultural tradition." (McCorduck 2004, p. 34) "Artificial intelligence in one form or another is an idea that has pervaded Western intellectual history, a dream in urgent need of being realized." (McCorduck 2004, p. xviii) "Our history is full of attempts—nutty, eerie, comical, earnest, legendary and real—to make artificial intelligences, to reproduce what is the essential us—bypassing the ordinary means. Back and forth between myth and reality, our imaginations supplying what our workshops couldn't, we have engaged for a long time in this odd form of self-reproduction." (McCorduck 2004, p. 3) She traces the desire back to its Hellenistic roots and calls it the urge to "forge the Gods." (McCorduck 2004, pp. 340–400)

[11] http://betanews.com/2016/10/21/artificial-intelligence-stephen-hawking/

[12] AI applications widely used behind the scenes:

- Russell & Norvig 2003, p. 28
- Kurzweil 2005, p. 265
- NRC 1999, pp. 216–222

[13] AI in myth:

- McCorduck 2004, pp. 4–5
- Russell & Norvig 2003, p. 939

[14] Russell & Norvig 2009, p. 16.

[15] AI in early science fiction.

- McCorduck 2004, pp. 17–25

[16] Nilsson 1998, Section 1.3.

[17] Formal reasoning:

- Berlinski, David (2000). *The Advent of the Algorithm*. Harcourt Books. ISBN 0-15-601391-6. OCLC 46890682.

[18] AI's immediate precursors:

- McCorduck 2004, pp. 51–107
- Crevier 1993, pp. 27–32
- Russell & Norvig 2003, pp. 15, 940
- Moravec 1988, p. 3

[19] 1947-, Crevier, Daniel, (1993-01-01). *The tumultuous history of the search for artificial intelligence*. Basic Books. ISBN 0465029973. OCLC 490227350.

[20] Dartmouth conference:

- McCorduck 2004, pp. 111–136
- Crevier 1993, pp. 47–49, who writes "the conference is generally recognized as the official birthdate of the new science."
- Russell & Norvig 2003, p. 17, who call the conference "the birth of artificial intelligence."
- NRC 1999, pp. 200–201

[21] Hegemony of the Dartmouth conference attendees:

- Russell & Norvig 2003, p. 17, who write "for the next 20 years the field would be dominated by these people and their students."
- McCorduck 2004, pp. 129–130

[22] Russell & Norvig 2003, p. 18.

[23] "Golden years" of AI (successful symbolic reasoning programs 1956–1973):

- McCorduck 2004, pp. 243–252
- Crevier 1993, pp. 52–107
- Moravec 1988, p. 9
- Russell & Norvig 2003, pp. 18–21

The programs described are Arthur Samuel's checkers program for the IBM 701, Daniel Bobrow's STUDENT, Newell and Simon's Logic Theorist and Terry Winograd's SHRDLU.

[24] DARPA pours money into undirected pure research into AI during the 1960s:

- McCorduck 2004, pp. 131
- Crevier 1993, pp. 51, 64–65
- NRC 1999, pp. 204–205

[25] AI in England:

- Howe 1994

[26] Optimism of early AI:

- Herbert Simon quote: Simon 1965, p. 96 quoted in Crevier 1993, p. 109.
- Marvin Minsky quote: Minsky 1967, p. 2 quoted in Crevier 1993, p. 109.

[27] Lighthill 1973.

[28] First AI Winter, Mansfield Amendment, Lighthill report

- Crevier 1993, pp. 115–117
- Russell & Norvig 2003, p. 22
- NRC 1999, pp. 212–213
- Howe 1994

[29] Expert systems:

- ACM 1998, I.2.1
- Russell & Norvig 2003, pp. 22–24
- Luger & Stubblefield 2004, pp. 227–331
- Nilsson 1998, chpt. 17.4
- McCorduck 2004, pp. 327–335, 434–435
- Crevier 1993, pp. 145–62, 197–203

[30] Boom of the 1980s: rise of expert systems, Fifth Generation Project, Alvey, MCC, SCI:

- McCorduck 2004, pp. 426–441
- Crevier 1993, pp. 161–162,197–203, 211, 240
- Russell & Norvig 2003, p. 24
- NRC 1999, pp. 210–211

[31] Second AI winter:

- McCorduck 2004, pp. 430–435
- Crevier 1993, pp. 209–210
- NRC 1999, pp. 214–216

[32] Formal methods are now preferred ("Victory of the neats"):

- Russell & Norvig 2003, pp. 25–26
- McCorduck 2004, pp. 486–487

[33] McCorduck 2004, pp. 480–483.

[34] Deep learning:

- citation in progress

[35] Machine learning and AI's successes in the early 21st century:

- citation in progress

[36] Markoff 2011.

[37] Administrator. "Kinect's AI breakthrough explained". *i-programmer.info*.

[38] Rowinski, Dan (15 January 2013). "Virtual Personal Assistants & The Future Of Your Smartphone [Infographic]". *ReadWrite*.

[39] "Artificial intelligence: Google's AlphaGo beats Go master Lee Se-dol". *BBC News*. 12 March 2016. Retrieved 1 October 2016.

[40] Clark, Jack (8 December 2015). "Why 2015 Was a Breakthrough Year in Artificial Intelligence". *Bloomberg News*. Retrieved 23 November 2016. After a half-decade of quiet breakthroughs in artificial intelligence, 2015 has been a landmark year. Computers are smarter and learning faster than ever.

[41] Sandewall, Erik. "The Goals of Artificial Intelligence Research – A Brief introduction". Knowledge Representation Framework Project – Linkoping University. N.p., 8 August 2010. 8 December 2016.

[42] Problem solving, puzzle solving, game playing and deduction:

- Russell & Norvig 2003, chpt. 3–9,
- Poole, Mackworth & Goebel 1998, chpt. 2,3,7,9,
- Luger & Stubblefield 2004, chpt. 3,4,6,8,
- Nilsson 1998, chpt. 7–12

[43] Uncertain reasoning:

- Russell & Norvig 2003, pp. 452–644,
- Poole, Mackworth & Goebel 1998, pp. 345–395,
- Luger & Stubblefield 2004, pp. 333–381,
- Nilsson 1998, chpt. 19

[44] Intractability and efficiency and the combinatorial explosion:

- Russell & Norvig 2003, pp. 9, 21–22

[45] Psychological evidence of sub-symbolic reasoning:

- Wason & Shapiro (1966) showed that people do poorly on completely abstract problems, but if the problem is restated to allow the use of intuitive social intelligence, performance dramatically improves. (See Wason selection task)
- Kahneman, Slovic & Tversky (1982) have shown that people are terrible at elementary problems that involve uncertain reasoning. (See list of cognitive biases for several examples).
- Lakoff & Núñez (2000) have controversially argued that even our skills at mathematics depend on knowledge and skills that come from "the body", i.e. sensorimotor and perceptual skills. (See Where Mathematics Comes From)

[46] Knowledge representation:

- ACM 1998, I.2.4,
- Russell & Norvig 2003, pp. 320–363,
- Poole, Mackworth & Goebel 1998, pp. 23–46, 69–81, 169–196, 235–277, 281–298, 319–345,
- Luger & Stubblefield 2004, pp. 227–243,
- Nilsson 1998, chpt. 18

[47] Knowledge engineering:

- Russell & Norvig 2003, pp. 260–266,
- Poole, Mackworth & Goebel 1998, pp. 199–233,
- Nilsson 1998, chpt. ≈17.1–17.4

[48] Representing categories and relations: Semantic networks, description logics, inheritance (including frames and scripts):

- Russell & Norvig 2003, pp. 349–354,
- Poole, Mackworth & Goebel 1998, pp. 174–177,
- Luger & Stubblefield 2004, pp. 248–258,
- Nilsson 1998, chpt. 18.3

[49] Representing events and time:Situation calculus, event calculus, fluent calculus (including solving the frame problem):

- Russell & Norvig 2003, pp. 328–341,
- Poole, Mackworth & Goebel 1998, pp. 281–298,
- Nilsson 1998, chpt. 18.2

[50] Causal calculus:

- Poole, Mackworth & Goebel 1998, pp. 335–337

[51] Representing knowledge about knowledge: Belief calculus, modal logics:

- Russell & Norvig 2003, pp. 341–344,
- Poole, Mackworth & Goebel 1998, pp. 275–277

[52] Ontology:

- Russell & Norvig 2003, pp. 320–328

[53] Qualification problem:

- McCarthy & Hayes 1969
- Russell & Norvig 2003

While McCarthy was primarily concerned with issues in the logical representation of actions, Russell & Norvig 2003 apply the term to the more general issue of default reasoning in the vast network of assumptions underlying all our commonsense knowledge.

[54] Default reasoning and default logic, non-monotonic logics, circumscription, closed world assumption, abduction (Poole *et al.* places abduction under "default reasoning". Luger *et al.* places this under "uncertain reasoning"):

- Russell & Norvig 2003, pp. 354–360,
- Poole, Mackworth & Goebel 1998, pp. 248–256, 323–335,
- Luger & Stubblefield 2004, pp. 335–363,
- Nilsson 1998, ~18.3.3

[55] Breadth of commonsense knowledge:

- Russell & Norvig 2003, p. 21,
- Crevier 1993, pp. 113–114,
- Moravec 1988, p. 13,
- Lenat & Guha 1989 (Introduction)

[56] Dreyfus & Dreyfus 1986.

[57] Gladwell 2005.

[58] Expert knowledge as embodied intuition:

- Dreyfus & Dreyfus 1986 (Hubert Dreyfus is a philosopher and critic of AI who was among the first to argue that most useful human knowledge was encoded sub-symbolically. See Dreyfus' critique of AI)
- Gladwell 2005 (Gladwell's *Blink* is a popular introduction to sub-symbolic reasoning and knowledge.)
- Hawkins & Blakeslee 2005 (Hawkins argues that sub-symbolic knowledge should be the primary focus of AI research.)

[59] Planning:

- ACM 1998, ~I.2.8,
- Russell & Norvig 2003, pp. 375–459,
- Poole, Mackworth & Goebel 1998, pp. 281–316,
- Luger & Stubblefield 2004, pp. 314–329,
- Nilsson 1998, chpt. 10.1–2, 22

[60] Information value theory:

- Russell & Norvig 2003, pp. 600–604

[61] Classical planning:

- Russell & Norvig 2003, pp. 375–430,
- Poole, Mackworth & Goebel 1998, pp. 281–315,
- Luger & Stubblefield 2004, pp. 314–329,
- Nilsson 1998, chpt. 10.1–2, 22

[62] Planning and acting in non-deterministic domains: conditional planning, execution monitoring, replanning and continuous planning:

- Russell & Norvig 2003, pp. 430–449

[63] Multi-agent planning and emergent behavior:

- Russell & Norvig 2003, pp. 449–455

[64] This is a form of Tom Mitchell's widely quoted definition of machine learning: "A computer program is set to learn from an experience *E* with respect to some task *T* and some performance measure *P* if its performance on *T* as measured by *P* improves with experience *E*."

[65] Learning:

- ACM 1998, I.2.6,
- Russell & Norvig 2003, pp. 649–788,
- Poole, Mackworth & Goebel 1998, pp. 397–438,
- Luger & Stubblefield 2004, pp. 385–542,
- Nilsson 1998, chpt. 3.3, 10.3, 17.5, 20

[66] Alan Turing discussed the centrality of learning as early as 1950, in his classic paper "Computing Machinery and Intelligence".(Turing 1950) In 1956, at the original Dartmouth AI summer conference, Ray Solomonoff wrote a report on unsupervised probabilistic machine learning: "An Inductive Inference Machine".(Solomonoff 1956)

[67] Reinforcement learning:

- Russell & Norvig 2003, pp. 763–788
- Luger & Stubblefield 2004, pp. 442–449

[68] Computational learning theory:

- CITATION IN PROGRESS.

[69] Weng et al. 2001.

[70] Lungarella et al. 2003.

[71] Asada et al. 2009.

[72] Oudeyer 2010.

[73] Natural language processing:

- ACM 1998, I.2.7
- Russell & Norvig 2003, pp. 790–831
- Poole, Mackworth & Goebel 1998, pp. 91–104
- Luger & Stubblefield 2004, pp. 591–632

[74] "Versatile question answering systems: seeing in synthesis", Mittal et al., IJIIDS, 5(2), 119-142, 2011

[75] Applications of natural language processing, including information retrieval (i.e. text mining) and machine translation:

- Russell & Norvig 2003, pp. 840–857,
- Luger & Stubblefield 2004, pp. 623–630

[76] Machine perception:

- Russell & Norvig 2003, pp. 537–581, 863–898
- Nilsson 1998, ~chpt. 6

[77] Computer vision:

- ACM 1998, I.2.10
- Russell & Norvig 2003, pp. 863–898
- Nilsson 1998, chpt. 6

[78] Speech recognition:

- ACM 1998, ~I.2.7
- Russell & Norvig 2003, pp. 568–578

[79] Object recognition:

- Russell & Norvig 2003, pp. 885–892

[80] Robotics:

- ACM 1998, I.2.9,
- Russell & Norvig 2003, pp. 901–942,
- Poole, Mackworth & Goebel 1998, pp. 443–460

[81] Moving and configuration space:

- Russell & Norvig 2003, pp. 916–932

[82] Tecuci 2012.

[83] Robotic mapping (localization, etc):

- Russell & Norvig 2003, pp. 908–915

[84] *Kismet*.

[85] Thro 1993.

[86] Edelson 1991.

[87] Tao & Tan 2005.

[88] James 1884.

[89] Picard 1995.

[90] Kleine-Cosack 2006: "The introduction of emotion to computer science was done by Pickard (sic) who created the field of affective computing."

[91] Diamond 2003: "Rosalind Picard, a genial MIT professor, is the field's godmother; her 1997 book, Affective Computing, triggered an explosion of interest in the emotional side of computers and their users."

[92] Emotion and affective computing:

- Minsky 2006

[93] Roberts, Jacob (2016). "Thinking Machines: The Search for Artificial Intelligence". *Distillations*. **2** (2): 14–23. Retrieved 17 February 2017.

[94] Gerald Edelman, Igor Aleksander and others have argued that artificial consciousness is required for strong AI. (Aleksander 1995; Edelman 2007)

[95] Artificial brain arguments: AI requires a simulation of the operation of the human brain

- Russell & Norvig 2003, p. 957
- Crevier 1993, pp. 271 and 279

A few of the people who make some form of the argument:

- Moravec 1988
- Kurzweil 2005, p. 262
- Hawkins & Blakeslee 2005

The most extreme form of this argument (the brain replacement scenario) was put forward by Clark Glymour in the mid-1970s and was touched on by Zenon Pylyshyn and John Searle in 1980.

[96] AI complete: Shapiro 1992, p. 9

[97] Nils Nilsson writes: "Simply put, there is wide disagreement in the field about what AI is all about" (Nilsson 1983, p. 10).

[98] Biological intelligence vs. intelligence in general:

- Russell & Norvig 2003, pp. 2–3, who make the analogy with aeronautical engineering.
- McCorduck 2004, pp. 100–101, who writes that there are "two major branches of artificial intelligence: one aimed at producing intelligent behavior regardless of how it was accomplioshed, and the other aimed at modeling intelligent processes found in nature, particularly human ones."
- Kolata 1982, a paper in *Science*, which describes McCarthy's indifference to biological models. Kolata quotes McCarthy as writing: "This is AI, so we don't care if it's psychologically real". McCarthy recently reiterated his position at the AI@50 conference where he said "Artificial intelligence is not, by definition, simulation of human intelligence" (Maker 2006).

[99] Neats vs. scruffies:

- McCorduck 2004, pp. 421–424, 486–489
- Crevier 1993, pp. 168
- Nilsson 1983, pp. 10–11

[100] Symbolic vs. sub-symbolic AI:

- Nilsson (1998, p. 7), who uses the term "sub-symbolic".

[101] Haugeland 1985, p. 255.

[102] Law 1994.

[103] Bach 2008.

[104] Shapiro, Stuart C. (1992), "Artificial Intelligence", in Stuart C. Shapiro (ed.), *Encyclopedia of Artificial Intelligence*, 2nd edition (New York: John Wiley & Sons): 54-57. 4 December 2016.

[105] Haugeland 1985, pp. 112–117

[106] The most dramatic case of sub-symbolic AI being pushed into the background was the devastating critique of perceptrons by Marvin Minsky and Seymour Papert in 1969. See History of AI, AI winter, or Frank Rosenblatt.

[107] Cognitive simulation, Newell and Simon, AI at CMU (then called Carnegie Tech):

- McCorduck 2004, pp. 139–179, 245–250, 322–323 (EPAM)
- Crevier 1993, pp. 145–149

[108] Soar (history):

- McCorduck 2004, pp. 450–451
- Crevier 1993, pp. 258–263

[109] McCarthy and AI research at SAIL and SRI International:

- McCorduck 2004, pp. 251–259
- Crevier 1993

[110] AI research at Edinburgh and in France, birth of Prolog:

- Crevier 1993, pp. 193–196
- Howe 1994

[111] AI at MIT under Marvin Minsky in the 1960s :

- McCorduck 2004, pp. 259–305
- Crevier 1993, pp. 83–102, 163–176
- Russell & Norvig 2003, p. 19

[112] Cyc:

- McCorduck 2004, p. 489, who calls it "a determinedly scruffy enterprise"
- Crevier 1993, pp. 239–243
- Russell & Norvig 2003, p. 363–365
- Lenat & Guha 1989

[113] Knowledge revolution:

- McCorduck 2004, pp. 266–276, 298–300, 314, 421
- Russell & Norvig 2003, pp. 22–23

[114] Embodied approaches to AI:

- McCorduck 2004, pp. 454–462
- Brooks 1990
- Moravec 1988

[115] Revival of connectionism:

- Crevier 1993, pp. 214–215
- Russell & Norvig 2003, p. 25

[116] Computational intelligence

- IEEE Computational Intelligence Society

[117] Hutter 2012.

[118] Langley 2011.

[119] Katz 2012.

[120] Norvig 2012.

[121] Agent architectures, hybrid intelligent systems:

- Russell & Norvig (2003, pp. 27, 932, 970–972)
- Nilsson (1998, chpt. 25)

[122] Hierarchical control system:

- Albus 2002

[123] Subsumption architecture:

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[124] Search algorithms:

- Russell & Norvig 2003, pp. 59–189
- Poole, Mackworth & Goebel 1998, pp. 113–163
- Luger & Stubblefield 2004, pp. 79–164, 193–219
- Nilsson 1998, chpt. 7–12

[125] Forward chaining, backward chaining, Horn clauses, and logical deduction as search:

- Russell & Norvig 2003, pp. 217–225, 280–294
- Poole, Mackworth & Goebel 1998, pp. ~46–52
- Luger & Stubblefield 2004, pp. 62–73
- Nilsson 1998, chpt. 4.2, 7.2

[126] State space search and planning:

- Russell & Norvig 2003, pp. 382–387
- Poole, Mackworth & Goebel 1998, pp. 298–305
- Nilsson 1998, chpt. 10.1–2

[127] Uninformed searches (breadth first search, depth first search and general state space search):

- Russell & Norvig 2003, pp. 59–93
- Poole, Mackworth & Goebel 1998, pp. 113–132
- Luger & Stubblefield 2004, pp. 79–121
- Nilsson 1998, chpt. 8

[128] Heuristic or informed searches (e.g., greedy best first and A*):

- Russell & Norvig 2003, pp. 94–109,
- Poole, Mackworth & Goebel 1998, pp. pp. 132–147,
- Luger & Stubblefield 2004, pp. 133–150,
- Nilsson 1998, chpt. 9

[129] Optimization searches:

- Russell & Norvig 2003, pp. 110–116,120–129
- Poole, Mackworth & Goebel 1998, pp. 56–163
- Luger & Stubblefield 2004, pp. 127–133

[130] Artificial life and society based learning:

- Luger & Stubblefield 2004, pp. 530–541

[131] Genetic programming and genetic algorithms:

- Luger & Stubblefield 2004, pp. 509–530,
- Nilsson 1998, chpt. 4.2,
- Holland 1975,
- Koza 1992,
- Poli, Langdon & McPhee 2008.

[132] Logic:

- ACM 1998, ~I.2.3,
- Russell & Norvig 2003, pp. 194–310,
- Luger & Stubblefield 2004, pp. 35–77,
- Nilsson 1998, chpt. 13–16

[133] Satplan:

- Russell & Norvig 2003, pp. 402–407,
- Poole, Mackworth & Goebel 1998, pp. 300–301,
- Nilsson 1998, chpt. 21

[134] Explanation based learning, relevance based learning, inductive logic programming, case based reasoning:

- Russell & Norvig 2003, pp. 678–710,
- Poole, Mackworth & Goebel 1998, pp. 414–416,
- Luger & Stubblefield 2004, pp. ~422–442,
- Nilsson 1998, chpt. 10.3, 17.5

[135] Propositional logic:

- Russell & Norvig 2003, pp. 204–233,
- Luger & Stubblefield 2004, pp. 45–50
- Nilsson 1998, chpt. 13

[136] First-order logic and features such as equality:

- ACM 1998, ~I.2.4,
- Russell & Norvig 2003, pp. 240–310,
- Poole, Mackworth & Goebel 1998, pp. 268–275,
- Luger & Stubblefield 2004, pp. 50–62,
- Nilsson 1998, chpt. 15

[137] Fuzzy logic:

- Russell & Norvig 2003, pp. 526–527

[138] Subjective logic:

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[139] "The Belief Calculus and Uncertain Reasoning", Yen-Teh Hsia

[140] Stochastic methods for uncertain reasoning:

- ACM 1998, ~I.2.3,
- Russell & Norvig 2003, pp. 462–644,
- Poole, Mackworth & Goebel 1998, pp. 345–395,
- Luger & Stubblefield 2004, pp. 165–191, 333–381,
- Nilsson 1998, chpt. 19

[141] Bayesian networks:

- Russell & Norvig 2003, pp. 492–523,
- Poole, Mackworth & Goebel 1998, pp. 361–381,
- Luger & Stubblefield 2004, pp. ~182–190, ≈363–379,
- Nilsson 1998, chpt. 19.3–4

[142] Bayesian inference algorithm:

- Russell & Norvig 2003, pp. 504–519,
- Poole, Mackworth & Goebel 1998, pp. 361–381,
- Luger & Stubblefield 2004, pp. ~363–379,
- Nilsson 1998, chpt. 19.4 & 7

[143] Bayesian learning and the expectation-maximization algorithm:

- Russell & Norvig 2003, pp. 712–724,
- Poole, Mackworth & Goebel 1998, pp. 424–433,
- Nilsson 1998, chpt. 20

[144] Bayesian decision theory and Bayesian decision networks:

- Russell & Norvig 2003, pp. 597–600

[145] Stochastic temporal models:

- Russell & Norvig 2003, pp. 537–581

Dynamic Bayesian networks:

- Russell & Norvig 2003, pp. 551–557

Hidden Markov model:

- (Russell & Norvig 2003, pp. 549–551)

Kalman filters:

- Russell & Norvig 2003, pp. 551–557

[146] decision theory and decision analysis:

- Russell & Norvig 2003, pp. 584–597,
- Poole, Mackworth & Goebel 1998, pp. 381–394

[147] Markov decision processes and dynamic decision networks:

- Russell & Norvig 2003, pp. 613–631

[148] Game theory and mechanism design:

- Russell & Norvig 2003, pp. 631–643

[149] Statistical learning methods and classifiers:

- Russell & Norvig 2003, pp. 712–754,
- Luger & Stubblefield 2004, pp. 453–541

[150] Neural networks and connectionism:

- Russell & Norvig 2003, pp. 736–748,
- Poole, Mackworth & Goebel 1998, pp. 408–414,
- Luger & Stubblefield 2004, pp. 453–505,
- Nilsson 1998, chpt. 3

[151] kernel methods such as the support vector machine:

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- Crevier 1993, pp. 120–132

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- Russell & Norvig 2003, pp. 950–952,

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Making the Mathematical Objection:

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- McCorduck 2004, pp. 356–373
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2.13 External links

- What Is AI? – An introduction to artificial intelligence by John McCarthy—a co-founder of the field, and the person who coined the term.
- The Handbook of Artificial Intelligence Volume I by Avron Barr and Edward A. Feigenbaum (Stanford University)
- "Artificial Intelligence". *Internet Encyclopedia of Philosophy*.
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- AI at DMOZ
- AITopics – A large directory of links and other resources maintained by the Association for the Advancement of Artificial Intelligence, the leading organization of academic AI researchers.

Chapter 3

Our Final Invention

Our Final Invention: Artificial Intelligence and the End of the Human Era is a 2013 non-fiction book by the American author James Barrat. The book discusses the potential benefits and possible risks of human-level or super-human artificial intelligence.[1] Those purported risks include extermination of the human race.[2]

3.1 Summary

James Barrat weaves together explanations of AI concepts, AI history, and interviews with prominent AI researchers including Eliezer Yudkowsky and Ray Kurzweil. The book starts with an account of how an artificial general intelligence could become an artificial super-intelligence through recursive self-improvement. In subsequent chapters, the book covers the history of AI, including an account of the work done by I. J. Good, up to the work and ideas of researchers in the field today.

Throughout the book, Barrat takes a cautionary tone, focusing on the threats artificial super-intelligence poses to human existence. Barrat emphasizes how difficult it would be to control, or even to predict the actions of, something that may become orders of magnitude more intelligent than the most intelligent humans.

3.2 Reception

On 13 December 2013, journalist Matt Miller interviewed Barrat for his podcast, "This... is interesting". The interview and related matters to Barrat's book, *Our Final Invention*, were then captured in Miller's weekly opinion piece for the Washington Post.[3]

Seth Baum, executive director of the Global Catastrophic Risk Institute and one of the people cited by Barrat in his book, reviewed the book favorably on *Scientific American's* "invited guest" blog, calling it a welcome counterpoint to the vision articulated by Ray Kurzweil in his book *The Singularity is Near*.[4]

Gary Marcus questions Barrat's argument "that tendencies toward self-preservation and resource acquisition are inherent in any sufficiently complex, goal-driven system", noting that present-day AI does not have such drives, but Marcus concedes "that the goals of machines could change as they get smarter", and he feels that "Barrat is right to ask" about these important issues.[5]

Our Final Invention was a *Huffington Post* Definitive Tech Book of 2013.[6]

3.3 See also

- Artificial intelligence
- Ethics of artificial intelligence
- Technological singularity
- AI box
- Friendly artificial intelligence

3.4 References

[1] Barrat, James. "Our Final Invention: Artificial Intelligence and the End of the Human Era (Book Review)". *New York Journal of Books*. Retrieved 30 October 2013.

[2] Scoblete, Greg. "Our Final Invention: How the Human Race Goes and Gets Itself Killed", *Real Clear Technology* (December 6, 2013).

[3] Artificial intelligence: Our final invention?, Matt Miller, Washington Post opinion

[4] Baum, Seth (October 11, 2013). "*Our Final Invention*: Is AI the Defining Issue for Humanity?". *Scientific American*. Retrieved February 2, 2014.

[5] Marcus, Gary (24 Oct 2013). "Why We Should Think About the Threat of Artificial Intelligence". New Yorker. Retrieved 15 July 2014.

[6] "The Definitive Tech Books Of 2013". December 23, 2013. Retrieved June 11, 2014.

3.5 External links

- Kirkus Review
- Scientific American Review

Chapter 4

Internet of things

Drawing representing the Internet of things

The **Internet of things** (**IoT**) is the inter-networking of physical devices, vehicles (also referred to as "connected devices" and "smart devices"), buildings, and other items—embedded with electronics, software, sensors, actuators, and network connectivity that enable these objects to collect and exchange data.[1][2][3] In 2013 the Global Standards Initiative on Internet of Things (IoT-GSI) defined the IoT as "the infrastructure of the information society."[3] The IoT allows objects to be sensed or controlled remotely across existing network infrastructure,[4] creating opportunities for more direct integration of the physical world into computer-based systems, and resulting in improved efficiency, accuracy and economic benefit in addition to reduced human intervention.[5][6][7][8][9][10] When IoT is augmented with sensors and actuators, the technology becomes an instance of the more general class of cyber-physical systems, which also encompasses technologies such as smart grids, virtual power plants, smart homes, intelligent transportation and smart cities. Each thing is uniquely identifiable through its embedded computing system but is able to interoperate within the existing Internet infrastructure. Experts estimate that the IoT will consist of almost 50 billion objects by 2020.[11]

Typically, IoT is expected to offer advanced connectivity of devices, systems, and services that goes beyond machine-to-machine (M2M) communications and covers a variety of protocols, domains, and applications.[12] The interconnection of these embedded devices (including smart objects), is expected to usher in automation in nearly all fields, while also enabling advanced applications like a smart grid,[13] and expanding to areas such as smart cities.[14][15]

"Things," in the IoT sense, can refer to a wide variety of devices such as heart monitoring implants, biochip transponders on farm animals, electric clams in coastal waters,[16] automobiles with built-in sensors, DNA analysis devices for environmental/food/pathogen monitoring[17] or field operation devices that assist firefighters in search and rescue operations.[18] Legal scholars suggest to look at "Things" as an "inextricable mixture of hardware, software, data and service".[19] These devices collect useful data with the help of various existing technologies and then autonomously flow the data between other devices.[20] Current market examples include home automation (also known as smart home devices) such as the control and automation of lighting, heating (like smart thermostat), ventilation, air conditioning (HVAC) systems, and appliances such as washer/dryers, robotic vacuums, air purifiers, ovens or refrigerators/freezers that use Wi-Fi for remote monitoring.

As well as the expansion of Internet-connected automation into a plethora of new application areas, IoT is also expected to generate large amounts of data from diverse locations, with the consequent necessity for quick aggregation of the data, and an increase in the need to index, store, and process such data more effectively. IoT is one of the platforms of today's Smart City, and Smart Energy Management Systems.[21][22]

The term "the Internet of Things" was coined by Kevin Ashton of Procter & Gamble, later MIT's Auto-ID Center, in 1999.

4.1 History

As of 2016, the vision of the Internet of Things has evolved due to a convergence of multiple technolo-

gies, including ubiquitous wireless communication, real-time analytics, machine learning, commodity sensors, and embedded systems.[18] This means that the traditional fields of embedded systems, wireless sensor networks, control systems, automation (including home and building automation), and others all contribute to enabling the Internet of things[23] (IoT).

The concept of a network of smart devices was discussed as early as 1982, with a modified Coke machine at Carnegie Mellon University becoming the first Internet-connected appliance,[24] able to report its inventory and whether newly loaded drinks were cold.[25] Mark Weiser's seminal 1991 paper on ubiquitous computing, "The Computer of the 21st Century", as well as academic venues such as UbiComp and PerCom produced the contemporary vision of IoT.[26][27] In 1994 Reza Raji described the concept in *IEEE Spectrum* as "[moving] small packets of data to a large set of nodes, so as to integrate and automate everything from home appliances to entire factories".[28] Between 1993 and 1996 several companies proposed solutions like Microsoft's at Work or Novell's NEST. However, only in 1999 did the field start gathering momentum. Bill Joy envisioned Device to Device (D2D) communication as part of his "Six Webs" framework, presented at the World Economic Forum at Davos in 1999.[29]

The concept of the Internet of Things became popular in 1999, through the Auto-ID Center at MIT and related market-analysis publications.[30] Radio-frequency identification (RFID) was seen by Kevin Ashton (one of the founders of the original Auto-ID Center) as a prerequisite for the Internet of things at that point.[31] Ashton prefers the phrase "Internet *for* Things."[32] If all objects and people in daily life were equipped with identifiers, computers could manage and inventory them.[33][34][35] Besides using RFID, the *tagging* of things may be achieved through such technologies as near field communication, barcodes, QR codes and digital watermarking.[36][37]

In its original interpretation, one of the first consequences of implementing the Internet of things by equipping all objects in the world with minuscule identifying devices or machine-readable identifiers would be to transform daily life.[38][39] For instance, instant and ceaseless inventory control would become ubiquitous.[39] A person's ability to interact with objects could be altered remotely based on immediate or present needs, in accordance with existing end-user agreements.[31] For example, such technology could grant motion-picture publishers much more control over end-user private devices by remotely enforcing copyright restrictions and digital rights management, so the ability of a customer who bought a Blu-ray disc to watch the movie could become dependent on the copyright holder's decision, similar to Circuit City's failed DIVX.

A Nest learning thermostat reporting on energy usage and local weather

A 2012 Internet refrigerator from LG

4.2 Applications

According to Gartner, Inc. (a technology research and advisory corporation), there will be nearly 20.8 billion devices on the Internet of things by 2020.[40] ABI Research estimates that more than 30 billion devices will be wirelessly connected to the Internet of things by 2020.[41] As per a 2014 survey and study done by Pew Research Internet Project, a large majority of the technology experts and engaged Internet users who responded—83 percent—agreed with the notion that the Internet/Cloud of Things, embedded and wearable computing (and the corresponding dynamic systems[42]) will have widespread and beneficial effects by 2025.[43] As such, it is clear that the IoT will consist of a very large number of devices being connected to the Internet.[44] In an active move to accommodate new and emerging technological innovation, the UK Government, in their 2015 budget, allocated £40,000,000 towards research into the Internet of things. The former British Chancellor of the Exchequer George Osborne, posited that the Internet of things is the next stage of the information revolution and referenced the inter-connectivity of everything from urban transport to medical devices to household appliances.[45]

The ability to network embedded devices with limited CPU, memory and power resources means that IoT finds applications in nearly every field.[46] Such systems could be in charge of collecting information in settings ranging from natural ecosystems to buildings and factories,[47] thereby finding applications in fields of environmental sensing and urban planning.[48]

On the other hand, IoT systems could also be responsible for performing actions, not just sensing things. Intelligent shopping systems, for example, could monitor specific users' purchasing habits in a store by tracking their specific mobile phones. These users could then be provided with special offers on their favorite products, or even location of items that they need, which their fridge has automatically conveyed to the phone.[49][50] Additional examples of sensing and actuating are reflected in applications that deal with heat, water, electricity and energy management, as well as cruise-assisting transportation systems.[51][52] Other applications that the Internet of things can provide is enabling extended home security features and home automation.[53] The concept of an "Internet of living things" has been proposed to describe networks of biological sensors that could use cloud-based analyses to allow users to study DNA or other molecules.[54][55]

However, the application of the IoT is not only restricted to these areas. Other specialized use cases of the IoT may also exist. An overview of some of the most prominent application areas is provided here.

4.2.1 Media

In order to hone the manner in which things, media and big data are interconnected, it is first necessary to provide some context into the mechanism used for media process. It has been suggested by Nick Couldry and Joseph Turow that practitioners in media approach big data as many actionable points of information about millions of individuals. The industry appears to be moving away from the traditional approach of using specific media environments such as newspapers, magazines, or television shows and instead tap into consumers with technologies that reach targeted people at optimal times in optimal locations. The ultimate aim is of course to serve, or convey, a message or content that is (statistically speaking) in line with the consumer's mindset. For example, publishing environments are increasingly tailoring the messages (advertisements) and content (articles) to appeal to consumers that have been exclusively gleaned through various data-mining activities.[56]

The media industries process big data in a dual, interconnected manner:

- Targeting of consumers (for advertising by marketers)
- Data-capture

Thus, the Internet of things creates an opportunity to measure, collect and analyse an ever-increasing variety of behavioural statistics. Cross-correlation of this data could revolutionise the targeted marketing of products and services.[57] For example, as noted by Danny Meadows-Klue, the combination of analytics for conversion tracking with behavioural targeting has unlocked a new level of precision that enables display advertising to be focused on the devices of people with relevant interests.[58] Big data and the IoT work in conjunction. From a media perspective, data is the key derivative of device interconnectivity, whilst being pivotal in allowing clearer accuracy in targeting. The Internet of things therefore transforms the media industry, companies and even governments, opening up a new era of economic growth and competitiveness.[59] The wealth of data generated by this industry (i.e. big data) will allow practitioners in advertising and media to gain an elaborate layer on the present targeting mechanisms used by the industry.

4.2.2 Environmental monitoring

Environmental monitoring applications of the IoT typically use sensors to assist in environmental protection[60] by monitoring air or water quality,[16] atmospheric or soil conditions,[61] and can even include areas like monitoring the movements of wildlife and their habitats.[62] Development of resource constrained devices connected to the Internet also means that other applications like earthquake

or tsunami early-warning systems can also be used by emergency services to provide more effective aid. IoT devices in this application typically span a large geographic area and can also be mobile.[47] It has been argued that the standardization IoT brings to wireless sensing will revolutionize this area.[63]

4.2.3 Infrastructure management

Monitoring and controlling operations of urban and rural infrastructures like bridges, railway tracks, on- and offshore- wind-farms is a key application of the IoT.[64] The IoT infrastructure can be used for monitoring any events or changes in structural conditions that can compromise safety and increase risk. It can also be used for scheduling repair and maintenance activities in an efficient manner, by coordinating tasks between different service providers and users of these facilities.[47] IoT devices can also be used to control critical infrastructure like bridges to provide access to ships. Usage of IoT devices for monitoring and operating infrastructure is likely to improve incident management and emergency response coordination, and quality of service, up-times and reduce costs of operation in all infrastructure related areas.[65] Even areas such as waste management can benefit from automation and optimization that could be brought in by the IoT.[66]

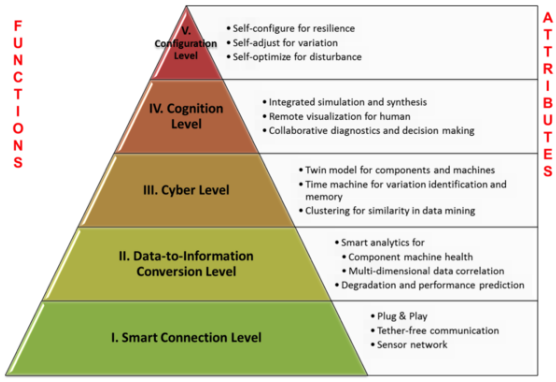
4.2.4 Manufacturing

Network control and management of manufacturing equipment, asset and situation management, or manufacturing process control bring the IoT within the realm of industrial applications and smart manufacturing as well.[67] The IoT intelligent systems enable rapid manufacturing of new products, dynamic response to product demands, and real-time optimization of manufacturing production and supply chain networks, by networking machinery, sensors and control systems together.[47]

Digital control systems to automate process controls, operator tools and service information systems to optimize plant safety and security are within the purview of the IoT.[64] But it also extends itself to asset management via predictive maintenance, statistical evaluation, and measurements to maximize reliability.[68] Smart industrial management systems can also be integrated with the Smart Grid, thereby enabling real-time energy optimization. Measurements, automated controls, plant optimization, health and safety management, and other functions are provided by a large number of networked sensors.[47]

National Science Foundation established an Industry/University Cooperative Research Center on intelligent maintenance systems (IMS) in 2001 with a research focus to use IoT-based predictive analytics technologies to monitor connected machines and to predict machine degradation, and further to prevent potential failures.[69] The vision to achieve near-zero breakdown using IoT-based predictive analytics led the future development of e-manufacturing and e-maintenance activities.[70]

The term IIoT (Industrial Internet of Things) is often encountered in the manufacturing industries, referring to the industrial subset of the IoT. IIoT in manufacturing would probably generate so much business value that it will eventually lead to the fourth industrial revolution, so the so-called Industry 4.0. It is estimated that in the future, successful companies will be able to increase their revenue through Internet of things by creating new business models and improve productivity, exploit analytics for innovation, and transform workforce.[71] The potential of growth by implementing IIoT will generate $12 trillion of global GDP by 2030.[71]



Design architecture of cyber-physical systems-enabled manufacturing system[72]

While connectivity and data acquisition are imperative for IIoT, they should not be the purpose, rather the foundation and path to something bigger. Among all the technologies, predictive maintenance is probably a relatively "easier win" since it is applicable to existing assets and management systems. The objective of intelligent maintenance systems is to reduce unexpected downtime and increase productivity. And to realize that alone would generate around up to 30% over total maintenance costs.[71] Industrial big data analytics will play a vital role in manufacturing asset predictive maintenance, although that is not the only capability of industrial big data.[73][74] Cyber-physical systems (CPS) is the core technology of industrial big data and it will be an interface between human and the cyber world. Cyber-physical systems can be designed by following the *5C* (connection, conversion, cyber, cognition, configuration) architecture,[72] and it will transform the collected data into actionable information, and eventually interfere with the physical assets to optimize processes.

An IoT-enabled intelligent system of such cases has been demonstrated by the NSF Industry/University Collaborative Research Center for Intelligent Maintenance Systems (IMS) at University of Cincinnati on a band saw machine in IMTS 2014 in Chicago.[75] Band saw machines are not necessarily expensive, but the band saw belt expenses

are enormous since they degrade much faster. However, without sensing and intelligent analytics, it can be only determined by experience when the band saw belt will actually break. The developed prognostics system will be able to recognize and monitor the degradation of band saw belts even if the condition is changing, so that users will know in near real time when is the best time to replace band saw. This will significantly improve user experience and operator safety, and save costs on replacing band saw belts before they actually break. The developed analytical algorithms were realized on a cloud server, and was made accessible via the Internet and on mobile devices.[75]

4.2.5 Energy management

Integration of sensing and actuation systems, connected to the Internet, is likely to optimize energy consumption as a whole.[47] It is expected that IoT devices will be integrated into all forms of energy consuming devices (switches, power outlets, bulbs, televisions, etc.) and be able to communicate with the utility supply company in order to effectively balance power generation and energy usage.[76] Such devices would also offer the opportunity for users to remotely control their devices, or centrally manage them via a cloud based interface, and enable advanced functions like scheduling (e.g., remotely powering on or off heating systems, controlling ovens, changing lighting conditions etc.).[47]

Besides home based energy management, the IoT is especially relevant to the Smart Grid since it provides systems to gather and act on energy and power-related information in an automated fashion with the goal to improve the efficiency, reliability, economics, and sustainability of the production and distribution of electricity.[76] Using advanced metering infrastructure (AMI) devices connected to the Internet backbone, electric utilities can not only collect data from end-user connections, but also manage other distribution automation devices like transformers and reclosers.[47]

4.2.6 Medical and healthcare

IoT devices can be used to enable remote health monitoring and emergency notification systems. These health monitoring devices can range from blood pressure and heart rate monitors to advanced devices capable of monitoring specialized implants, such as pacemakers Fitbit electronic wristbands or advanced hearing aids.[47] Some hospitals have begun implementing "smart beds" that can detect when they are occupied and when a patient is attempting to get up. It can also adjust itself to ensure appropriate pressure and support is applied to the patient without the manual interaction of nurses.[77] Specialized sensors can also be equipped within living spaces to monitor the health and general well-being of senior citizens, while also ensuring that proper treatment is being administered and assisting people regain lost mobility via therapy as well.[78] Other consumer devices to encourage healthy living, such as, connected scales or wearable heart monitors, are also a possibility with the IoT.[79] More and more end-to-end health monitoring IoT platforms are coming up for antenatal and chronic patients, helping one manage health vitals and recurring medication requirements.

4.2.7 Building and home automation

IoT devices can be used to monitor and control the mechanical, electrical and electronic systems used in various types of buildings (e.g., public and private, industrial, institutions, or residential)[47] in home automation and building automation systems.

4.2.8 Transportation

Digital variable speed-limit sign

The IoT can assist in integration of communications, control, and information processing across various transportation systems. Application of the IoT extends to all aspects of transportation systems (i.e. the vehicle, the infrastructure, and the driver or user). Dynamic interaction between these components of a transport system enables inter and intra vehicular communication, smart traffic control, smart parking, electronic toll collection systems, logistic and fleet management, vehicle control, and safety and road assistance.[47]

4.2.9 Metropolitan scale deployments

There are several planned or ongoing large-scale deployments of the IoT, to enable better management of cities and systems. For example, Songdo, South Korea, the first of its kind fully equipped and wired smart city, is near completion. Nearly everything in this city is planned to be wired, connected and turned into a constant stream of data that would be monitored and analyzed by an array of computers with little, or no human intervention.

Another application is a currently undergoing project in Santander, Spain. For this deployment, two approaches have been adopted. This city of 180,000 inhabitants, has already seen 18,000 city application downloads for their smartphones. This application is connected to 10,000 sensors that enable services like parking search, environmental monitoring, digital city agenda among others. City context information is used in this deployment so as to benefit merchants through a spark deals mechanism based on city behavior that aims at maximizing the impact of each notification.[80]

Other examples of large-scale deployments underway include the Sino-Singapore Guangzhou Knowledge City;[81] work on improving air and water quality, reducing noise pollution, and increasing transportation efficiency in San Jose, California;[82] and smart traffic management in western Singapore.[83] French company, Sigfox, commenced building an ultra-narrowband wireless data network in the San Francisco Bay Area in 2014, the first business to achieve such a deployment in the U.S.[84][85] It subsequently announced it would set up a total of 4000 base stations to cover a total of 30 cities in the U.S. by the end of 2016, making it the largest IoT network coverage provider in the country thus far.[86][87]

Another example of a large deployment is the one completed by New York Waterways in New York City to connect all the city's vessels and be able to monitor them live 24/7. The network was designed and engineered by Fluidmesh Networks, a Chicago-based company developing wireless networks for critical applications. The NYWW network is currently providing coverage on the Hudson River, East River, and Upper New York Bay. With the wireless network in place, NY Waterway is able to take control of its fleet and passengers in a way that was not previously possible. New applications can include security, energy and fleet management, digital signage, public Wi-Fi, paperless ticketing and others.[88]

4.2.10 Consumer application

A growing portion of IoT devices are created for consumer use. Examples of consumer applications include connected car, entertainment, residences and smart homes, wearable technology, quantified self, connected health, and smart retail. Consumer IoT provides new opportunities for user experience and interfaces.

Some consumer applications have been criticized for their lack of redundancy and their inconsistency, leading to a popular parody known as the "Internet of Shit."[89] Companies have been criticized for their rush into IoT, creating devices of questionable value,[90] and not setting up stringent security standards.[91]

4.3 Unique addressability of things

The original idea of the Auto-ID Center is based on RFID-tags and unique identification through the Electronic Product Code however this has evolved into objects having an IP address or URI.

An alternative view, from the world of the Semantic Web[92] focuses instead on making all things (not just those electronic, smart, or RFID-enabled) addressable by the existing naming protocols, such as URI. The objects themselves do not converse, but they may now be referred to by other agents, such as powerful centralized servers acting for their human owners.

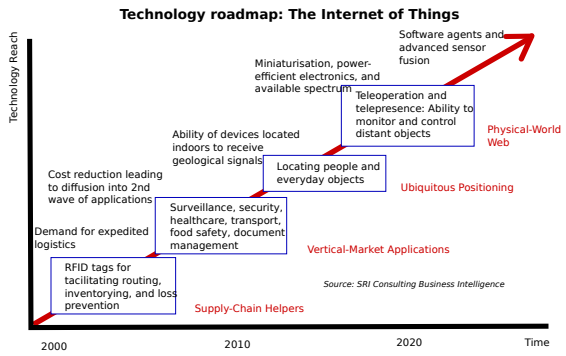
Integration with the Internet implies that devices will use an IP address as a unique identifier. Due to the limited address space of IPv4 (which allows for 4.3 billion unique addresses), objects in the IoT will have to use the next generation of the Internet protocol (IPv6) to scale to the extremely large address space required.[93] [94] [95] Internet of things devices additionally will benefit from the stateless address auto-configuration present in IPv6,[96] as it reduces the configuration overhead on the hosts,[94] and the IETF 6LoWPAN header compression. To a large extent, the future of the Internet of things will not be possible without the support of IPv6; and consequently the global adoption of IPv6 in the coming years will be critical for the successful development of the IoT in the future.[95]

A combination of these ideas can be found in the current GS1/EPCglobal EPC Information Services[97] (EPCIS) specifications. This system is being used to identify objects in industries ranging from aerospace to fast moving consumer products and transportation logistics.[98]

4.4 Trends and characteristics

4.4.1 Intelligence

Ambient intelligence and autonomous control are not part of the original concept of the Internet of things. Ambient intelligence and autonomous control do not necessarily require Internet structures, either. However, there is a shift in research to integrate the concepts of the Internet of things and autonomous control, with initial outcomes towards this direction considering objects as the driving force for autonomous IoT.



Technology roadmap: Internet of things

In the future the Internet of things may be a non-deterministic and open network in which auto-organized or intelligent entities (Web services, SOA components), virtual objects (avatars) will be interoperable and able to act independently (pursuing their own objectives or shared ones) depending on the context, circumstances or environments. Autonomous behavior through the collection and reasoning of context information as well as the objects ability to detect changes in the environment, faults affecting sensors and introduce suitable mitigation measures constitute a major research trend,[99] clearly needed to provide credibility to the IoT technology. Modern IoT products and solutions in the marketplace use a variety of different technologies to support such context-aware automation but more sophisticated forms of intelligence are requested to permit sensor units to be deployed in real environments.

4.4.2 Architecture

The system will likely be an example of event-driven architecture,[100] *bottom-up* made (based on the context of processes and operations, in real-time) and will consider any subsidiary level. Therefore, model driven and functional approaches will coexist with new ones able to treat exceptions and unusual evolution of processes (multi-agent systems, B-ADSc, etc.).

In an Internet of things, the meaning of an event will not necessarily be based on a deterministic or syntactic model but would instead be based on the context of the event itself: this will also be a semantic web.[101] Consequently, it will not necessarily need common standards that would not be able to address every context or use: some actors (services, components, avatars) will accordingly be self-referenced and, if ever needed, adaptive to existing common standards (*predicting everything* would be no more than defining a "global finality" for everything that is just not possible with any of the current *top-down* approaches and standardizations).

Building on top of the Internet of things, the web of things is an architecture for the application layer of the Internet of things looking at the convergence of data from IoT devices into Web applications to create innovative use-cases. In order to program and control the flow of information in the Internet of things, a predicted architectural direction is being called BPM Everywhere which is a blending of traditional process management with process mining and special capabilities to automate the control of large numbers of coordinated devices.

Network architecture

[102]

The Internet of things requires huge scalability in the network space to handle the surge of devices. IETF 6LoWPAN would be used to connect devices to IP networks. With billions of devices[40] being added to the Internet space, IPv6 will play a major role in handling the network layer scalability. IETF's Constrained Application Protocol, MQTT and ZeroMQ would provide lightweight data transport.

Fog computing is a viable alternative to prevent such large burst of data flow through Internet.[103] The edge devices' computation power can be used to analyse and process data, thus providing easy real time scalability.

4.4.3 Complexity

In semi-open or closed loops (i.e. value chains, whenever a global finality can be settled) IoT will often be considered and studied as a complex system[104] due to the huge number of different links, interactions between autonomous actors, and its capacity to integrate new actors. At the overall stage (full open loop) it will likely be seen as a chaotic environment (since systems always have finality). As a practical approach, not all elements in the Internet of things run in a global, public space. Subsystems are often implemented to mitigate the risks of privacy, control and reliability. For example, Domestic Robotics (Domotics) running inside a smart home might only share data within and be available via a local network.

4.4.4 Size considerations

The Internet of things would encode 50 to 100 trillion objects, and be able to follow the movement of those objects. Human beings in surveyed urban environments are each surrounded by 1000 to 5000 trackable objects.[105]

4.4.5 Space considerations

In the Internet of things, the precise geographic location of a thing—and also the precise geographic dimensions of a thing—will be critical.[106] Therefore, facts about a thing, such as its location in time and space, have been less critical to track because the person processing the

information can decide whether or not that information was important to the action being taken, and if so, add the missing information (or decide to not take the action). (Note that some things in the Internet of things will be sensors, and sensor location is usually important.[107]) The GeoWeb and Digital Earth are promising applications that become possible when things can become organized and connected by location. However, the challenges that remain include the constraints of variable spatial scales, the need to handle massive amounts of data, and an indexing for fast search and neighbor operations. In the Internet of things, if things are able to take actions on their own initiative, this human-centric mediation role is eliminated. Thus, the time-space context that we as humans take for granted must be given a central role in this information ecosystem. Just as standards play a key role in the Internet and the Web, geospatial standards will play a key role in the Internet of things.

4.4.6 Sectors

There are three core sectors of the IoT: enterprise, home, and government, with the Enterprise Internet of Things (EIoT) being the largest of the three. By 2019, the EIoT sector is estimated to account for nearly 40% or 9.1 billion devices.[108]

4.4.7 A Solution to "basket of remotes"

According to the CEO of Cisco, the commercial opportunity for "connected products ranging from cars to household goods" is expected to be a $USD 19 trillion.[109] Many IoT devices have a potential to take a piece of this market. Jean-Louis Gassée (Apple initial alumni team, and BeOS co-founder) has addressed this topic in an article on *Monday Note*,[110] where he predicts that the most likely problem will be what he calls the "basket of remotes" problem, where we'll have hundreds of applications to interface with hundreds of devices that don't share protocols for speaking with one another.

There are multiple approaches to solve this problem, one of them called the "predictive interaction",[111] where cloud or fog based decision makers will predict the user's next action and trigger some reaction.

For user interaction, new technology leaders are joining forces to create standards for communication between devices. While AllJoyn alliance is composed of the top 20 World technology leaders, there are also big companies that promote their own protocol like CCF from Intel.

Manufacturers are becoming more conscious of this problem, and many companies have begun releasing their devices with open APIs. Many of these APIs are used by smaller companies looking to take advantage of quick integration.

4.5 Frameworks

IoT frameworks might help support the interaction between "things" and allow for more complex structures like distributed computing and the development of distributed applications. Currently, some IoT frameworks seem to focus on real-time data logging solutions like Jasper Technologies, Inc. and Xively (formerly Cosm and before that Pachube), offering some basis to work with many "things" and have them interact. Future developments might lead to specific software-development environments to create the software to work with the hardware used in the Internet of things. Companies are developing technology platforms to provide this type of functionality for the Internet of things. Newer platforms are being developed, which add more intelligence. Foremost, IBM has announced cognitive IoT, which combines traditional IoT with machine intelligence and learning, contextual information, industry-specific models, and even natural language processing. The XMPP Standards Foundation (XSF) is creating such a framework in a fully open standard that is neither tied to any company nor connected to any cloud services. This XMPP initiative is called Chatty Things.[112] XMPP provides a set of needed building blocks and a proven distributed solution that can scale with high security levels.

REST is a scalable architecture that allows things to communicate over Hypertext Transfer Protocol and is easily adopted for IoT applications to provide communication from a thing to a central web server.

MQTT is a publish-subscribe architecture on top of TCP/IP that allows bidirectional communication between a thing and an MQTT broker.

4.6 Standards and standards organizations

This is a list of technical standards for the IoT, most of which are open standards, and the standards organizations that aspire to successfully setting them.

4.7 Enabling technologies for IoT

There are many technologies that enable IoT. Crucial to the field is the network used to communicate between devices of an IoT installation, a role that several wireless or wired technologies may fulfill:[113][114][115][116]

4.7.1 Short-range wireless

- Bluetooth low energy (BLE) – Specification providing a low power variant to classic Bluetooth with a comparable communication range.

- Light-Fidelity (Li-Fi) – Wireless communication technology similar to the Wi-Fi standard, but using visible light communication for increased bandwidth.
- Near-field communication (NFC) – Communication protocols enabling two electronic devices to communicate within a 4 cm range.
- QR codes and barcodes – Machine-readable optical tags that store information about the item to which they are attached.
- Radio-frequency identification (RFID) – Technology using electromagnetic fields to read data stored in tags embedded in other items.
- Thread – Network protocol based on the IEEE 802.15.4 standard, similar to ZigBee, providing IPv6 addressing.
- Transport Layer Security (network protocol)|TLS – Network security protocol.
- Wi-Fi – Widely used technology for local area networking based on the IEEE 802.11 standard, where devices may communicate through a shared access point.
- Wi-Fi Direct – Variant of the Wi-Fi standard for peer-to-peer communication, eliminating the need for an access point.
- Z-Wave – Communication protocol providing short-range, low-latency data transfer at rates and power consumption lower than Wi-Fi. Used primarily for home automation.
- ZigBee – Communication protocols for personal area networking based on the IEEE 802.15.4 standard, providing low power consumption, low data rate, low cost, and high throughput.

4.7.2 Medium-range wireless

- HaLow – Variant of the Wi-Fi standard providing extended range for low-power communication at a lower data rate.
- LTE-Advanced – High-speed communication specification for mobile networks. Provides enhancements to the LTE standard with extended coverage, higher throughput, and lower latency.

4.7.3 Long-range wireless

- Low-power wide-area networking (LPWAN) – Wireless networks designed to allow long-range communication at a low data rate, reducing power and cost for transmission.
- Very small aperture terminal (VSAT) – Satellite communication technology using small dish antennas for narrowband and broadband data.

4.7.4 Wired

- Ethernet – General purpose networking standard using twisted pair and fiber optic links in conjunction with hubs or switches.
- Multimedia over Coax Alliance (MoCA) – Specification enabling whole-home distribution of high definition video and content over existing coaxial cabling.
- Power-line communication (PLC) – Communication technology using electrical wiring to carry power and data. Specifications such as HomePlug utilize PLC for networking IoT devices.

4.8 Simulation

IoT modeling and simulation (and emulation) is typically carried out at the design stage before deployment of the network. Network simulators like OPNET, NetSim and NS2 can be used to simulate IoT networks.

4.9 Politics and civic engagement

Some scholars and activists argue that the IoT can be used to create new models of civic engagement if device networks can be open to user control and inter-operable platforms. Philip N. Howard, a professor and author, writes that political life in both democracies and authoritarian regimes will be shaped by the way the IoT will be used for civic engagement. For that to happen, he argues that any connected device should be able to divulge a list of the "ultimate beneficiaries" of its sensor data and that individual citizens should be able to add new organizations to the beneficiary list. In addition, he argues that civil society groups need to start developing their IoT strategy for making use of data and engaging with the public.[117]

4.10 Government regulation on IoT

One of the key drivers of the IoT is data. The success of the idea of connecting devices to make them more efficient is dependent upon access to and storage & processing of data. For this purpose, companies working on IoT collect data from multiple sources and store it in their cloud network for further processing. This leaves the door wide open for privacy and security dangers and

single point vulnerability of multiple systems.[118] The other issues pertain to consumer choice and ownership of data[119] and how it is used. Presently the regulators have shown more interest in protecting the first three issues identified above.

Current regulatory environment:

A report published by the Federal Trade Commission (FTC) in January 2015 made the following three recommendations:[120]

- Data security – At the time of designing IoT companies should ensure that data collection, storage and processing would be secure at all times. Companies should adopt a "defence in depth" approach and encrypt data at each stage.[121]
- Data consent – users should have a choice as to what data they share with IoT companies and the users must be informed if their data gets exposed.
- Data minimization – IoT companies should collect only the data they need and retain the collected information only for a limited time.

However, the FTC stopped at just making recommendations for now. According to an FTC analysis, the existing framework, consisting of the FTC Act, the Fair Credit Reporting Act, and the Children's Online Privacy Protection Act, along with developing consumer education and business guidance, participation in multi-stakeholder efforts and advocacy to other agencies at the federal, state and local level, is sufficient to protect consumer rights.[122]

A resolution passed by the Senate in March 2015, is already being considered by the Congress.[123] This resolution recognized the need for formulating a National Policy on IoT and the matter of privacy, security and spectrum. Furthermore, to provide an impetus to the IoT ecosystem, in March 2016, a bipartisan group of four Senators proposed a bill, The Developing Innovation and Growing the Internet of Things (DIGIT) Act, to direct the Federal Communications Commission to assess the need for more spectrum to connect IoT devices.

Several standards for the IoT industry are actually being established relating to automobiles because most concerns arising from use of connected cars apply to healthcare devices as well. In fact, the National Highway Traffic Safety Administration (NHTSA) is preparing cybersecurity guidelines and a database of best practices to make automotive computer systems more secure.[124]

4.11 Criticism and controversies

4.11.1 Platform fragmentation

IoT suffers from platform fragmentation and lack of technical standards[125][126][127][128][129][130][131] a situation where the variety of IoT devices, in terms of both hardware variations and differences in the software running on them, makes the task of developing applications that work consistently between different inconsistent technology ecosystems hard.[1] Customers may be hesitant to bet their IoT future on a proprietary software or hardware devices that uses proprietary protocols that may fade or become difficult to customize and interconnect.[2]

IoT's amorphous computing nature is also a problem for security, since patches to bugs found in the core operating system often do not reach users of older and lower-price devices.[132][133][134] One set of researchers say that the failure of vendors to support older devices with patches and updates leaves more than 87% of active devices vulnerable.[135][136]

4.11.2 Privacy, autonomy and control

Philip N. Howard, a professor and author, writes that the Internet of things offers immense potential for empowering citizens, making government transparent, and broadening information access. Howard cautions, however, that privacy threats are enormous, as is the potential for social control and political manipulation.[137]

Concerns about privacy have led many to consider the possibility that big data infrastructures such as the Internet of things and Data Mining are inherently incompatible with privacy.[138] Writer Adam Greenfield claims that these technologies are not only an invasion of public space but are also being used to perpetuate normative behavior, citing an instance of billboards with hidden cameras that tracked the demographics of passersby who stopped to read the advertisement.[139]

The Internet of Things Council compared the increased prevalence of digital surveillance due to the Internet of things to the conceptual panopticon described by Jeremy Bentham in the 18th Century.[140] The assertion was defended by the works of French philosophers Michel Foucault and Gilles Deleuze. In *Discipline and Punish: The Birth of the Prison* Foucault asserts that the panopticon was a central element of the discipline society developed during the Industrial Era.[141] Foucault also argued that the discipline systems established in factories and school reflected Bentham's vision of panopticism.[141] In his 1992 paper "Postscripts on the Societies of Control," Deleuze wrote that the discipline society had transitioned into a control society, with the computer replacing the panopticon as an instrument of discipline and control while still maintaining the qualities similar to that of panopticism.[142]

The privacy of households could be compromised by

solely analyzing smart home network traffic patterns without dissecting the contents of encrypted application data, yet a synthetic packet injection scheme can be used to safely overcome such invasion of privacy.[143]

Peter-Paul Verbeek, a professor of philosophy of technology at the University of Twente, Netherlands, writes that technology already influences our moral decision making, which in turn affects human agency, privacy and autonomy. He cautions against viewing technology merely as a human tool and advocates instead to consider it as an active agent.[144]

Justin Brookman, of the Center for Democracy and Technology, expressed concern regarding the impact of IoT on consumer privacy, saying that "There are some people in the commercial space who say, 'Oh, big data — well, let's collect everything, keep it around forever, we'll pay for somebody to think about security later.' The question is whether we want to have some sort of policy framework in place to limit that."[145]

Tim O'Reilly believes that the way companies sell the IoT devices on consumers are misplaced, disputing the notion that the IoT is about gaining efficiency from putting all kinds of devices online and postulating that "IoT is really about human augmentation. The applications are profoundly different when you have sensors and data driving the decision-making."[146]

Editorials at WIRED have also expressed concern, one stating "What you're about to lose is your privacy. Actually, it's worse than that. You aren't just going to lose your privacy, you're going to have to watch the very concept of privacy be rewritten under your nose."[147]

The American Civil Liberties Union (ACLU) expressed concern regarding the ability of IoT to erode people's control over their own lives. The ACLU wrote that "There's simply no way to forecast how these immense powers – disproportionately accumulating in the hands of corporations seeking financial advantage and governments craving ever more control – will be used. Chances are big data and the Internet of Things will make it harder for us to control our own lives, as we grow increasingly transparent to powerful corporations and government institutions that are becoming more opaque to us."[148]

In response to rising concerns about privacy and smart technology, in 2007 the British Government stated it would follow formal Privacy by Design principles when implementing their smart metering program. The program would lead to replacement of traditional power meters with smart power meters, which could track and manage energy usage more accurately.[149] However the British Computer Society is doubtful these principles were ever actually implemented.[150] In 2009 the Dutch Parliament rejected a similar smart metering program, basing their decision on privacy concerns. The Dutch program later revised and passed in 2011.[150]

4.11.3 Data storage and analytics

A challenge for producers of IoT applications is to clean, process and interpret the vast amount of data which is gathered by the sensors. There is a solution proposed for the analytics of the information referred to as Wireless Sensor Networks.[151] These networks share data among sensor nodes that are send to a distributed system for the analytics of the sensory data.

Another challenge is the storage of this bulk data. Depending on the application there could be high data acquisition requirements which in turn lead to high storage requirements. Currently the internet is already responsible for 5% of the total energy generated[151] and this consumption will increase significantly when we start utilizing applications with multiple embedded sensors.

4.11.4 Security

Concerns have been raised that the Internet of things is being developed rapidly without appropriate consideration of the profound security challenges involved[152] and the regulatory changes that might be necessary.[153][154]

Most of the technical security issues are similar to those of conventional servers, workstations and smartphones, but the firewalling, security update and anti-malware systems used for those are generally unsuitable for the much smaller, less capable, IoT devices.

According to the Business Insider Intelligence Survey conducted in the last quarter of 2014, 39% of the respondents said that security is the biggest concern in adopting Internet of things technology.[155] In particular, as the Internet of things spreads widely, cyber attacks are likely to become an increasingly physical (rather than simply virtual) threat.[156] In a January 2014 article in *Forbes*, cybersecurity columnist Joseph Steinberg listed many Internet-connected appliances that can already "spy on people in their own homes" including televisions, kitchen appliances,[157] cameras, and thermostats.[158] Computer-controlled devices in automobiles such as brakes, engine, locks, hood and truck releases, horn, heat, and dashboard have been shown to be vulnerable to attackers who have access to the onboard network. In some cases, vehicle computer systems are Internet-connected, allowing them to be exploited remotely.[159] By 2008 security researchers had shown the ability to remotely control pacemakers without authority. Later hackers demonstrated remote control of insulin pumps [160] and implantable cardioverter defibrillators.[161] David Pogue wrote[162] that some recently published reports about hackers remotely controlling certain functions of automobiles were not as serious as one might otherwise guess because of various mitigating circumstances; such as the bug that allowed the hack having been fixed before the report was published, or that the hack required security researchers having physical access to the car prior to the hack to prepare

for it.

The U.S. National Intelligence Council in an unclassified report maintains that it would be hard to deny "access to networks of sensors and remotely-controlled objects by enemies of the United States, criminals, and mischief makers... An open market for aggregated sensor data could serve the interests of commerce and security no less than it helps criminals and spies identify vulnerable targets. Thus, massively parallel sensor fusion may undermine social cohesion, if it proves to be fundamentally incompatible with Fourth-Amendment guarantees against unreasonable search."[163] In general, the intelligence community views the Internet of things as a rich source of data.[164]

As a response to increasing concerns over security, the Internet of Things Security Foundation (IoTSF) was launched on 23 September 2015. IoTSF has a mission to secure the Internet of things by promoting knowledge and best practice. Its founding board is made from technology providers and telecommunications companies including BT, Vodafone, Imagination Technologies and Pen Test Partners.[165][166]

In 2016, a distributed denial of service attack powered by Internet of things devices running the Mirai malware took down a DNS provider and major web sites.

4.11.5 Design

Given widespread recognition of the evolving nature of the design and management of the Internet of things, sustainable and secure deployment of IoT solutions must design for "anarchic scalability."[167] Application of the concept of anarchic scalability can be extended to physical systems (i.e. controlled real-world objects), by virtue of those systems being designed to account for uncertain management futures. This "hard anarchic scalability" thus provides a pathway forward to fully realize the potential of Internet of things solutions by selectively constraining physical systems to allow for all management regimes without risking physical failure.

Brown University computer scientist Michael Littman has argued that successful execution of the Internet of things requires consideration of the interface's usability as well as the technology itself. These interfaces need to be not only more user-friendly but also better integrated: "If users need to learn different interfaces for their vacuums, their locks, their sprinklers, their lights, and their coffeemakers, it's tough to say that their lives have been made any easier."[168]

4.11.6 Environmental sustainability impact

A concern regarding Internet of things technologies pertains to the environmental impacts of the manufacture, use, and eventual disposal of all these semiconductor-rich devices.[169] Modern electronics are replete with a wide variety of heavy metals and rare-earth metals, as well as highly toxic synthetic chemicals. This makes them extremely difficult to properly recycle. Electronic components are often incinerated or placed in regular landfills. Furthermore, the human and environmental cost of mining the rare-earth metals that are integral to modern electronic components continues to grow. With production of electronic equipment growing globally yet little of the metals (from end-of-life equipment) are being recovered for reuse, the environmental impacts can be expected to increase.

Also, because the concept of Internet of things entails adding electronics to mundane devices (for example, simple light switches), and because the major driver for replacement of electronic components is often technological obsolescence rather than actual failure to function, it is reasonable to expect that items that previously were kept in service for many decades would see an accelerated replacement cycle if they were part of the IoT. For example, a traditional house built with 30 light switches and 30 electrical outlets might stand for 50 years, with all those components still original at the end of that period. But a modern house built with the same number of switches and outlets set up for IoT might see each switch and outlet replaced at five-year intervals, in order to keep up to date with technological changes. This translates into a ten-fold increase in waste requiring disposal.

4.11.7 Intentional obsolescence of devices

The Electronic Frontier Foundation has raised concerns that companies can use the technologies necessary to support connected devices to intentionally disable or "brick" their customers' devices via a remote software update or by disabling a service necessary to the operation of the device. In one example, home automation devices sold with the promise of a "Lifetime Subscription" were rendered useless after Nest Labs acquired Revolv and made the decision to shut down the central servers the Revolv devices had used to operate.[170] As Nest is a company owned by Alphabet (Google's parent company), the EFF argues this sets a "terrible precedent for a company with ambitions to sell self-driving cars, medical devices, and other high-end gadgets that may be essential to a person's livelihood or physical safety."[171]

Owners should be free to point their devices to a different server or collaborate on improved software. But such action violates the United States DMCA section 1201, which only has an exemption for "local use". This forces tinkerers who want to keep using their own equipment into a legal grey area. EFF thinks buyers should refuse electronics and software that prioritize the manufacturer's wishes above their own.[171]

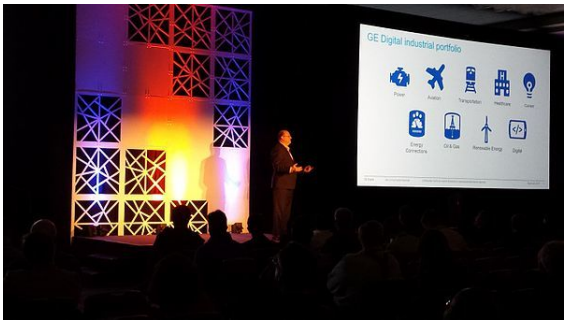
Examples of post-sale manipulations include Google Nest

Revolv, disabled privacy settings on Android, Sony disabling GNU/Linux on PlayStation 3, enforced EULA on Wii U.[171]

4.11.8 Confusing terminology

Kevin Lonergan at Information Age, a business-technology magazine, has referred to the terms surrounding IoT as a "terminology zoo".[172] The lack of clear terminology is not "useful from a practical point of view" and a "source of confusion for the end user".[172] A company operating in the IoT space could be working in anything related to sensor technology, networking, embedded systems, or analytics.[172] According to Lonergan, the term IoT was coined before smart phones, tablets, and devices as we know them today existed, and there is a long list of terms with varying degrees of overlap and technological convergence: Internet of Things (IoT), Internet of Everything (IoE), Industrial Internet, Pervasive Computing, Pervasive Sensing, Ubiquitous Computing, Cyber-Physical Systems (CPS), Wireless Sensor Networks (WSN), Smart Objects, Cooperating Objects, Machine-to-Machine (M2M), Ambient Intelligence (AmI), Operational Technology (OT), and Information Technology (IT).[172] Regarding IIoT, an industrial sub-field of IoT, the Industrial Internet Consortium's Vocabulary Task Group has created a "common and reusable vocabulary of terms"[173] to ensure "consistent terminology"[173][174] across publications issued by the Industrial Internet Consortium. IoT One has created an IoT Terms Database including a New Term Alert[175] to be notified when a new term is published. As of March 2017, this database aggregates 711 IoT-related terms,[176] however, without any attempts to reduce terminological ambiguity and complexity.

4.12 IoT adoption barriers



GE Digital CEO William Ruh speaking about GE's attempts to gain a foothold in the market for IoT services at the first IEEE Computer Society TechIgnite conference

4.12.1 Complexity and unclear value propositions

Despite a shared belief in the potential of IoT, industry leaders and consumers are facing barriers to adopt IoT technology more widely. Dan Yarmoluk from ATEK Access Technologies has written that "the IoT industry appears heavily focused on gadgets and not making them relevant to the particular business verticals"[177] and "can appear expensive and intimidating."[177] Mike Farley has argued in Forbes that many IoT solutions are either too complex or lack a clear use case for end-users.[178] "Instead of convincing consumers that they need complex systems to serve needs they don't have, we should fix real problems people struggle with every day."[178] Many gadgets in the consumer IoT space have appealed to early adopters, yet failed to demonstrate relevance to ordinary people's lives. In order to overcome barriers, "we need to stop making toys no one cares about and instead work on building simple solutions to real, everyday problems for real people."[178] A recent study by Ericsson regarding the adoption of IoT among Danish companies, has suggested that many are struggling "to pinpoint exactly where the value of IoT lies for them".[179] A company must identify where the value of IoT lies in order to capture it, otherwise non-action is the consequence.[179] This indicates that a major roadblock to IoT adoption is not technical but analytical in nature.

4.12.2 Privacy and security concerns

According to a recent study by Noura Aleisa and Karen Renaud at the University of Glasgow, "the Internet of Things' potential for major privacy invasion is a concern"[180] with much of research "disproportionally focused on the security concerns of IoT."[180] Among the "proposed solutions in terms of the techniques they deployed and the extent to which they satisfied core privacy principles",[180] only very few turned out to be fully satisfactory. Louis Basenese, investment director at Wall Street Daily, has criticized that "despite high-profile and alarming hacks, device manufacturers remain undeterred, focusing on profitability over security".[181] He has further stated that "consumers need to have ultimate control over collected data, including the option to delete it if they choose"[181] and "without privacy assurances, wide-scale consumer adoption simply won't happen."[181]

In a post-Snowden world of global surveillance disclosures, consumers take a more active interest in protecting their privacy and demand IoT devices to be screened for potential security vulnerabilities and privacy violations before purchasing them. According to the 2016 Accenture Digital Consumer Survey, in which 28000 consumers in 28 countries were polled on their use of consumer technology, security "has moved from being a nagging problem to a top barrier as consumers are now choosing to abandon IoT devices and services over secu-

rity concerns."[182] The survey revealed that "out of the consumers aware of hacker attacks and owning or planning to own IoT devices in the next five years, 18 percent decided to terminate the use of the services and related services until they get safety guarantees."[182] This suggests that consumers increasingly perceive privacy risks and security concerns to outweigh the value propositions of IoT devices and opt to postpone planned purchases or service subscriptions.[182]

4.12.3 Traditional governance structures

A study issued by Ericsson regarding the adoption of Internet of Things among Danish companies identified a "clash between IoT and companies' traditional governance structures, as IoT still presents both uncertainties and a lack of historical precedence."[179] Among the respondents interviewed, 60 percent stated that they "do not believe they have the organizational capabilities, and three of four do not believe they have the processes needed, to capture the IoT opportunity."[179] This has led to a need to understand organizational culture in order to facilitate organizational design processes and to test new innovation management practices. A lack of digital leadership in the age of digital transformation has also stifled innovation and IoT adoption to a degree that many companies, in the face of uncertainty, "were waiting for the market dynamics to play out",[179] or further action in regards to IoT "was pending competitor moves, customer pull, or regulatory requirements."[179] Some of these companies risk being 'kodaked' - "Kodak was a market leader until digital disruption eclipsed film photography with digital photos"[177] - failing to "see the disruptive forces affecting their industry"[183] and "to truly embrace the new business models the disruptive change opens up."[183] Scott Anthony has written in Harvard Business Review that Kodak "created a digital camera, invested in the technology, and even understood that photos would be shared online"[183] but ultimately failed to realize that "online photo sharing *was* the new business, not just a way to expand the printing business."[183]

4.13 See also

- Home automation
- Web of Things
- Smart grid
- Algorithmic regulation
- Cloud manufacturing
- Data Distribution Service
- Device ecology
- MCU (Micro Controller Unit)
- Digital object memory
- Indoor positioning system
- Open Interconnect Consortium
- OpenWSN
- 5G

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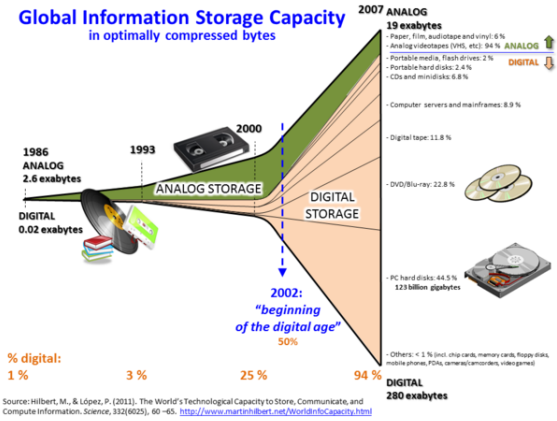
Chapter 5

Big data

This article is about large collections of data. For the band, see Big Data (band).

Big data is a term for data sets that are so large or complex that traditional data processing application software is inadequate to deal with them. Challenges include capture, storage, analysis, data curation, search, sharing, transfer, visualization, querying, updating and information privacy. The term "big data" often refers simply to the use of predictive analytics, user behavior analytics, or certain other advanced data analytics methods that extract value from data, and seldom to a particular size of data set. "There is little doubt that the quantities of data now available are indeed large, but that's not the most relevant characteristic of this new data ecosystem."[2] Analysis of data sets can find new correlations to "spot business trends, prevent diseases, combat crime and so on."[3] Scientists, business executives, practitioners of medicine, advertising and governments alike regularly meet difficulties with large data-sets in areas including Internet search, finance, urban informatics, and business informatics. Scientists encounter limitations in e-Science work, including meteorology, genomics,[4] connectomics, complex physics simulations, biology and environmental research.[5]



Growth of and digitization of global information-storage capacity[1]

Data sets grow rapidly - in part because they are increasingly gathered by cheap and numerous information-sensing mobile devices, aerial (remote sensing), software logs, cameras, microphones, radio-frequency identification (RFID) readers and wireless sensor networks.[6][7] The world's technological per-capita capacity to store information has roughly doubled every 40 months since the 1980s;[8] as of 2012, every day 2.5 exabytes (2.5×10^{18}) of data are generated.[9] One question for large enterprises is determining who should own big-data initiatives that affect the entire organization.[10]

Relational database management systems and desktop statistics- and visualization-packages often have difficulty handling big data. The work may require "massively parallel software running on tens, hundreds, or even thousands of servers".[11] What counts as "big data" varies depending on the capabilities of the users and their tools, and expanding capabilities make big data a moving target. "For some organizations, facing hundreds of gigabytes of data for the first time may trigger a need to reconsider data management options. For others, it may take tens or hundreds of terabytes before data size becomes a significant consideration."[12]

5.1 Definition

Visualization of daily Wikipedia edits created by IBM. At multiple terabytes in size, the text and images of Wikipedia are an example of big data.

The term has been in use since the 1990s, with some giving credit to John Mashey for coining or at least mak-

ing it popular.[13][14] Big data usually includes data sets with sizes beyond the ability of commonly used software tools to capture, curate, manage, and process data within a tolerable elapsed time.[15] Big data "size" is a constantly moving target, as of 2012 ranging from a few dozen terabytes to many petabytes of data.[16] Big data requires a set of techniques and technologies with new forms of integration to reveal insights from datasets that are diverse, complex, and of a massive scale.[17]

In a 2001 research report[18] and related lectures, META Group (now Gartner) defined data growth challenges and opportunities as being three-dimensional, i.e. increasing volume (amount of data), velocity (speed of data in and out), and variety (range of data types and sources). Gartner, and now much of the industry, continue to use this "3Vs" model for describing big data.[19] In 2012, Gartner updated its definition as follows: "Big data is high volume, high velocity, and/or high variety information assets that require new forms of processing to enable enhanced decision making, insight discovery and process optimization." Gartner's definition of the 3Vs is still widely used, and in agreement with a consensual definition that states that "Big Data represents the Information assets characterized by such a High Volume, Velocity and Variety to require specific Technology and Analytical Methods for its transformation into Value".[20] Additionally, a new V "Veracity" is added by some organizations to describe it,[21] revisionism challenged by some industry authorities.[22] The 3Vs have been expanded to other complementary characteristics of big data:[23][24]

- Volume: big data doesn't sample; it just observes and tracks what happens
- Velocity: big data is often available in real-time
- Variety: big data draws from text, images, audio, video; plus it completes missing pieces through data fusion
- Machine learning: big data often doesn't ask why and simply detects patterns[25]
- Digital footprint: big data is often a cost-free byproduct of digital interaction[24][26]

The growing maturity of the concept more starkly delineates the difference between big data and Business Intelligence:[27]

- Business Intelligence uses descriptive statistics with data with high information density to measure things, detect trends, etc..
- Big data uses inductive statistics and concepts from nonlinear system identification[28] to infer laws (regressions, nonlinear relationships, and causal effects) from large sets of data with low information density[29] to reveal relationships and dependencies, or to perform predictions of outcomes and behaviors.[28][30]

5.2 Characteristics

Big data can be described by the following characteristics:[23][24]

Volume The quantity of generated and stored data. The size of the data determines the value and potential insight- and whether it can actually be considered big data or not.

Variety The type and nature of the data. This helps people who analyze it to effectively use the resulting insight.

Velocity In this context, the speed at which the data is generated and processed to meet the demands and challenges that lie in the path of growth and development.

Variability Inconsistency of the data set can hamper processes to handle and manage it.

Veracity The quality of captured data can vary greatly, affecting accurate analysis.

Factory work and Cyber-physical systems may have a 6C system:

- Connection (sensor and networks)
- Cloud (computing and data on demand)[31][32]
- Cyber (model and memory)
- Content/context (meaning and correlation)
- Community (sharing and collaboration)
- Customization (personalization and value)

Data must be processed with advanced tools (analytics and algorithms) to reveal meaningful information. For example, to manage a factory one must consider both visible and invisible issues with various components. Information generation algorithms must detect and address invisible issues such as machine degradation, component wear, etc. on the factory floor.[33][34]

5.3 Architecture

In 2000, Seisint Inc. (now LexisNexis Group) developed a C++-based distributed file-sharing framework for data storage and query. The system stores and distributes structured, semi-structured, and unstructured data across multiple servers. Users can build queries in a C++ dialect called ECL. ECL uses an "apply schema on read" method to infer the structure of stored data when it is queried,

instead of when it is stored. In 2004, LexisNexis acquired Seisint Inc.[35] and in 2008 acquired ChoicePoint, Inc.[36] and their high-speed parallel processing platform. The two platforms were merged into HPCC (or High-Performance Computing Cluster) Systems and in 2011, HPCC was open-sourced under the Apache v2.0 License. Quantcast File System was available about the same time.[37]

In 2004, Google published a paper on a process called MapReduce that uses a similar architecture. The MapReduce concept provides a parallel processing model, and an associated implementation was released to process huge amounts of data. With MapReduce, queries are split and distributed across parallel nodes and processed in parallel (the Map step). The results are then gathered and delivered (the Reduce step). The framework was very successful,[38] so others wanted to replicate the algorithm. Therefore, an implementation of the MapReduce framework was adopted by an Apache open-source project named Hadoop.[39]

MIKE2.0 is an open approach to information management that acknowledges the need for revisions due to big data implications identified in an article titled "Big Data Solution Offering".[40] The methodology addresses handling big data in terms of useful permutations of data sources, complexity in interrelationships, and difficulty in deleting (or modifying) individual records.[41]

2012 studies showed that a multiple-layer architecture is one option to address the issues that big data presents. A distributed parallel architecture distributes data across multiple servers; these parallel execution environments can dramatically improve data processing speeds. This type of architecture inserts data into a parallel DBMS, which implements the use of MapReduce and Hadoop frameworks. This type of framework looks to make the processing power transparent to the end user by using a front-end application server.[42]

Big data analytics for manufacturing applications is marketed as a 5C architecture (connection, conversion, cyber, cognition, and configuration).[43]

The data lake allows an organization to shift its focus from centralized control to a shared model to respond to the changing dynamics of information management. This enables quick segregation of data into the data lake, thereby reducing the overhead time.[44][45]

5.4 Technologies

A 2011 McKinsey Global Institute report characterizes the main components and ecosystem of big data as follows:[46]

- Techniques for analyzing data, such as A/B testing, machine learning and natural language processing
- Big data technologies, like business intelligence, cloud computing and databases
- Visualization, such as charts, graphs and other displays of the data

Multidimensional big data can also be represented as tensors, which can be more efficiently handled by tensor-based computation,[47] such as multilinear subspace learning.[48] Additional technologies being applied to big data include massively parallel-processing (MPP) databases, search-based applications, data mining,[49] distributed file systems, distributed databases, cloud-based infrastructure (applications, storage and computing resources) and the Internet.

Some but not all MPP relational databases have the ability to store and manage petabytes of data. Implicit is the ability to load, monitor, back up, and optimize the use of the large data tables in the RDBMS.[50]

DARPA's Topological Data Analysis program seeks the fundamental structure of massive data sets and in 2008 the technology went public with the launch of a company called Ayasdi.[51]

The practitioners of big data analytics processes are generally hostile to slower shared storage,[52] preferring direct-attached storage (DAS) in its various forms from solid state drive (Ssd) to high capacity SATA disk buried inside parallel processing nodes. The perception of shared storage architectures—Storage area network (SAN) and Network-attached storage (NAS) —is that they are relatively slow, complex, and expensive. These qualities are not consistent with big data analytics systems that thrive on system performance, commodity infrastructure, and low cost.

Real or near-real time information delivery is one of the defining characteristics of big data analytics. Latency is therefore avoided whenever and wherever possible. Data in memory is good—data on spinning disk at the other end of a FC SAN connection is not. The cost of a SAN at the scale needed for analytics applications is very much higher than other storage techniques.

There are advantages as well as disadvantages to shared storage in big data analytics, but big data analytics practitioners as of 2011 did not favour it.[53]

5.5 Applications

Big data has increased the demand of information management specialists so much so that Software AG, Oracle Corporation, IBM, Microsoft, SAP, EMC, HP and Dell have spent more than $15 billion on software firms specializing in data management and analytics. In 2010, this industry was worth more than $100 billion and was growing at almost 10 percent a year: about twice as fast as the software business as a whole.[3]

Bus wrapped with SAP Big data parked outside IDF13.

Developed economies increasingly use data-intensive technologies. There are 4.6 billion mobile-phone subscriptions worldwide, and between 1 billion and 2 billion people accessing the internet.[3] Between 1990 and 2005, more than 1 billion people worldwide entered the middle class, which means more people became more literate, which in turn lead to information growth. The world's effective capacity to exchange information through telecommunication networks was 281 petabytes in 1986, 471 petabytes in 1993, 2.2 exabytes in 2000, 65 exabytes in 2007[8] and predictions put the amount of internet traffic at 667 exabytes annually by 2014.[3] According to one estimate, one third of the globally stored information is in the form of alphanumeric text and still image data,[54] which is the format most useful for most big data applications. This also shows the potential of yet unused data (i.e. in the form of video and audio content).

While many vendors offer off-the-shelf solutions for big data, experts recommend the development of in-house solutions custom-tailored to solve the company's problem at hand if the company has sufficient technical capabilities.[55]

5.5.1 Government

The use and adoption of big data within governmental processes allows efficiencies in terms of cost, productivity, and innovation,[56] but does not come without its flaws. Data analysis often requires multiple parts of government (central and local) to work in collaboration and create new and innovative processes to deliver the desired outcome. Below are some examples of initiatives the governmental big data space.

United States of America

- In 2012, the Obama administration announced the Big Data Research and Development Initiative, to explore how big data could be used to address important problems faced by the government.[57] The initiative is composed of 84 different big data programs spread across six departments.[58]
- Big data analysis played a large role in Barack Obama's successful 2012 re-election campaign.[59]
- The United States Federal Government owns six of the ten most powerful supercomputers in the world.[60]
- The Utah Data Center has been constructed by the United States National Security Agency. When finished, the facility will be able to handle a large amount of information collected by the NSA over the Internet. The exact amount of storage space is unknown, but more recent sources claim it will be on the order of a few exabytes.[61][62][63]

India

- Big data analysis was in part responsible for the BJP to win the Indian General Election 2014.[64]
- The Indian government utilizes numerous techniques to ascertain how the Indian electorate is responding to government action, as well as ideas for policy augmentation.

United Kingdom

Examples of uses of big data in public services:

- Data on prescription drugs: by connecting origin, location and the time of each prescription, a research unit was able to exemplify the considerable delay between the release of any given drug, and a UK-wide adaptation of the National Institute for Health and Care Excellence guidelines. This suggests that new or most up-to-date drugs take some time to filter through to the general patient.[65]
- Joining up data: a local authority blended data about services, such as road gritting rotas, with services for people at risk, such as 'meals on wheels'. The connection of data allowed the local authority to avoid any weather-related delay.[66]

5.5.2 International development

Research on the effective usage of information and communication technologies for development (also known as ICT4D) suggests that big data technology can make important contributions but also present unique challenges to International development.[67][68] Advancements in big data analysis offer cost-effective opportunities to improve decision-making in critical development areas such as health care, employment, economic productivity, crime, security, and natural disaster and resource

management.[69][70][71] Additionally, user-generated data offers new opportunities to give the unheard a voice.[72] However, longstanding challenges for developing regions such as inadequate technological infrastructure and economic and human resource scarcity exacerbate existing concerns with big data such as privacy, imperfect methodology, and interoperability issues.[69]

5.5.3 Manufacturing

Based on TCS 2013 Global Trend Study, improvements in supply planning and product quality provide the greatest benefit of big data for manufacturing. Big data provides an infrastructure for transparency in manufacturing industry, which is the ability to unravel uncertainties such as inconsistent component performance and availability. Predictive manufacturing as an applicable approach toward near-zero downtime and transparency requires vast amount of data and advanced prediction tools for a systematic process of data into useful information.[73] A conceptual framework of predictive manufacturing begins with data acquisition where different type of sensory data is available to acquire such as acoustics, vibration, pressure, current, voltage and controller data. Vast amount of sensory data in addition to historical data construct the big data in manufacturing. The generated big data acts as the input into predictive tools and preventive strategies such as Prognostics and Health Management (PHM).[74][75]

Cyber-physical models

Current PHM implementations mostly use data during the actual usage while analytical algorithms can perform more accurately when more information throughout the machine's lifecycle, such as system configuration, physical knowledge and working principles, are included. There is a need to systematically integrate, manage and analyze machinery or process data during different stages of machine life cycle to handle data/information more efficiently and further achieve better transparency of machine health condition for manufacturing industry.

With such motivation a cyber-physical (coupled) model scheme has been developed. The coupled model is a digital twin of the real machine that operates in the cloud platform and simulates the health condition with an integrated knowledge from both data driven analytical algorithms as well as other available physical knowledge. It can also be described as a 5S systematic approach consisting of sensing, storage, synchronization, synthesis and service. The coupled model first constructs a digital image from the early design stage. System information and physical knowledge are logged during product design, based on which a simulation model is built as a reference for future analysis. Initial parameters may be statistically generalized and they can be tuned using data from testing or the manufacturing process using parameter estimation. After that step, the simulation model can be considered a mirrored image of the real machine—able to continuously record and track machine condition during the later utilization stage. Finally, with the increased connectivity offered by cloud computing technology, the coupled model also provides better accessibility of machine condition for factory managers in cases where physical access to actual equipment or machine data is limited.[34]

5.5.4 Healthcare

Big data analytics has helped healthcare improve by providing personalized medicine and prescriptive analytics, clinical risk intervention and predictive analytics, waste and care variability reduction, automated external and internal reporting of patient data, standardized medical terms and patient registries and fragmented point solutions.[76] Some areas of improvement are more aspirational than actually implemented. The level of data generated within healthcare systems is not trivial. With the added adoption of mHealth, eHealth and wearable technologies the volume of data will continue to increase. This includes electronic health record data, imaging data, patient generated data, sensor data, and other forms of difficult to process data. There is now an even greater need for such environments to pay greater attention to data and information quality.[77] "Big data very often means `dirty data' and the fraction of data inaccuracies increases with data volume growth." Human inspection at the big data scale is impossible and there is a desperate need in health service for intelligent tools for accuracy and believability control and handling of information missed.[78] While extensive information in healthcare is now electronic, it fits under the big data umbrella as most is unstructured and difficult to use.[79]

5.5.5 Education

A McKinsey Global Institute study found a shortage of 1.5 million highly trained data professionals and managers[46] and a number of universities[80] including University of Tennessee and UC Berkeley, have created masters programs to meet this demand. Private bootcamps have also developed programs to meet that demand, including free programs like The Data Incubator or paid programs like General Assembly.[81]

5.5.6 Media

To understand how the media utilises big data, it is first necessary to provide some context into the mechanism used for media process. It has been suggested by Nick Couldry and Joseph Turow that practitioners in Media and Advertising approach big data as many actionable points of information about millions of individuals. The industry appears to be moving away from

the traditional approach of using specific media environments such as newspapers, magazines, or television shows and instead taps into consumers with technologies that reach targeted people at optimal times in optimal locations. The ultimate aim is to serve, or convey, a message or content that is (statistically speaking) in line with the consumer's mindset. For example, publishing environments are increasingly tailoring messages (advertisements) and content (articles) to appeal to consumers that have been exclusively gleaned through various data-mining activities.[82]

- Targeting of consumers (for advertising by marketers)
- Data-capture
- Data journalism: publishers and journalists use big data tools to provide unique and innovative insights and infographics.

Internet of Things (IoT)

Main article: Internet of Things

Big data and the IoT work in conjunction. Data extracted from IoT devices provides a mapping of device interconnectivity. Such mappings have been used by the media industry, companies and governments to more accurately target their audience and increase media efficiency. IoT is also increasingly adopted as a means of gathering sensory data, and this sensory data has been used in medical [83] and manufacturing [84] contexts.

Technology

- eBay.com uses two data warehouses at 7.5 petabytes and 40PB as well as a 40PB Hadoop cluster for search, consumer recommendations, and merchandising.[85]
- Amazon.com handles millions of back-end operations every day, as well as queries from more than half a million third-party sellers. The core technology that keeps Amazon running is Linux-based and as of 2005 they had the world's three largest Linux databases, with capacities of 7.8 TB, 18.5 TB, and 24.7 TB.[86]
- Facebook handles 50 billion photos from its user base.[87]
- Google was handling roughly 100 billion searches per month as of August 2012.[88]
- Oracle NoSQL Database has been tested to past the 1M ops/sec mark with 8 shards and proceeded to hit 1.2M ops/sec with 10 shards.[89]

5.5.7 Information Technology

Especially since 2015, big data has come to prominence within Business Operations as a tool to help employees work more efficiently and streamline the collection and distribution of Information Technology (IT). The use of big data to resolve IT and data collection issues within an enterprise is called IT Operations Analytics (ITOA).[90] By applying big data principles into the concepts of machine intelligence and deep computing, IT departments can predict potential issues and move to provide solutions before the problems even happen.[90] In this time, ITOA businesses were also beginning to play a major role in systems management by offering platforms that brought individual data silos together and generated insights from the whole of the system rather than from isolated pockets of data.

Retail

- Walmart handles more than 1 million customer transactions every hour, which are imported into databases estimated to contain more than 2.5 petabytes (2560 terabytes) of data—the equivalent of 167 times the information contained in all the books in the US Library of Congress.[3]

Retail banking

- FICO Card Detection System protects accounts worldwide.[91]
- The volume of business data worldwide, across all companies, doubles every 1.2 years, according to estimates.[92][93]

Real estate

- Windermere Real Estate uses anonymous GPS signals from nearly 100 million drivers to help new home buyers determine their typical drive times to and from work throughout various times of the day.[94]

5.5.8 Science

The Large Hadron Collider experiments represent about 150 million sensors delivering data 40 million times per second. There are nearly 600 million collisions per second. After filtering and refraining from recording more than 99.99995%[95] of these streams, there are 100 collisions of interest per second.[96][97][98]

- As a result, only working with less than 0.001% of the sensor stream data, the data flow from all four LHC experiments represents 25 petabytes annual

rate before replication (as of 2012). This becomes nearly 200 petabytes after replication.

- If all sensor data were recorded in LHC, the data flow would be extremely hard to work with. The data flow would exceed 150 million petabytes annual rate, or nearly 500 exabytes per day, before replication. To put the number in perspective, this is equivalent to 500 quintillion (5×10^{20}) bytes per day, almost 200 times more than all the other sources combined in the world.

The Square Kilometre Array is a radio telescope built of thousands of antennas. It is expected to be operational by 2024. Collectively, these antennas are expected to gather 14 exabytes and store one petabyte per day.[99][100] It is considered one of the most ambitious scientific projects ever undertaken.[101]

Science and research

- When the Sloan Digital Sky Survey (SDSS) began to collect astronomical data in 2000, it amassed more in its first few weeks than all data collected in the history of astronomy previously. Continuing at a rate of about 200 GB per night, SDSS has amassed more than 140 terabytes of information.[3] When the Large Synoptic Survey Telescope, successor to SDSS, comes online in 2020, its designers expect it to acquire that amount of data every five days.[3]

- Decoding the human genome originally took 10 years to process, now it can be achieved in less than a day. The DNA sequencers have divided the sequencing cost by 10,000 in the last ten years, which is 100 times cheaper than the reduction in cost predicted by Moore's Law.[102]

- The NASA Center for Climate Simulation (NCCS) stores 32 petabytes of climate observations and simulations on the Discover supercomputing cluster.[103][104]

- Google's DNAStack compiles and organizes DNA samples of genetic data from around the world to identify diseases and other medical defects. These fast and exact calculations eliminate any 'friction points,' or human errors that could be made by one of the numerous science and biology experts working with the DNA. DNAStack, a part of Google Genomics, allows scientists to use the vast sample of resources from Google's search server to scale social experiments that would usually take years, instantly.[105][106]

- 23andme's DNA database contains genetic information of over 1,000,000 people worldwide.[107] The company explores selling the "anonymous aggregated genetic data" to other researchers and pharmaceutical companies for research purposes if patients give their consent.[108][109][110][111][112] Ahmad Hariri, professor of psychology and neuroscience at Duke University who has been using 23andMe in his research since 2009 states that the most important aspect of the company's new service is that it makes genetic research accessible and relatively cheap for scientists.[108] A study that identified 15 genome sites linked to depression in 23andMe's database lead to a surge in demands to access the repository with 23andMe fielding nearly 20 requests to access the depression data in the two weeks after publication of the paper.[113]

5.5.9 Sports

Big data can be used to improve training and understanding competitors, using sport sensors. It is also possible to predict winners in a match using big data analytics.[114] Future performance of players could be predicted as well. Thus, players' value and salary is determined by data collected throughout the season.[115]

The movie *MoneyBall* demonstrates how big data could be used to scout players and also identify undervalued players.[116]

In Formula One races, race cars with hundreds of sensors generate terabytes of data. These sensors collect data points from tire pressure to fuel burn efficiency.[117] Based on the data, engineers and data analysts decide whether adjustments should be made in order to win a race. Besides, using big data, race teams try to predict the time they will finish the race beforehand, based on simulations using data collected over the season.[118]

5.6 Research activities

Encrypted search and cluster formation in big data was demonstrated in March 2014 at the American Society of Engineering Education. Gautam Siwach engaged at *Tackling the challenges of Big Data* by MIT Computer Science and Artificial Intelligence Laboratory and Dr. Amir Esmailpour at UNH Research Group investigated the key features of big data as formation of clusters and their interconnections. They focused on the security of big data and the actual orientation of the term towards the presence of different type of data in an encrypted form at cloud interface by providing the raw definitions and real time examples within the technology. Moreover, they proposed an approach for identifying the encoding technique to advance towards an expedited search over encrypted text leading to the security enhancements in big data.[119]

In March 2012, The White House announced a national

"Big Data Initiative" that consisted of six Federal departments and agencies committing more than $200 million to big data research projects.[120]

The initiative included a National Science Foundation "Expeditions in Computing" grant of $10 million over 5 years to the AMPLab[121] at the University of California, Berkeley.[122] The AMPLab also received funds from DARPA, and over a dozen industrial sponsors and uses big data to attack a wide range of problems from predicting traffic congestion[123] to fighting cancer.[124]

The White House Big Data Initiative also included a commitment by the Department of Energy to provide $25 million in funding over 5 years to establish the Scalable Data Management, Analysis and Visualization (SDAV) Institute,[125] led by the Energy Department's Lawrence Berkeley National Laboratory. The SDAV Institute aims to bring together the expertise of six national laboratories and seven universities to develop new tools to help scientists manage and visualize data on the Department's supercomputers.

The U.S. state of Massachusetts announced the Massachusetts Big Data Initiative in May 2012, which provides funding from the state government and private companies to a variety of research institutions.[126] The Massachusetts Institute of Technology hosts the Intel Science and Technology Center for Big Data in the MIT Computer Science and Artificial Intelligence Laboratory, combining government, corporate, and institutional funding and research efforts.[127]

The European Commission is funding the 2-year-long Big Data Public Private Forum through their Seventh Framework Program to engage companies, academics and other stakeholders in discussing big data issues. The project aims to define a strategy in terms of research and innovation to guide supporting actions from the European Commission in the successful implementation of the big data economy. Outcomes of this project will be used as input for Horizon 2020, their next framework program.[128]

The British government announced in March 2014 the founding of the Alan Turing Institute, named after the computer pioneer and code-breaker, which will focus on new ways to collect and analyse large data sets.[129]

At the University of Waterloo Stratford Campus Canadian Open Data Experience (CODE) Inspiration Day, participants demonstrated how using data visualization can increase the understanding and appeal of big data sets and communicate their story to the world.[130]

To make manufacturing more competitive in the United States (and globe), there is a need to integrate more American ingenuity and innovation into manufacturing ; Therefore, National Science Foundation has granted the Industry University cooperative research center for Intelligent Maintenance Systems (IMS) at university of Cincinnati to focus on developing advanced predictive tools and techniques to be applicable in a big data environment.[131] In May 2013, IMS Center held an industry advisory board meeting focusing on big data where presenters from various industrial companies discussed their concerns, issues and future goals in big data environment.

Computational social sciences – Anyone can use Application Programming Interfaces (APIs) provided by big data holders, such as Google and Twitter, to do research in the social and behavioral sciences.[132] Often these APIs are provided for free.[132] Tobias Preis *et al.* used Google Trends data to demonstrate that Internet users from countries with a higher per capita gross domestic product (GDP) are more likely to search for information about the future than information about the past. The findings suggest there may be a link between online behaviour and real-world economic indicators.[133][134][135] The authors of the study examined Google queries logs made by ratio of the volume of searches for the coming year ('2011') to the volume of searches for the previous year ('2009'), which they call the 'future orientation index'.[136] They compared the future orientation index to the per capita GDP of each country, and found a strong tendency for countries where Google users inquire more about the future to have a higher GDP. The results hint that there may potentially be a relationship between the economic success of a country and the information-seeking behavior of its citizens captured in big data.

Tobias Preis and his colleagues Helen Susannah Moat and H. Eugene Stanley introduced a method to identify online precursors for stock market moves, using trading strategies based on search volume data provided by Google Trends.[137] Their analysis of Google search volume for 98 terms of varying financial relevance, published in *Scientific Reports*,[138] suggests that increases in search volume for financially relevant search terms tend to precede large losses in financial markets.[139][140][141][142][143][144][145][146]

Big data sets come with algorithmic challenges that previously did not exist. Hence, there is a need to fundamentally change the processing ways.[147]

The Workshops on Algorithms for Modern Massive Data Sets (MMDS) bring together computer scientists, statisticians, mathematicians, and data analysis practitioners to discuss algorithmic challenges of big data.[148]

5.6.1 Sampling big data

An important research question that can be asked about big data sets is whether you need to look at the full data to draw certain conclusions about the properties of the data or is a sample good enough. The name big data itself contains a term related to size and this is an important characteristic of big data. But Sampling (statistics) enables the selection of right data points from within the larger data set to estimate the characteristics of the whole population. For example, there are about 600 million tweets

produced every day. Is it necessary to look at all of them to determine the topics that are discussed during the day? Is it necessary to look at all the tweets to determine the sentiment on each of the topics? In manufacturing different types of sensory data such as acoustics, vibration, pressure, current, voltage and controller data are available at short time intervals. To predict down-time it may not be necessary to look at all the data but a sample may be sufficient. Big Data can be broken down by various data point categories such as demographic, psychographic, behavioral, and transactional data. With large sets of data points, marketers are able to create and utilize more customized segments of consumers for more strategic targeting.

There has been some work done in Sampling algorithms for big data. A theoretical formulation for sampling Twitter data has been developed.[149]

5.7 Critique

Critiques of the big data paradigm come in two flavors, those that question the implications of the approach itself, and those that question the way it is currently done.[150] One approach to this criticism is the field of Critical data studies.

5.7.1 Critiques of the big data paradigm

"A crucial problem is that we do not know much about the underlying empirical micro-processes that lead to the emergence of the[se] typical network characteristics of Big Data".[15] In their critique, Snijders, Matzat, and Reips point out that often very strong assumptions are made about mathematical properties that may not at all reflect what is really going on at the level of micro-processes. Mark Graham has leveled broad critiques at Chris Anderson's assertion that big data will spell the end of theory:[151] focusing in particular on the notion that big data must always be contextualized in their social, economic, and political contexts.[152] Even as companies invest eight- and nine-figure sums to derive insight from information streaming in from suppliers and customers, less than 40% of employees have sufficiently mature processes and skills to do so. To overcome this insight deficit, big data, no matter how comprehensive or well analysed, must be complemented by "big judgment," according to an article in the Harvard Business Review.[153]

Much in the same line, it has been pointed out that the decisions based on the analysis of big data are inevitably "informed by the world as it was in the past, or, at best, as it currently is".[69] Fed by a large number of data on past experiences, algorithms can predict future development if the future is similar to the past.[154] If the systems dynamics of the future change (if it is not a stationary process), the past can say little about the future. In order to make predictions in changing environments, it would be necessary to have a thorough understanding of the systems dynamic, which requires theory.[154] As a response to this critique it has been suggested to combine big data approaches with computer simulations, such as agent-based models[69] and Complex Systems. Agent-based models are increasingly getting better in predicting the outcome of social complexities of even unknown future scenarios through computer simulations that are based on a collection of mutually interdependent algorithms.[155][156] In addition, use of multivariate methods that probe for the latent structure of the data, such as factor analysis and cluster analysis, have proven useful as analytic approaches that go well beyond the bi-variate approaches (cross-tabs) typically employed with smaller data sets.

In health and biology, conventional scientific approaches are based on experimentation. For these approaches, the limiting factor is the relevant data that can confirm or refute the initial hypothesis.[157] A new postulate is accepted now in biosciences: the information provided by the data in huge volumes (omics) without prior hypothesis is complementary and sometimes necessary to conventional approaches based on experimentation.[158][159] In the massive approaches it is the formulation of a relevant hypothesis to explain the data that is the limiting factor.[160] The search logic is reversed and the limits of induction ("Glory of Science and Philosophy scandal", C. D. Broad, 1926) are to be considered.

Privacy advocates are concerned about the threat to privacy represented by increasing storage and integration of personally identifiable information; expert panels have released various policy recommendations to conform practice to expectations of privacy.[161][162][163]

Nayef Al-Rodhan argues that a new kind of social contract will be needed to protect individual liberties in a context of Big Data and giant corporations that own vast amounts of information. The use of Big Data should be monitored and better regulated at the national and international levels.[164]

5.7.2 Critiques of big data execution

Ulf-Dietrich Reips and Uwe Matzat wrote in 2014 that big data had become a "fad" in scientific research.[132] Researcher Danah Boyd has raised concerns about the use of big data in science neglecting principles such as choosing a representative sample by being too concerned about actually handling the huge amounts of data.[165] This approach may lead to results bias in one way or another. Integration across heterogeneous data resources—some that might be considered big data and others not—presents formidable logistical as well as analytical challenges, but many researchers argue that such integrations are likely to represent the most promising new frontiers in science.[166] In the provocative article "Critical Questions for Big Data",[167] the authors title big data a part

Danah Boyd

of mythology: "large data sets offer a higher form of intelligence and knowledge [...], with the aura of truth, objectivity, and accuracy". Users of big data are often "lost in the sheer volume of numbers", and "working with Big Data is still subjective, and what it quantifies does not necessarily have a closer claim on objective truth".[167] Recent developments in BI domain, such as pro-active reporting especially target improvements in usability of big data, through automated filtering of non-useful data and correlations.[168]

Big data analysis is often shallow compared to analysis of smaller data sets.[169] In many big data projects, there is no large data analysis happening, but the challenge is the extract, transform, load part of data preprocessing.[169]

Big data is a buzzword and a "vague term",[170][171] but at the same time an "obsession"[171] with entrepreneurs, consultants, scientists and the media. Big data showcases such as Google Flu Trends failed to deliver good predictions in recent years, overstating the flu outbreaks by a factor of two. Similarly, Academy awards and election predictions solely based on Twitter were more often off than on target. Big data often poses the same challenges as small data; and adding more data does not solve problems of bias, but may emphasize other problems. In particular data sources such as Twitter are not representative of the overall population, and results drawn from such sources may then lead to wrong conclusions. Google Translate—which is based on big data statistical analysis of text—does a good job at translating web pages. However, results from specialized domains may be dramatically skewed. On the other hand, big data may also introduce new problems, such as the multiple comparisons problem: simultaneously testing a large set of hypotheses is likely to produce many false results that mistakenly appear significant. Ioannidis argued that "most published research findings are false"[172] due to essentially the same effect: when many scientific teams and researchers each perform many experiments (i.e. process a big amount of scientific data; although not with big data technology), the likelihood of a "significant" result being actually false grows fast – even more so, when only positive results are published. Furthermore, big data analytics results are only as good as the model on which they are predicated. In an example, big data took part in attempting to predict the results of the 2016 U.S. Presidential Election[173] with varying degrees of success. Forbes predicted "If you believe in *Big Data* analytics, it's time to begin planning for a Hillary Clinton presidency and all that entails.".[174]

5.8 See also

For a list of companies, and tools, see also: Category:Big data.

- Big memory
- Datafication
- Data defined storage
- Data journalism
- Data lineage
- Data philanthropy
- Data science
- Statistics
- Surveillance capitalism
- Small data
- Urban informatics

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5.11 External links

- Media related to Big data at Wikimedia Commons
- The dictionary definition of big data at Wiktionary

Chapter 6

Disruptive innovation

The free, online encyclopedia Wikipedia was a disruptive innovation that had a major impact on both the traditional, for-profit printed paper encyclopedia market (e.g., Encyclopædia Britannica) and the for-profit digital encyclopedia market (e.g., Encarta). The English Wikipedia provides over 5 million articles for free; in contrast, a $1,000 set of Britannica volumes had 120,000 articles.

A **disruptive innovation** is an innovation that creates a new market and value network and eventually disrupts an existing market and value network, displacing established market leading firms, products and alliances. The term was defined and phenomenon analyzed by Clayton M. Christensen beginning in 1995.[2] In the early 2000s, "significant societal impact" has also been used as an aspect of disruptive innovation.[3]

Not all innovations are disruptive, even if they are revolutionary. For example, the first automobiles in the late 19th century were not a disruptive innovation, because early automobiles were expensive luxury items that did not disrupt the market for horse-drawn vehicles. The market for transportation essentially remained intact until the debut of the lower-priced Ford Model T in 1908.[4] The *mass-produced* automobile was a disruptive innovation, because it changed the transportation market, whereas the first thirty years of automobiles did not.

Disruptive innovations tend to be produced by outsiders and entrepreneurs, rather than existing market-leading companies. The business environment of market leaders does not allow them to pursue disruptive innovations when they first arise, because they are not profitable enough at first and because their development can take scarce resources away from sustaining innovations (which are needed to compete against current competition).[5] A disruptive process can take longer to develop than by the conventional approach and the risk associated to it is higher than the other more incremental or evolutionary forms of innovations, but once it is deployed in the market, it achieves a much faster penetration and higher degree of impact on the established markets.[3]

Beyond business and economics disruptive innovations can also be considered to disrupt complex systems, only including economic and business-related aspects.[6]

6.1 History and usage of the term

The term **disruptive technologies** was coined by Clayton M. Christensen and introduced in his 1995 article *Disruptive Technologies: Catching the Wave*,[7] which he cowrote with Joseph Bower. The article is aimed at management executives who make the funding or purchasing decisions in companies, rather than the research community. He describes the term further in his book *The Innovator's Dilemma*.[8] *Innovator's Dilemma* explored the cases of the disk drive industry (which, with its rapid generational change, is to the study of business what fruit flies are to the study of genetics, as Christensen was advised in the 1990s[9]) and the excavating equipment industry (where hydraulic actuation slowly displaced cable-actuated movement). In his sequel with Michael E. Raynor, *The Innovator's Solution*,[10] Christensen replaced the term *disruptive technology* with *disruptive innovation* because he recognized that few technologies are intrinsically disruptive or sustaining in character; rather, it is the *business model* that the technology enables that creates the disruptive impact. However, Christensen's evolution from a technological focus

to a business-modelling focus is central to understanding the evolution of business at the market or industry level. Christensen and Mark W. Johnson, who cofounded the management consulting firm Innosight, described the dynamics of "business model innovation" in the 2008 *Harvard Business Review* article "Reinventing Your Business Model".[11] The concept of disruptive technology continues a long tradition of identifying radical technical change in the study of innovation by economists, and the development of tools for its management at a firm or policy level.

In the late 1990s, the automotive sector began to embrace a perspective of "constructive disruptive technology" by working with the consultant David E. O'Ryan, whereby the use of current off-the-shelf technology was integrated with newer innovation to create what he called "an unfair advantage". The process or technology change as a whole had to be "constructive" in improving the current method of manufacturing, yet disruptively impact the whole of the business case model, resulting in a significant reduction of waste, energy, materials, labor, or legacy costs to the user.

In keeping with the insight that what matters economically is the business model, not the technological sophistication itself, Christensen's theory explains why many disruptive innovations are *not* "advanced technologies", which the technology mudslide hypothesis would lead one to expect. Rather, they are often novel combinations of existing off-the-shelf components, applied cleverly to a small, fledgling value network.

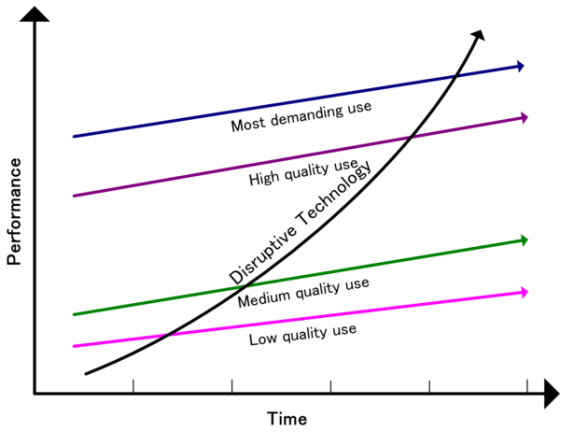
6.2 Theory

Christensen defines a disruptive innovation as a product or service designed for a new set of customers.

> "Generally, disruptive innovations were technologically straightforward, consisting of off-the-shelf components put together in a product architecture that was often simpler than prior approaches. They offered less of what customers in established markets wanted and so could rarely be initially employed there. They offered a different package of attributes valued only in emerging markets remote from, and unimportant to, the mainstream."[12]

Christensen argues that disruptive innovations can hurt successful, well-managed companies that are responsive to their customers and have excellent research and development. These companies tend to ignore the markets most susceptible to disruptive innovations, because the markets have very tight profit margins and are too small to provide a good growth rate to an established (sizable) firm.[13] Thus, disruptive technology provides an example of an instance when the common business-world advice to "focus on the customer" (or "stay close to the customer", or "listen to the customer") can be strategically counterproductive.

While Christensen argued that disruptive innovations can hurt successful, well-managed companies, O'Ryan countered that "constructive" integration of existing, new, and forward-thinking innovation could improve the economic benefits of these same well-managed companies, once decision-making management understood the systemic benefits as a whole.



How low-end disruption occurs over time.

Christensen distinguishes between "low-end disruption", which targets customers who do not need the full performance valued by customers at the high end of the market, and "new-market disruption", which targets customers who have needs that were previously unserved by existing incumbents.[14]

"Low-end disruption" occurs when the rate at which products improve exceeds the rate at which customers can adopt the new performance. Therefore, at some point the performance of the product overshoots the needs of certain customer segments. At this point, a disruptive technology may enter the market and provide a product that has lower performance than the incumbent but that exceeds the requirements of certain segments, thereby gaining a foothold in the market.

In low-end disruption, the disruptor is focused initially on serving the least profitable customer, who is happy with a good enough product. This type of customer is not willing to pay premium for enhancements in product functionality. Once the disruptor has gained a foothold in this customer segment, it seeks to improve its profit margin. To get higher profit margins, the disruptor needs to enter the segment where the customer is willing to pay a little more for higher quality. To ensure this quality in its product, the disruptor needs to innovate. The incumbent will not do much to retain its share in a not-so-profitable segment, and will move up-market and focus on its more attractive customers. After a number of such encounters, the incumbent is squeezed into smaller markets than it was previously serving. And then, finally, the disruptive technology meets the demands of the most profitable segment

and drives the established company out of the market.

"New market disruption" occurs when a product fits a new or emerging market segment that is not being served by existing incumbents in the industry.

The extrapolation of the theory to all aspects of life has been challenged,[15][16] as has the methodology of relying on selected case studies as the principal form of evidence.[15] Jill Lepore points out that some companies identified by the theory as victims of disruption a decade or more ago, rather than being defunct, remain dominant in their industries today (including Seagate Technology, U.S. Steel, and Bucyrus).[15] Lepore questions whether the theory has been oversold and misapplied, as if it were able to explain everything in every sphere of life, including not just business but education and public institutions.[15]

6.3 Disruptive technology

In 2009, Milan Zeleny described high technology as disruptive technology and raised the question of what is being disrupted. The answer, according to Zeleny, is the *support network* of high technology.[17] For example, introducing electric cars disrupts the support network for gasoline cars (network of gas and service stations). Such disruption is fully expected and therefore effectively resisted by support net owners. In the long run, high (disruptive) technology bypasses, upgrades, or replaces the outdated support network.

Technology, being a form of social relationship, always evolves. No technology remains fixed. Technology starts, develops, persists, mutates, stagnates, and declines, just like living organisms.[18] The evolutionary life cycle occurs in the use and development of any technology. A new high-technology core emerges and challenges existing technology support nets (TSNs), which are thus forced to coevolve with it. New versions of the core are designed and fitted into an increasingly appropriate TSN, with smaller and smaller high-technology effects. High technology becomes regular technology, with more efficient versions fitting the same support net. Finally, even the efficiency gains diminish, emphasis shifts to product tertiary attributes (appearance, style), and technology becomes TSN-preserving appropriate technology. This technological equilibrium state becomes established and fixated, resisting being interrupted by a technological mutation; then new high technology appears and the cycle is repeated.

Regarding this evolving process of technology, Christensen said:

> "The technological changes that damage established companies are usually not radically new or difficult from a technological point of view. They do, however, have two important characteristics: First, they typically present a different package of performance attributes—ones that, at least at the outset, are not valued by existing customers. Second, the performance attributes that existing customers do value improve at such a rapid rate that the new technology can later invade those established markets."[19]

Joseph Bower[20] explained the process of how disruptive technology, through its requisite support net, dramatically transforms a certain industry.

> "When the technology that has the potential for revolutionizing an industry emerges, established companies typically see it as unattractive: it's not something their mainstream customers want, and its projected profit margins aren't sufficient to cover big-company cost structure. As a result, the new technology tends to get ignored in favor of what's currently popular with the best customers. But then another company steps in to bring the innovation to a new market. Once the disruptive technology becomes established there, smaller-scale innovation rapidly raise the technology's performance on attributes that mainstream customers' value."[21]

The automobile was high technology with respect to the horse carriage; however, it evolved into technology and finally into appropriate technology with a stable, unchanging TSN. The main high-technology advance in the offing is some form of electric car—whether the energy source is the sun, hydrogen, water, air pressure, or traditional charging outlet. Electric cars preceded the gasoline automobile by many decades and are now returning to replace the traditional gasoline automobile.

Milan Zeleny described the above phenomenon.[22] He also wrote that:

> "Implementing high technology is often resisted. This resistance is well understood on the part of active participants in the requisite TSN. The electric car will be resisted by gas-station operators in the same way automated teller machines (ATMs) were resisted by bank tellers and automobiles by horsewhip makers. Technology does not qualitatively restructure the TSN and therefore will not be resisted and never has been resisted. Middle management resists business process reengineering because BPR represents a direct assault on the support net (coordinative hierarchy) they thrive on. Teamwork and multi-functionality is resisted by those whose TSN provides the comfort of narrow specialization and command-driven work."[23]

6.4 High-technology effects

High technology is a technology core that changes the very architecture (structure and organization) of the components of the technology support net. High technology therefore transforms the qualitative nature of the TSN's tasks and their relations, as well as their requisite physical, energy, and information flows. It also affects the skills required, the roles played, and the styles of management and coordination—the organizational culture itself.

This kind of technology core is different from regular technology core, which preserves the qualitative nature of flows and the structure of the support and only allows users to perform the same tasks in the same way, but faster, more reliably, in larger quantities, or more efficiently. It is also different from appropriate technology core, which preserves the TSN itself with the purpose of technology implementation and allows users to do the same thing in the same way at comparable levels of efficiency, instead of improving the efficiency of performance.[24]

As for the difference between high technology and low technology, Milan Zeleny once said:

> " The effects of high technology always breaks the direct comparability by changing the system itself, therefore requiring new measures and new assessments of its productivity. High technology cannot be compared and evaluated with the existing technology purely on the basis of cost, net present value or return on investment. Only within an unchanging and relatively stable TSN would such direct financial comparability be meaningful. For example, you can directly compare a manual typewriter with an electric typewriter, but not a typewriter with a word processor. Therein lies the management challenge of high technology. "[25]

However, not all modern technologies are high technologies. They have to be used as such, function as such, and be embedded in their requisite TSNs. They have to empower the individual because only through the individual can they empower knowledge. Not all information technologies have integrative effects. Some information systems are still designed to improve the traditional hierarchy of command and thus preserve and entrench the existing TSN. The administrative model of management, for instance, further aggravates the division of task and labor, further specializes knowledge, separates management from workers, and concentrates information and knowledge in centers.

As knowledge surpasses capital, labor, and raw materials as the dominant economic resource, technologies are also starting to reflect this shift. Technologies are rapidly shifting from centralized hierarchies to distributed networks. Nowadays knowledge does not reside in a supermind, super-book, or super-database, but in a complex relational pattern of networks brought forth to coordinate human action.

6.5 Practical example of disruption

In the practical world, the popularization of personal computers illustrates how knowledge contributes to the ongoing technology innovation. The original centralized concept (one computer, many persons) is a knowledge-defying idea of the prehistory of computing, and its inadequacies and failures have become clearly apparent. The era of personal computing brought powerful computers "on every desk" (one person, one computer). This short transitional period was necessary for getting used to the new computing environment, but was inadequate from the vantage point of producing knowledge. Adequate knowledge creation and management come mainly from networking and distributed computing (one person, many computers). Each person's computer must form an access point to the entire computing landscape or ecology through the Internet of other computers, databases, and mainframes, as well as production, distribution, and retailing facilities, and the like. For the first time, technology empowers individuals rather than external hierarchies. It transfers influence and power where it optimally belongs: at the loci of the useful knowledge. Even though hierarchies and bureaucracies do not innovate, free and empowered individuals do; knowledge, innovation, spontaneity, and self-reliance are becoming increasingly valued and promoted.[26]

6.6 Examples

6.7 See also

- Blue Ocean Strategy
- Creative destruction
- Culture lag
- Digital Revolution
- Hype cycle
- Killer application
- Leapfrogging
- List of emerging technologies
- Obsolescence
- Pace of innovation

- Paradigm shift
- Product lifecycle
- Technology readiness level (NASA)
- Technology strategy

6.8 Notes

[1] Christensen 1997, p. xviii. Christensen describes as "revolutionary" innovations as "discontinuous" "sustaining innovations".

[2] Bower, Joseph L. & Christensen, Clayton M. (1995)

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[4] Christensen 2003, p. 49.

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[8] Christensen 1997.

[9] Christensen 1997, p. 3.

[10] Christensen 2003.

[11] Johnson, Mark, Christensen, Clayton, et al., 2008, "Reinventing Your Business Model, *Harvard Business Review*, December 2008.

[12] Christensen 1997, p. 15.

[13] Christensen 1997, p. i-iii.

[14] Christensen 2003, p. 23-45.

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[30] Christensen 1997, p. 3-28.

[31] Christensen 1997, pp. 61–76.

[32] Christensen 2003, pp. 37–39.

[33] Christensen 2003, p. 64.

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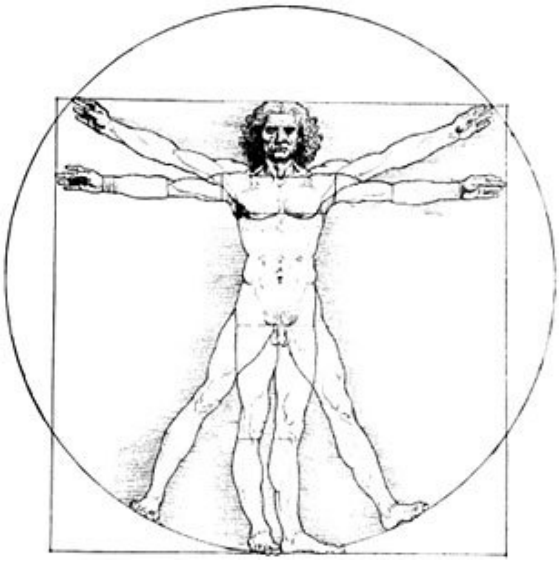
6.11 External links

- Peer-reviewed chapter on Disruptive Innovation by Clayton Christensen with public commentaries by notable designers like Donald Norman
- The Myth of Disruptive Technologies. Note that Dvorák's definition of disruptive technology describes the low cost disruption model, above. He reveals the overuse of the term and shows how many disruptive technologies are not truly disruptive.
- "The Disruptive Potential of Game Technologies: Lessons Learned from its Impact on the Military Simulation Industry", by Roger Smith in Research Technology Management (September/October 2006)
- Disruptive Innovation Theory
- Bibliography of Christensen's "Theory of Disruptive Innovation" as it relates to higher education

- What does Disruption mean?
- Diffusion of Innovations, Strategy and Innovations The D.S.I Framework by Francisco Rodrigues Gomes, Academia.edu share research
- CREATING THE FUTURE: Building Tomorrow's World
- Lecture (video), VoIP as an example of disruptive technology

Chapter 7

Human Genome Project



Logo HGP; Vitruvian Man, Leonardo da Vinci

The **Human Genome Project** (**HGP**) was an international scientific research project with the goal of determining the sequence of nucleotide base pairs that make up human DNA, and of identifying and mapping all of the genes of the human genome from both a physical and a functional standpoint.[1] It remains the world's largest collaborative biological project.[2] After the idea was picked up in 1984 by the US government when the planning started, the project formally launched in 1990 and was declared complete in 2003. Funding came from the US government through the National Institutes of Health (NIH) as well as numerous other groups from around the world. A parallel project was conducted outside of government by the Celera Corporation, or Celera Genomics, which was formally launched in 1998. Most of the government-sponsored sequencing was performed in twenty universities and research centers in the United States, the United Kingdom, Japan, France, Germany, Canada, and China.[3]

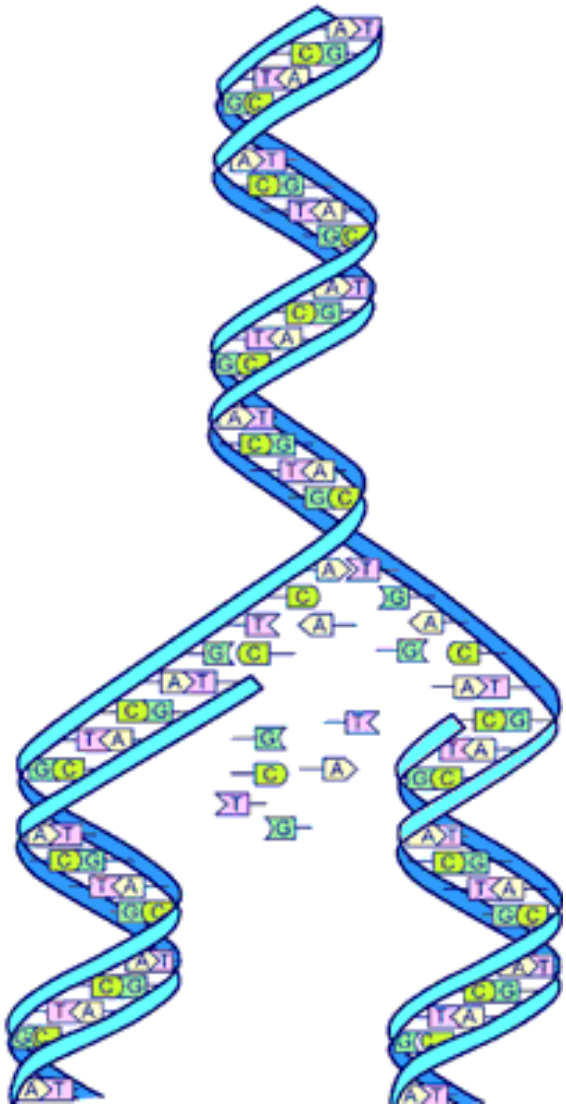
The Human Genome Project originally aimed to map the nucleotides contained in a human haploid reference genome (more than three billion). The "genome" of any given individual is unique; mapping the "human genome" involved sequencing a small number of individuals and then assembling these together to get a complete sequence for each chromosome. The finished human genome is thus a mosaic, not representing any one individual.

7.1 Human Genome Project

7.1.1 History

The Human Genome Project was a 13-year-long, publicly funded project initiated in 1990 with the objective of determining the DNA sequence of the entire euchromatic human genome within 15 years.[4] In May 1985, Robert Sinsheimer organized a workshop to discuss sequencing the human genome,[5] but for a number of reasons the NIH was uninterested in pursuing the proposal. The following March, the Santa Fe Workshop was organized by Charles DeLisi and David Smith of the Department of Energy's Office of Health and Environmental Research (OHER).[6] At the same time Renato Dulbecco proposed whole genome sequencing in an essay in Science.[7] James Watson followed two months later with a workshop held at the Cold Spring Harbor Laboratory.

The fact that the Santa Fe workshop was motivated and supported by a Federal Agency opened a path, albeit a difficult and tortuous one,[8] for converting the idea into public policy. In a memo to the Assistant Secretary for Energy Research (Alvin Trivelpiece), Charles DeLisi, who was then Director of OHER, outlined a broad plan for the project.[9] This started a long and complex chain of events which led to approved reprogramming of funds that enabled OHER to launch the Project in 1986, and to recommend the first line item for the HGP, which was in President Reagan's 1988 budget submission,[8] and ultimately approved by the Congress. Of particular importance in Congressional approval was the advocacy of Senator Peter Domenici, whom DeLisi had befriended.[10] Domenici chaired the Senate Committee on Energy and Natural Resources, as well as the Budget Committee, both of which were key in the DOE budget process. Congress added a comparable amount to the NIH budget, thereby beginning official funding by both agencies.



DNA replication

Alvin Trivelpiece sought and obtained the approval of DeLisi's proposal by Deputy Secretary William Flynn Martin. This chart[11] was used in the spring of 1986 by Trivelpiece, then Director of the Office of Energy Research in the Department of Energy, to brief Martin and Under Secretary Joseph Salgado regarding his intention to reprogram $4 million to initiate the project with the approval of Secretary Herrington. This reprogramming was followed by a line item budget of $16 million in the Reagan Administration's 1987 budget submission to Congress.[12] It subsequently passed both Houses. The Project was planned for 15 years.[13]

Candidate technologies were already being considered for the proposed undertaking at least as early as 1985.[14]

In 1990, the two major funding agencies, DOE and NIH, developed a memorandum of understanding in order to coordinate plans and set the clock for the initiation of the Project to 1990.[15] At that time, David Galas was Director of the renamed "Office of Biological and Environmental Research" in the U.S. Department of Energy's Office of Science and James Watson headed the NIH Genome Program. In 1993, Aristides Patrinos succeeded Galas and Francis Collins succeeded James Watson, assuming the role of overall Project Head as Director of the U.S. National Institutes of Health (NIH) National Center for Human Genome Research (which would later become the National Human Genome Research Institute). A working draft of the genome was announced in 2000 and the papers describing it were published in February 2001. A more complete draft was published in 2003, and genome "finishing" work continued for more than a decade.

The $3-billion project was formally founded in 1990 by the US Department of Energy and the National Institutes of Health, and was expected to take 15 years.[16] In addition to the United States, the international consortium comprised geneticists in the United Kingdom, France, Australia, China and myriad other spontaneous relationships.[17]

Due to widespread international cooperation and advances in the field of genomics (especially in sequence analysis), as well as major advances in computing technology, a 'rough draft' of the genome was finished in 2000 (announced jointly by U.S. President Bill Clinton and the British Prime Minister Tony Blair on June 26, 2000).[18] This first available rough draft assembly of the genome was completed by the Genome Bioinformatics Group at the University of California, Santa Cruz, primarily led by then graduate student Jim Kent. Ongoing sequencing led to the announcement of the essentially complete genome on April 14, 2003, two years earlier than planned.[19][20] In May 2006, another milestone was passed on the way to completion of the project, when the sequence of the last chromosome was published in *Nature*.[21]

7.1.2 State of completion

The project was not able to sequence all the DNA found in human cells. It sequenced only "euchromatic" regions of the genome, which make up more than 95% of the genome. The other regions, called "heterochromatic" are found in centromeres and telomeres, and were not sequenced under the project.[22]

The Human Genome Project was declared complete in April 2003. An initial rough draft of the human genome was available in June 2000 and by February 2001 a working draft had been completed and published followed by the final sequencing mapping of the human genome on April 14, 2003. Although this was reported to cover 99% of the euchromatic human genome with 99.99% accuracy, a major quality assessment of the human genome sequence was published on May 27, 2004 indicating over 92% of sampling exceeded 99.99% accuracy which was within the intended goal.[23] Further analyses and papers on the HGP continue to occur.[24]

7.2 Applications and proposed benefits

The sequencing of the human genome holds benefits for many fields, from molecular medicine to human evolution. The Human Genome Project, through its sequencing of the DNA, can help us understand diseases including: genotyping of specific viruses to direct appropriate treatment; identification of mutations linked to different forms of cancer; the design of medication and more accurate prediction of their effects; advancement in forensic applied sciences; biofuels and other energy applications; agriculture, animal husbandry, bioprocessing; risk assessment; bioarcheology, anthropology and evolution. Another proposed benefit is the commercial development of genomics research related to DNA based products, a multibillion-dollar industry.

The sequence of the DNA is stored in databases available to anyone on the Internet. The U.S. National Center for Biotechnology Information (and sister organizations in Europe and Japan) house the gene sequence in a database known as GenBank, along with sequences of known and hypothetical genes and proteins. Other organizations, such as the UCSC Genome Browser at the University of California, Santa Cruz,[25] and Ensembl[26] present additional data and annotation and powerful tools for visualizing and searching it. Computer programs have been developed to analyze the data, because the data itself is difficult to interpret without such programs. Generally speaking, advances in genome sequencing technology have followed Moore's Law, a concept from computer science which states that integrated circuits can increase in complexity at an exponential rate.[27] This means that the speeds at which whole genomes can be sequenced can increase at a similar rate, as was seen during the development of the above-mentioned Human Genome Project.

7.3 Techniques and analysis

The process of identifying the boundaries between genes and other features in a raw DNA sequence is called genome annotation and is in the domain of bioinformatics. While expert biologists make the best annotators, their work proceeds slowly, and computer programs are increasingly used to meet the high-throughput demands of genome sequencing projects. Beginning in 2008, a new technology known as RNA-seq was introduced that allowed scientists to directly sequence the messenger RNA in cells. This replaced previous methods of annotation, which relied on inherent properties of the DNA sequence, with direct measurement, which was much more accurate. Today, annotation of the human genome and other genomes relies primarily on deep sequencing of the transcripts in every human tissue using RNA-seq. These experiments have revealed that over 90% of genes contain at least one and usually several alternative splice variants, in which the exons are combined in different ways to produce 2 or more gene products from the same locus.

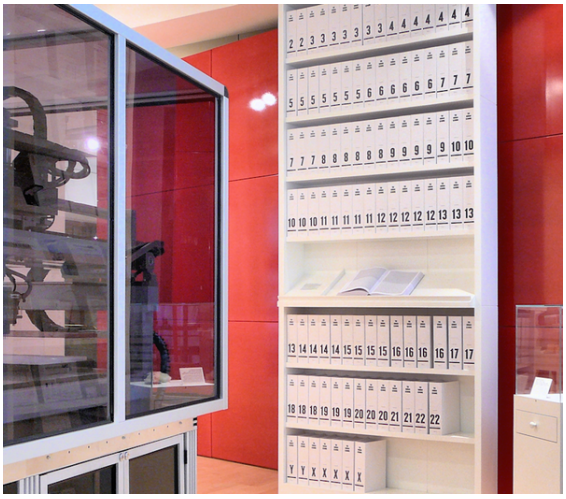
The genome published by the HGP does not represent the sequence of every individual's genome. It is the combined mosaic of a small number of anonymous donors, all of European origin. The HGP genome is a scaffold for future work in identifying differences among individuals. Subsequent projects sequenced the genomes of multiple distinct ethnic groups, though as of today there is still only one "reference genome."

7.3.1 Findings

Key findings of the draft (2001) and complete (2004) genome sequences include:

1. There are approximately 22,300[28] protein-coding genes in human beings, the same range as in other mammals.
2. The human genome has significantly more segmental duplications (nearly identical, repeated sections of DNA) than had been previously suspected.[29][30][31]
3. At the time when the draft sequence was published fewer than 7% of protein families appeared to be vertebrate specific.[32]

7.3.2 Accomplishment



The first printout of the human genome to be presented as a series of books, displayed at the Wellcome Collection, London

The Human Genome Project was started in 1990 with the goal of sequencing and identifying all three billion chemical units in the human genetic instruction set, finding the genetic roots of disease and then developing treatments. It is considered a Mega Project because the human

genome has approximately 3.3 billion base-pairs. With the sequence in hand, the next step was to identify the genetic variants that increase the risk for common diseases like cancer and diabetes.[15][33]

It was far too expensive at that time to think of sequencing patients' whole genomes. So the National Institutes of Health embraced the idea for a "shortcut", which was to look just at sites on the genome where many people have a variant DNA unit. The theory behind the shortcut was that, since the major diseases are common, so too would be the genetic variants that caused them. Natural selection keeps the human genome free of variants that damage health before children are grown, the theory held, but fails against variants that strike later in life, allowing them to become quite common. (In 2002 the National Institutes of Health started a $138 million dollar project called the HapMap to catalog the common variants in European, East Asian and African genomes.)[34]

The genome was broken into smaller pieces; approximately 150,000 base pairs in length.[33] These pieces were then ligated into a type of vector known as "bacterial artificial chromosomes", or BACs, which are derived from bacterial chromosomes which have been genetically engineered. The vectors containing the genes can be inserted into bacteria where they are copied by the bacterial DNA replication machinery. Each of these pieces was then sequenced separately as a small "shotgun" project and then assembled. The larger, 150,000 base pairs go together to create chromosomes. This is known as the "hierarchical shotgun" approach, because the genome is first broken into relatively large chunks, which are then mapped to chromosomes before being selected for sequencing.[35][36]

Funding came from the US government through the National Institutes of Health in the United States, and a UK charity organization, the Wellcome Trust, as well as numerous other groups from around the world. The funding supported a number of large sequencing centers including those at Whitehead Institute, the Sanger Centre, Washington University in St. Louis, and Baylor College of Medicine.[16][37]

The United Nations Educational, Scientific and Cultural Organization (UNESCO) served as an important channel for the involvement of developing countries in the Human Genome Project.[38]

7.4 Public versus private approaches

In 1998, a similar, privately funded quest was launched by the American researcher Craig Venter, and his firm Celera Genomics. Venter was a scientist at the NIH during the early 1990s when the project was initiated. The $300,000,000 Celera effort was intended to proceed at a faster pace and at a fraction of the cost of the roughly $3 billion publicly funded project. The Celera approach was able to proceed at a much more rapid rate, and at a lower cost than the public project because it relied upon data made available by the publicly funded project.[39]

Celera used a technique called whole genome shotgun sequencing, employing pairwise end sequencing,[40] which had been used to sequence bacterial genomes of up to six million base pairs in length, but not for anything nearly as large as the three billion base pair human genome.

Celera initially announced that it would seek patent protection on "only 200–300" genes, but later amended this to seeking "intellectual property protection" on "fully-characterized important structures" amounting to 100–300 targets. The firm eventually filed preliminary ("place-holder") patent applications on 6,500 whole or partial genes. Celera also promised to publish their findings in accordance with the terms of the 1996 "Bermuda Statement", by releasing new data annually (the HGP released its new data daily), although, unlike the publicly funded project, they would not permit free redistribution or scientific use of the data. The publicly funded competitors were compelled to release the first draft of the human genome before Celera for this reason. On July 7, 2000, the UCSC Genome Bioinformatics Group released a first working draft on the web. The scientific community downloaded about 500 GB of information from the UCSC genome server in the first 24 hours of free and unrestricted access.[41]

In March 2000, President Clinton announced that the genome sequence could not be patented, and should be made freely available to all researchers. The statement sent Celera's stock plummeting and dragged down the biotechnology-heavy Nasdaq. The biotechnology sector lost about $50 billion in market capitalization in two days.

Although the working draft was announced in June 2000, it was not until February 2001 that Celera and the HGP scientists published details of their drafts. Special issues of *Nature* (which published the publicly funded project's scientific paper)[42] and *Science* (which published Celera's paper[43]) described the methods used to produce the draft sequence and offered analysis of the sequence. These drafts covered about 83% of the genome (90% of the euchromatic regions with 150,000 gaps and the order and orientation of many segments not yet established). In February 2001, at the time of the joint publications, press releases announced that the project had been completed by both groups. Improved drafts were announced in 2003 and 2005, filling in to approximately 92% of the sequence currently.

7.5 Genome donors

In the IHGSC international public-sector HGP, researchers collected blood (female) or sperm (male) sam-

ples from a large number of donors. Only a few of many collected samples were processed as DNA resources. Thus the donor identities were protected so neither donors nor scientists could know whose DNA was sequenced. DNA clones from many different libraries were used in the overall project, with most of those libraries being created by Pieter J. de Jong's. Much of the sequence (>70%) of the reference genome produced by the public HGP came from a single anonymous male donor from Buffalo, New York (code name RP11).[44][45]

HGP scientists used white blood cells from the blood of two male and two female donors (randomly selected from 20 of each) – each donor yielding a separate DNA library. One of these libraries (RP11) was used considerably more than others, due to quality considerations. One minor technical issue is that male samples contain just over half as much DNA from the sex chromosomes (one X chromosome and one Y chromosome) compared to female samples (which contain two X chromosomes). The other 22 chromosomes (the autosomes) are the same for both sexes.

Although the main sequencing phase of the HGP has been completed, studies of DNA variation continue in the International HapMap Project, whose goal is to identify patterns of single-nucleotide polymorphism (SNP) groups (called haplotypes, or "haps"). The DNA samples for the HapMap came from a total of 270 individuals: Yoruba people in Ibadan, Nigeria; Japanese people in Tokyo; Han Chinese in Beijing; and the French Centre d'Etude du Polymorphisme Humain (CEPH) resource, which consisted of residents of the United States having ancestry from Western and Northern Europe.

In the Celera Genomics private-sector project, DNA from five different individuals were used for sequencing. The lead scientist of Celera Genomics at that time, Craig Venter, later acknowledged (in a public letter to the journal *Science*) that his DNA was one of 21 samples in the pool, five of which were selected for use.[46][47]

In 2007, a team led by Jonathan Rothberg published James Watson's entire genome, unveiling the six-billion-nucleotide genome of a single individual for the first time.[48]

7.6 Developments

The work on interpretation and analysis of genome data is still in its initial stages. It is anticipated that detailed knowledge of the human genome will provide new avenues for advances in medicine and biotechnology. Clear practical results of the project emerged even before the work was finished. For example, a number of companies, such as Myriad Genetics, started offering easy ways to administer genetic tests that can show predisposition to a variety of illnesses, including breast cancer, hemostasis disorders, cystic fibrosis, liver diseases and many others. Also, the etiologies for cancers, Alzheimer's disease and other areas of clinical interest are considered likely to benefit from genome information and possibly may lead in the long term to significant advances in their management.[34][49]

There are also many tangible benefits for biologists. For example, a researcher investigating a certain form of cancer may have narrowed down his/her search to a particular gene. By visiting the human genome database on the World Wide Web, this researcher can examine what other scientists have written about this gene, including (potentially) the three-dimensional structure of its product, its function(s), its evolutionary relationships to other human genes, or to genes in mice or yeast or fruit flies, possible detrimental mutations, interactions with other genes, body tissues in which this gene is activated, and diseases associated with this gene or other datatypes. Further, deeper understanding of the disease processes at the level of molecular biology may determine new therapeutic procedures. Given the established importance of DNA in molecular biology and its central role in determining the fundamental operation of cellular processes, it is likely that expanded knowledge in this area will facilitate medical advances in numerous areas of clinical interest that may not have been possible without them.[50]

The analysis of similarities between DNA sequences from different organisms is also opening new avenues in the study of evolution. In many cases, evolutionary questions can now be framed in terms of molecular biology; indeed, many major evolutionary milestones (the emergence of the ribosome and organelles, the development of embryos with body plans, the vertebrate immune system) can be related to the molecular level. Many questions about the similarities and differences between humans and our closest relatives (the primates, and indeed the other mammals) are expected to be illuminated by the data in this project.[34][51]

The project inspired and paved the way for genomic work in other fields, such as agriculture. For example, by studying the genetic composition of Tritium aestivum, the world's most commonly used bread wheat, great insight has been gained into the ways that domestication has impacted the evolution of the plant.[52] Which loci are most susceptible to manipulation, and how does this play out in evolutionary terms? Genetic sequencing has allowed these questions to be addressed for the first time, as specific loci can be compared in wild and domesticated strains of the plant. This will allow for advances in genetic modification in the future which could yield healthier, more disease-resistant wheat crops.

7.7 Ethical, legal and social issues

At the onset of the Human Genome Project several ethical, legal, and social concerns were raised in regards to

how increased knowledge of the human genome could be used to discriminate against people. One of the main concerns of most individuals was the fear that both employers and health insurance companies would refuse to hire individuals or refuse to provide insurance to people because of a health concern indicated by someone's genes.[53] In 1996 the United States passed the Health Insurance Portability and Accountability Act (HIPAA) which protects against the unauthorized and non-consensual release of individually identifiable health information to any entity not actively engaged in the provision of healthcare services to a patient.[54]

Along with identifying all of the approximately 20,000–25,000 genes in the human genome, the Human Genome Project also sought to address the ethical, legal, and social issues that were created by the onset of the project. For that the Ethical, Legal, and Social Implications (ELSI) program was founded in 1990. Five percent of the annual budget was allocated to address the ELSI arising from the project.[16][55] This budget started at approximately $1.57 million in the year 1990, but increased to approximately $18 million in the year 2014.[56]

Whilst the project may offer significant benefits to medicine and scientific research, some authors have emphasized the need to address the potential social consequences of mapping the human genome. "Molecularising disease and their possible cure will have a profound impact on what patients expect from medical help and the new generation of doctors' perception of illness."[57]

7.8 See also

- 1000 Genomes Project
- Chimpanzee Genome Project
- ENCODE
- EuroPhysiome
- Genome Compiler
- HUGO Gene Nomenclature Committee
- Human Brain Project
- Human Connectome Project
- Human Cytome Project
- Human Microbiome Project
- Human proteome project
- Human Variome Project
- List of biological databases
- Neanderthal Genome Project
- Sanger Institute
- The Genographic Project

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7.10 Further reading

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- Venter, J. Craig (October 18, 2007). *A Life Decoded: My Genome: My Life*. New York, New York: Viking Adult. ISBN 0-670-06358-4. OCLC 165048736.
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7.11 External links

- **Human Genome Project** — official information page
- National Human Genome Research Institute (NHGRI). NHGRI led the National Institutes of Health's contribution to the International Human Genome Project. This project, which had as its primary goal the sequencing of the three thousand million base pairs that make up human genome, was successfully completed in April 2003.
- Human Genome News. Published from 1989 to 2002 by the US Department of Energy, this newsletter was a major communications method for coordination of the Human Genome Project. Complete online archives are available.
- The HGP information pages Department of Energy's portal to the international Human Genome Project, Microbial Genome Program, and Genomics:GTL systems biology for energy and environment
- yourgenome.org: The Sanger Institute public information pages has general and detailed primers on DNA, genes and genomes, the Human Genome Project and science spotlights.
- Ensembl project, an automated annotation system and browser for the human genome
- UCSC genome browser, This site contains the reference sequence and working draft assemblies for a large collection of genomes. It also provides a portal to the ENCODE project.
- Nature magazine's human genome gateway, including the HGP's paper on the draft genome sequence
- Wellcome Trust Human Genome website A free resource allowing you to explore the human genome, your health and your future.
- Learning about the Human Genome. Part 1: Challenge to Science Educators. ERIC Digest.
- Learning about the Human Genome. Part 2: Resources for Science Educators. ERIC Digest.
- *Patenting Life* by Merrill Goozner
- Prepared Statement of Craig Venter of Celera Venter discusses Celera's progress in deciphering the human genome sequence and its relationship to healthcare and to the federally funded Human Genome Project.

- Cracking the Code of Life Companion website to 2-hour NOVA program documenting the race to decode the genome, including the entire program hosted in 16 parts in either QuickTime or RealPlayer format.
- Lone Dog L (1999). "Whose genes are they? The Human Genome Diversity Project". *J Health Soc Policy*. **10** (4): 51–66. doi:10.1300/J045v10n04_04. PMID 10538186.
- Bioethics Research Library Numerous original documents at Georgetown University.

Works by archive

- Works by Human Genome Project at Project Gutenberg
  - Project Gutenberg hosts e-texts for Human Genome Project, titled *Human Genome Project, Chromosome Number #* (# denotes 01-22, X and Y). This information is raw sequence, released in November 2002; access to entry pages with download links is available through https://www.gutenberg.org/etext/3501 for Chromosome 1 sequentially to https://www.gutenberg.org/etext/3524 for the Y Chromosome. Note that this sequence might not be considered definitive due to ongoing revisions and refinements. In addition to the chromosome files, there is a supplementary information file dated March 2004 which contains additional sequence information.
- Works by or about Human Genome Project at Internet Archive

Chapter 8

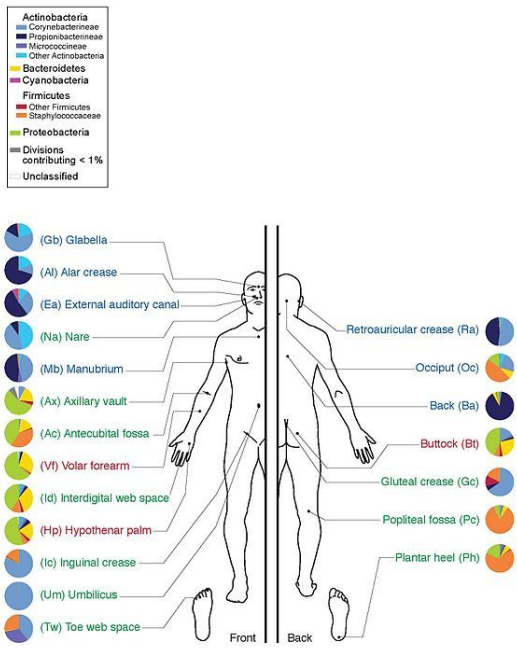
Human Microbiome Project

Logo of the Human Microbiome Project.

The **Human Microbiome Project** (**HMP**) was a United States National Institutes of Health (NIH) initiative with the goal of identifying and characterizing the microorganisms which are found in association with both healthy and diseased humans (the human microbiome). Launched in 2008,[1] it was a five-year project, best characterized as a feasibility study, and had a total budget of $115 million. The ultimate goal of this and similar NIH-sponsored microbiome projects was to test how changes in the human microbiome are associated with human health or disease. This topic is currently not well understood.

Important components of the Human Microbiome Project were culture-independent methods of microbial community characterization, such as metagenomics (which provides a broad genetic perspective on a single microbial community), as well as extensive whole genome sequencing (which provides a "deep" genetic perspective on certain aspects of a given microbial community, *i.e.* of individual bacterial species). The latter served as reference genomic sequences — 3000 such sequences of individual bacterial isolates are currently planned — for comparison purposes during subsequent metagenomic analysis. The microbiology of five body sites was emphasized: oral, skin, vaginal, gut, and nasal/lung. The project also financed deep sequencing of bacterial 16S rRNA sequences amplified by polymerase chain reaction from human subjects.[2]

8.1 Introduction



Depiction of prevalences of various classes of bacteria at selected sites on human skin

As of 2014, it was often reported in popular media and in the scientific literature that there are about 10 times as many microbial cells in the human body than there are human cells; this figure was based on estimates that the human microbiome includes around 100 trillion bacterial cells and an adult human typically has around 10 trillion human cells.[3] In 2014 the American Academy of Microbiology published an FAQ that emphasized that the number of microbial cells and the number of human cells are both estimates, and noted that recent research had arrived at a new estimate of the number of human cells at around 37 trillion cells, meaning that the ratio of microbial to human cells is probably about 3:1.[3][4] In 2016 another group published a new estimate of ratio as being roughly 1:1 (1.3:1, with "an uncertainty of 25% and a variation of 53% over the population of standard 70 kg males").[5][6]

Many of the organisms that make up the human microbiome have not been successfully cultured, identified, or otherwise characterized. Organisms thought to be found in the human microbiome, however, may generally be categorized as bacteria (the majority), members of domain Archaea, yeasts, and single-celled eukaryotes as well as various helminth parasites and viruses, the latter including viruses that infect the cellular microbiome organisms (e.g., bacteriophages, the viruses of bacteria).

> The HMP will address some of the most inspiring, vexing and fundamental scientific questions today. Importantly, it also has the potential to break down the artificial barriers between medical microbiology and environmental microbiology. It is hoped that the HMP will not only identify new ways to determine health and predisposition to diseases but also define the parameters needed to design, implement and monitor strategies for intentionally manipulating the human microbiota, to optimize its performance in the context of an individual's physiology.[7]

The HMP has been described as "a logical conceptual and experimental extension of the Human Genome Project."[7] In 2007 the Human Microbiome Project was listed on the NIH Roadmap for Medical Research[8] as one of the *New Pathways to Discovery*. Organized characterization of the human microbiome is also being done internationally under the auspices of the International Human Microbiome Consortium.[9] The Canadian Institutes of Health Research, through the CIHR Institute of Infection and Immunity, is leading the Canadian Microbiome Initiative[10] to develop a coordinated and focused research effort to analyze and characterize the microbes that colonize the human body and their potential alteration during chronic disease states.

8.2 Goals

The HMP includes the following goals:[11]

- To develop a reference set of microbial genome sequences and to perform preliminary characterization of the human microbiome
- To explore the relationship between disease and changes in the human microbiome
- To develop new technologies and tools for computational analysis
- To establish a resource repository
- To study the ethical, legal, and social implications of human microbiome research

8.3 Achievements

The impact to date of the Human Microbiome Project may be partially assessed by examination of research sponsored by the HMP. Over 190 peer-reviewed publications are listed on the HMP website from June 2009 through August 2012.[12]

Major categories of work funded by HMP include:

- Development of new database systems allowing efficient organization, storage, access, search and annotation of massive amounts of data. These include IMG, the Integrated Microbial Genomes database and comparative analysis system;[13] IMG/M, a related system that integrates metagenome data sets with isolate microbial genomes from the IMG system;[14] CharProtDB, a database of experimentally characterized protein annotations;[15] and the Genomes OnLine Database (GOLD), for monitoring the status of genomic and metagenomic projects worldwide and their associated metadata.[16]
- Development of tools for comparative analysis that facilitate the recognition of common patterns, major themes and trends in complex data sets. These include RAPSearch2, a fast and memory-efficient protein similarity search tool for next-generation sequencing data;[17] Boulder ALignment Editor (ALE), a web-based RNA alignment tool;[18] WebMGA, a customizable web server for fast metagenomic sequence analysis;[19] and DNACLUST, a tool for accurate and efficient clustering of phylogenetic marker genes[20]
- Development of new methods and systems for assembly of massive sequence data sets. No single assembly algorithm addresses all the known problems of assembling short-length sequences,[21] so next-generation assembly programs such as AMOS[22] are modular, offering a wide range of tools for assembly. Novel algorithms have been developed for improving the quality and utility of draft genome sequences.[23]
- Assembly of a catalog of sequenced reference genomes of pure bacterial strains from multiple body sites, against which metagenomic results can be compared. The original goal of 600 genomes has been far surpassed; the current goal is for 3000 genomes to be in this reference catalog, sequenced to at least a high-quality draft stage. As of March 2012, 742 genomes have been cataloged.[24]
- Establishment of the Data Analysis and Coordination Center (DACC),[25] which serves as the central repository for all HMP data.
- Various studies exploring legal and ethical issues associated with whole genome sequencing research.[26][27][28][29]

Developments funded by HMP include:

- New predictive methods for identifying active transcription factor binding sites.[30]
- Identification, on the basis of bioinformatic evidence, of a widely distributed, ribosomally produced electron carrier precursor[31]
- Time-lapse "moving pictures" of the human microbiome.[32]
- Identification of unique adaptations adopted by segmented filamentous bacteria (SFB) in their role as gut commensals.[33] SFB are medically important because they stimulate T helper 17 cells, thought to play a key role in autoimmune disease.
- Identification of factors distinguishing the microbiota of healthy and diseased gut.[34]
- Identification of a hitherto unrecognized dominant role of Verrucomicrobia in soil bacterial communities.[35]
- Identification of factors determining the virulence potential of *Gardnerella vaginalis* strains in vaginosis.[36]
- Identification of a link between oral microbiota and atherosclerosis.[37]
- Demonstration that pathogenic species of *Neisseria* involved in meningitis, septicemia, and sexually transmitted disease exchange virulence factors with commensal species.[38]

8.4 Milestones

8.4.1 Reference database established

On 13 June 2012, a major milestone of the Human Microbiome Project (HMP) was announced by the NIH director Francis Collins.[39] The announcement was accompanied with a series of coordinated articles published in Nature[40][41] and several journals in the Public Library of Science (PLoS) on the same day. By mapping the normal microbial make-up of healthy humans using genome sequencing techniques, the researchers of the HMP have created a reference database and the boundaries of normal microbial variation in humans.[42]

From 242 healthy U.S. volunteers, more than 5,000 samples were collected from tissues from 15 (men) to 18 (women) body sites such as mouth, nose, skin, lower intestine (stool) and vagina. All the DNA, human and microbial, were analyzed with DNA sequencing machines. The microbial genome data were extracted by identifying the bacterial specific ribosomal RNA, 16S rRNA. The researchers calculated that more than 10,000 microbial species occupy the human ecosystem and they have identified 81 – 99% of the genera. In addition to establishing the human microbiome reference database, the HMP project also discovered several "surprises", which include:

- Microbes contribute more genes responsible for human survival than humans' own genes. It is estimated that bacterial protein-coding genes are 360 times more abundant than human genes.
- Microbial metabolic activities; for example, digestion of fats; are not always provided by the same bacterial species. The presence of the activities seems to matter more.
- Components of the human microbiome change over time, affected by a patient disease state and medication. However, the microbiome eventually returns to a state of equilibrium, even though the composition of bacterial types has changed.

8.4.2 Clinical application

Among the first clinical applications utilizing the HMP data, as reported in several PLoS papers, the researchers found a shift to less species diversity in vaginal microbiome of pregnant women in preparation for birth, and high viral DNA load in the nasal microbiome of children with unexplained fevers. Other studies using the HMP data and techniques include role of microbiome in various diseases in the digestive tract, skin, reproductive organs and childhood disorders.[39]

8.4.3 Pharmaceutical application

Pharmaceutical microbiologists have considered the implications of the HMP data in relation to the presence / absence of 'objectionable' microorganisms in non-sterile pharmaceutical products and in relation to the monitoring of microorganisms within the controlled environments in which products are manufactured. The latter also has implications for media selection and disinfectant efficacy studies.[43]

8.5 See also

- Environmental microbiology
- Genome project
- Genomics
- Gut flora
- Human microbiome

- Human virome
- Medical microbiology
- Metagenomics
- Microbial ecology
- Microflora
- Multigenomic organism
- Oral microbiology
- Skin flora
- Superorganism
- Vaginal flora

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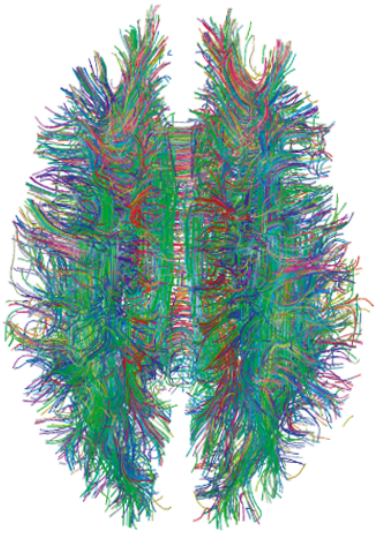
8.7 External links

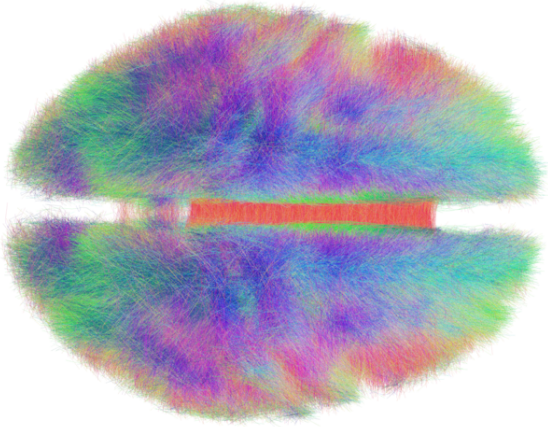
- Human Microbiome Project
- Data Analysis and Coordination Center
- The CIHR Canadian Microbiome Initiative
- The International Human Microbiome Consortium
- 2006, Lay summary of colon microbiome study (the actual study: Gill et al., 2006)
- Olivia Judson Microbes 'R' Us *New York Times* 22 July 2009
- Gina Kolata Good Health? Thank Your 100 Trillion Bacteria *New York Times* 13 June 2012

Chapter 9

Connectome



White matter tracts within a human brain, as visualized by MRI tractography



Rendering of a group connectome based on 20 subjects. Anatomical fibers that constitute the white matter architecture of the human brain are visulized color-coded by traversing direction (xyz-directions mapping to rgb colors respectively). Visualization of fibers was done using TrackVis software.[1]

A **connectome** (/kəˈnɛktoʊm/) is a comprehensive map of neural connections in the brain, and may be thought of as its "wiring diagram". More broadly, a connectome would include the mapping of all neural connections within an organism's nervous system.

The production and study of connectomes, known as connectomics, may range in scale from a detailed map of the full set of neurons and synapses within part or all of the nervous system of an organism to a macro scale description of the functional and structural connectivity between all cortical areas and subcortical structures. The term "connectome" is used primarily in scientific efforts to capture, map, and understand the organization of neural interactions within the brain.

Research has successfully constructed the full connectome of one animal: the roundworm *C. elegans* (White *et al.*, 1986,[2] Varshney *et al.*, 2011[3]). Partial connectomes of a mouse retina[4] and mouse primary visual cortex[5] have also been successfully constructed. Bock *et al.*'s complete 12 TB data set is publicly available at the Open Connectome Project.[6]

The ultimate goal of connectomics is to map the human brain. This effort is pursued by the Human Connectome Project, sponsored by the National Institutes of Health, whose focus is to build a network map of the human brain in healthy, living adults.

9.1 Origin and usage of the term

In 2005, Dr. Olaf Sporns at Indiana University and Dr. Patric Hagmann at Lausanne University Hospital independently and simultaneously suggested the term "connectome" to refer to a map of the neural connections within the brain. This term was directly inspired by the ongoing effort to sequence the human genetic code—to build a genome.

"Connectomics" (Hagmann, 2005) has been defined as the science concerned with assembling and analyzing connectome data sets.[7]

In their 2005 paper, "The Human Connectome, a structural description of the human brain", Sporns *et al.* wrote:

> To understand the functioning of a network, one must know its elements and their interconnections. The purpose of this article is

> to discuss research strategies aimed at a comprehensive structural description of the network of elements and connections forming the human brain. We propose to call this dataset the human "connectome," and we argue that it is fundamentally important in cognitive neuroscience and neuropsychology. The connectome will significantly increase our understanding of how functional brain states emerge from their underlying structural substrate, and will provide new mechanistic insights into how brain function is affected if this structural substrate is disrupted.[8]

In his 2005 Ph.D. thesis, *From diffusion MRI to brain connectomics*, Hagmann wrote:

> It is clear that, like the genome, which is much more than just a juxtaposition of genes, the set of all neuronal connections in the brain is much more than the sum of their individual components. The genome is an entity it-self, as it is from the subtle gene interaction that [life] emerges. In a similar manner, one could consider the brain connectome, set of all neuronal connections, as one single entity, thus emphasizing the fact that the huge brain neuronal communication capacity and computational power critically relies on this subtle and incredibly complex connectivity architecture.[7]

Pathways through cerebral white matter can be charted by histological dissection and staining, by degeneration methods, and by axonal tracing. Axonal tracing methods form the primary basis for the systematic charting of long-distance pathways into extensive, species-specific anatomical connection matrices between gray matter regions. Landmark studies have included the areas and connections of the visual cortex of the macaque (Felleman and Van Essen, 1991)[9] and the thalamo-cortical system in the feline brain (Scannell *et al.*, 1999).[10] The development of neuroinformatics databases for anatomical connectivity allow for continual updating and refinement of such anatomical connection maps. The online macaque cortex connectivity tool CoCoMac (Kötter, 2004)[11] is a prominent example of such a database.

In the human brain, the significance of the connectome stems from the realization that the structure and function of the human brain are intricately linked, through multiple levels and modes of brain connectivity. There are strong natural constraints on which neurons or neural populations can interact, or how strong or direct their interactions are. Indeed, the foundation of human cognition lies in the pattern of dynamic interactions shaped by the connectome.

However, structure-function relationships in the brain are unlikely to reduce to simple one-to-one mappings. In fact, the connectome can evidently support a great number of variable dynamic states, depending on current sensory inputs, global brain state, learning and development. Some changes in functional state may involve rapid changes of structural connectivity at the synaptic level, as has been elucidated by two-photon imaging experiments showing the rapid appearance and disappearance of dendritic spines (Bonhoeffer and Yuste, 2002).[12]

Despite such complex and variable structure-function mappings, the connectome is an indispensable basis for the mechanistic interpretation of dynamic brain data, from single-cell recordings to functional neuroimaging.

The term "connectome" was more recently popularized by Sebastian Seung's "I am my Connectome" speech given at the 2010 TED conference, which discusses the high-level goals of mapping the human connectome, as well as ongoing efforts to build a three-dimensional neural map of brain tissue at the microscale.[13] In 2012, Seung published the book *Connectome: How the Brain's Wiring Makes Us Who We Are*.

9.2 At multiple scales

Brain networks can be defined at different levels of scale, corresponding to levels of spatial resolution in brain imaging (Kötter, 2007, Sporns, 2010).[14][15] These scales can be roughly categorized as microscale, mesoscale and macroscale. Ultimately, it may be possible to join connectomic maps obtained at different scales into a single hierarchical map of the neural organization of a given species that ranges from single neurons to populations of neurons to larger systems like cortical areas. Given the methodological uncertainties involved in inferring connectivity from the primary experimental data, and given that there are likely to be large differences in the connectomes of different individuals, any unified map will likely rely on *probabilistic* representations of connectivity data (Sporns *et al.*, 2005).[8]

Mapping the connectome at the "microscale" (micrometer resolution) means building a complete map of the neural systems, neuron-by-neuron. The challenge of doing this becomes obvious: the number of neurons comprising the brain easily ranges into the billions in more highly evolved organisms. The human cerebral cortex alone contains on the order of 10^{10} neurons linked by 10^{14} synaptic connections.[16] By comparison, the number of base-pairs in a human genome is 3×10^{9}. A few of the main challenges of building a human connectome at the microscale today include: (1) data collection would take years given current technology; (2) machine vision tools to annotate the data remain in their infancy, and are inadequate; and (3) neither theory nor algorithms are readily available for the analysis of the resulting *brain-graphs*. To address the data collection issues, several groups are building high-throughput serial electron mi-

croscopes (Kasthuri *et al.*, 2009; Bock *et al.* 2011). To address the machine-vision and image-processing issues, the Open Connectome Project[6] is *alg-sourcing* (algorithm outsourcing) this hurdle. Finally, statistical graph theory is an emerging discipline which is developing sophisticated pattern recognition and inference tools to parse these brain-graphs (Goldenberg *et al.*, 2009).

A "mesoscale" connectome corresponds to a spatial resolution of hundreds of micrometers. Rather than attempt to map each individual neuron, a connectome at the mesoscale would attempt to capture anatomically and/or functionally distinct neuronal populations, formed by local circuits (e.g. cortical columns) that link hundreds or thousands of individual neurons. This scale still presents a very ambitious technical challenge at this time and can only be probed on a small scale with invasive techniques or very high field MRI on a local scale.

A connectome at the macroscale (millimeter resolution) attempts to capture large brain systems that can be parcellated into anatomically distinct modules (areas, parcels or nodes), each having a distinct pattern of connectivity. Connectomic databases at the mesoscale and macroscale may be significantly more compact than those at cellular resolution, but they require effective strategies for accurate anatomical or functional parcellation of the neural volume into network nodes (for complexities see, e.g., Wallace *et al.*, 2004).[17]

9.3 Mapping at the cellular level

Current non-invasive imaging techniques cannot capture the brain's activity on a neuron-by-neuron level. Mapping the connectome at the cellular level in vertebrates currently requires post-mortem microscopic analysis of limited portions of brain tissue. Non-optical techniques that rely on high-throughput DNA sequencing have been proposed recently by Anthony Zador (CSHL).[18]

Traditional histological circuit-mapping approaches rely on imaging and include light-microscopic techniques for cell staining, injection of labeling agents for tract tracing, or chemical brain preservation, staining and reconstruction of serially sectioned tissue blocks via electron microscopy (EM). Each of these classical approaches has specific drawbacks when it comes to deployment for connectomics. The staining of single cells, e.g. with the Golgi stain, to trace cellular processes and connectivity suffers from the limited resolution of light-microscopy as well as difficulties in capturing long-range projections. Tract tracing, often described as the "gold standard" of neuroanatomy for detecting long-range pathways across the brain, generally only allows the tracing of fairly large cell populations and single axonal pathways. EM reconstruction was successfully used for the compilation of the C. elegans connectome (White *et al.*, 1986).[2] However, applications to larger tissue blocks of entire nervous systems have traditionally had difficulty with projections that span longer distances.

Recent advances in mapping neural connectivity at the cellular level offer significant new hope for overcoming the limitations of classical techniques and for compiling cellular connectome data sets (Livet *et al.*, 2007; Lichtman *et al.*, 2008).[19][20][21] Using Brainbow, a combinatorial color labeling method based on the stochastic expression of several fluorescent proteins, Lichtman and colleagues were able to mark individual neurons with one of over 100 distinct colors. The labeling of individual neurons with a distinguishable hue then allows the tracing and reconstruction of their cellular structure including long processes within a block of tissue.

In March 2011, the journal *Nature* published a pair of articles on micro-connectomes: Bock *et al.*[5] and Briggman *et al.*[4] In both articles, the authors first characterized the functional properties of a small subset of cells, and then manually traced a subset of the processes emanating from those cells to obtain a partial subgraph. In alignment with the principles of open-science, the authors of Bock *et al.* (2011) have released their data for public access. The full resolution 12TB dataset from Bock *et al.* is available at the Open Connectome Project.[6] In 2012, a citizen science project called *EyeWire* began attempting to crowdsource the mapping of the connectome through an interactive game.[22] Independently, important topologies of functional interactions among several hundred cells are also gradually going to be declared (Shimono and Beggs, 2014).[23] Scaling up ultrastructural circuit mapping to the whole mouse brain is currently underway (Mikula, 2012).[24] An alternative approach to mapping connectivity was recently proposed by Zador and colleagues (Zador *et al.*, 2012).[18] Zador's technique, called BOINC (barcoding of individual neuronal connections) uses high-throughput sequencing to map neural circuits. Briefly, the approach consists of (1) labelling each neuron with a unique DNA barcode; (2) transferring barcodes between synaptically coupled neurons (for example using PRV); and (3) fusion of barcodes to represent a synaptic pair. This approach has the potential to be cheap, fast, and extremely high-throughput.

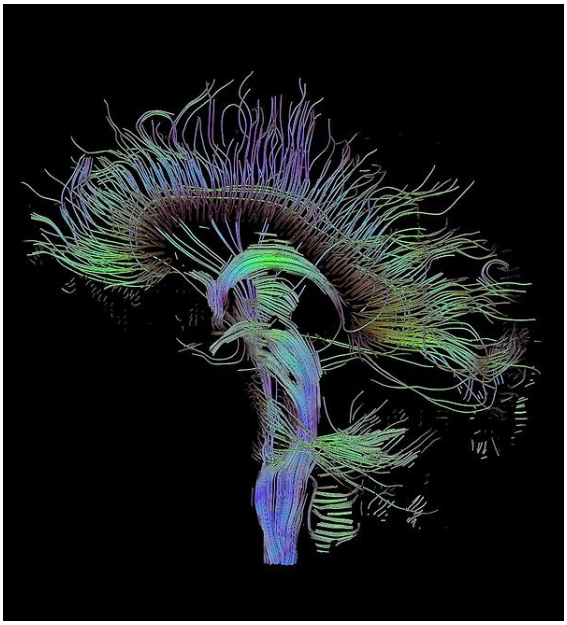
9.4 Mapping at the macro scale

Established methods of brain research, such as axonal tracing, provided early avenues for building connectome data sets. However, more recent advances in living subjects has been made by the use of non-invasive imaging technologies such as diffusion magnetic resonance imaging and functional magnetic resonance imaging (fMRI). The first, when combined with tractography allows reconstruction of the major fiber bundles in the brain. The second allows the researcher to capture the brain's network activity (either at rest or while performing directed tasks), enabling the identification of structurally and anatomi-

cally distinct areas of the brain that are functionally connected.

Notably, the goal of the Human Connectome Project, led by the WU-Minn consortium, is to build a *structural and functional map* of the healthy human brain at the macro scale, using a combination of multiple imaging technologies and resolutions.

9.4.1 Recent advances in connectivity mapping



Tractographic reconstruction of neural connections via DTI

Over the past few years, several investigators have attempted to map the large-scale structural architecture of the human cerebral cortex. One attempt exploited cross-correlations in cortical thickness or volume across individuals (He *et al.*, 2007).[25] Such gray-matter thickness correlations have been postulated as indicators for the presence of structural connections. A drawback of the approach is that it provides highly indirect information about cortical connection patterns and requires data from large numbers of individuals to derive a single connection data set across a subject group. Other investigators have attempted to build whole-brain connection matrices from diffusion imaging data.

9.4.2 Primary challenge for macroscale connectomics: determining parcellations of the brain

The initial explorations in macroscale human connectomics were done using either equally sized regions or anatomical regions with unclear relationship to the underlying functional organization of the brain (e.g. gyral and sulcal-based regions). While much can be learned from these approaches, it is highly desirable to parcellate the brain into functionally distinct parcels: brain regions with distinct architectonics, connectivity, function, and/or topography (Felleman and Van Essen, 1991).[26] Accurate parcellation allows each node in the macroscale connectome to be more informative by associating it with a distinct connectivity pattern and functional profile. Parcellation of localized areas of cortex have been accomplished using diffusion tractography (Beckmann *et al.* 2009)[27] and functional connectivity (Nelson *et al.* 2010)[28] to non-invasively measure connectivity patterns and define cortical areas based on distinct connectivity patterns. Such analyses may best be done on a whole brain scale and by integrating non-invasive modalities. Accurate whole brain parcellation may lead to more accurate macroscale connectomes for the normal brain, which can then be compared to disease states.

9.5 Mapping functional connectivity to complement anatomical connectivity

Using functional MRI (fMRI) in the resting state and during tasks, functions of the connectome circuits are being studied.[29] Just as detailed road maps of the earth's surface do not tell us much about the kind of vehicles that travel those roads or what cargo they are hauling, to understand how neural structures result in specific functional behavior such as consciousness, it is necessary to build theories that relate functions to anatomical connectivity.[30] However, the bond between structural and functional connectivity is not straightforward. Computational models of whole-brain network dynamics are valuable tools to investigate the role of the anatomical network in shaping functional connectivity.[31][32] In particular, computational models can be used to predict the dynamic effect of lesions in the connectome.[33][34]

9.6 As a network or graph

The connectome can be studied as a network by means of network science and graph theory. In case of a microscale connectome, the nodes of this network (or graph) are the neurons, and the edges correspond to the synapses between those neurons. For the macro-scale connectome, the nodes correspond to the ROIs (regions of interest), while the edges of the graph are derived from the axons interconnecting those areas. Thus connectomes are sometimes referred to as *brain graphs*, as they are indeed graphs in a mathematical sense which describe the connections in the brain (or, in a broader sense, the whole nervous system).

One group of researchers (Iturria-Medina *et al.*, 2008)[35]

has constructed connectome data sets using diffusion tensor imaging (DTI)[36][37] followed by the derivation of average connection probabilities between 70-90 cortical and basal brain gray matter areas. All networks were found to have small-world attributes and "broad-scale" degree distributions. An analysis of betweenness centrality in these networks demonstrated high centrality for the precuneus, the insula, the superior parietal and the superior frontal cortex. Another group (Gong *et al.* 2008)[38] has applied DTI to map a network of anatomical connections between 78 cortical regions. This study also identified several hub regions in the human brain, including the precuneus and the superior frontal gyrus.

Hagmann *et al.* (2007)[39] constructed a connection matrix from fiber densities measured between homogeneously distributed and equal-sized regions of interest (ROIs) numbering between 500 and 4000. A quantitative analysis of connection matrices obtained for approximately 1000 ROIs and approximately 50,000 fiber pathways from two subjects demonstrated an exponential (one-scale) degree distribution as well as robust small-world attributes for the network. The data sets were derived from diffusion spectrum imaging (DSI) (Wedeen, 2005),[40] a variant of diffusion-weighted imaging[41][42] that is sensitive to intra-voxel heterogeneities in diffusion directions caused by crossing fiber tracts and thus allows more accurate mapping of axonal trajectories than other diffusion imaging approaches (Wedeen, 2008).[43] The combination of whole-head DSI datasets acquired and processed according to the approach developed by Hagmann *et al.* (2007)[39] with the graph analysis tools conceived initially for animal tracing studies (Sporns, 2006; Sporns, 2007)[44][45] allow a detailed study of the network structure of human cortical connectivity (Hagmann *et al.*, 2008).[46] The human brain network was characterized using a broad array of network analysis methods including core decomposition, modularity analysis, hub classification and centrality. Hagmann *et al.* presented evidence for the existence of a structural core of highly and mutually interconnected brain regions, located primarily in posterior medial and parietal cortex. The core comprises portions of the posterior cingulate cortex, the precuneus, the cuneus, the paracentral lobule, the isthmus of the cingulate, the banks of the superior temporal sulcus, and the inferior and superior parietal cortex, all located in both cerebral hemispheres.

A subfield of connectomics deals with the comparison of the brain graphs of multiple subjects. It is possible to build a consensus graph such the Budapest Reference Connectome by allowing only edges that are present in at least k connectomes, for a selectable k parameter. The Budapest Reference Connectome has led the researchers to the discovery of the Consensus Connectome Dynamics of the human brain graphs. The edges appeared in all of the brain graphs form a connected subgraph around the brainstem. By allowing gradually less frequent edges, this core subgraph grows continuously, as a shrub. The growth dynamics may reflect the individual brain development and provide an opportunity to direct some edges of the human consensus brain graph.[47]

The possible causes of the difference between individual connectomes were also investigated. It has been found that the macro-scale connectomes of women contain significantly more edges than those of men, and a larger portion of the edges in the connectomes of women run between the two hemispheres.[48][49] In addition, connectomes generally exhibit a small-world character, with overall cortical connectivity decreasing with age.[50] The aim of the as of 2015 ongoing HCP Lifespan Pilot Project is to identify connectome differences between 6 age groups (4–6, 8–9, 14–15, 25–35, 45–55, 65–75).

More recently, connectograms have been used to visualize full-brain data by placing cortical areas around a circle, organized by lobe.[51][52] Inner circles then depict cortical metrics on a color scale. White matter fiber connections in DTI data are then drawn between these cortical regions and weighted by fractional anisotropy and strength of the connection. Such graphs have even been used to analyze the damage done to the famous traumatic brain injury patient Phineas Gage.[53]

Statistical graph theory is an emerging discipline which is developing sophisticated pattern recognition and inference tools to parse these brain graphs (Goldenberg et al., 2009).

9.7 See also

- Drosophila connectome
- Interactome
- List of animals by number of neurons
- Outline of brain mapping
- Outline of the human brain

9.8 References

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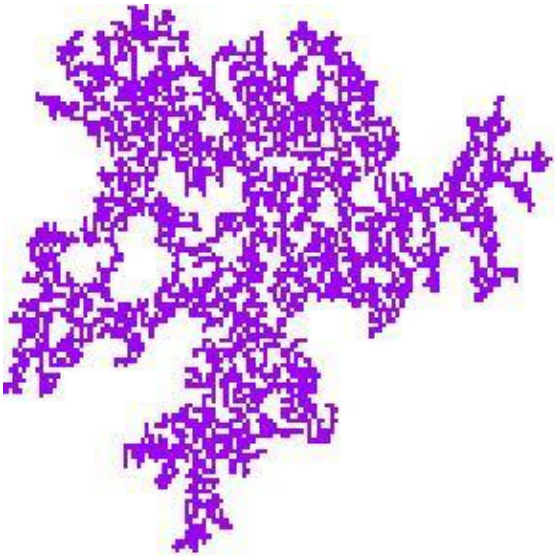
9.9 External links

- Database of hundreds of braingraphs with different resolutions and weight functions at braingraph.org
- The NIH Blueprint for Neuroscience Research
- TED talk by Sebastian Seung: I am my connectome
- EyeWire, a citizen science game to map the retinal connectome
- MITK Diffusion: Free software for the processing of diffusion-weighted MR data including connectomics

Chapter 10

Biological engineering



Modeling of the spread of disease using Cellular Automata and Nearest Neighbor Interactions

Biological engineering or **bio-engineering** (including biological systems engineering) is the application of concepts and methods of biology (and secondarily of physics, chemistry, mathematics, and computer science) to solve real-world problems related to life sciences or the application thereof, using engineering's own analytical and synthetic methodologies and also its traditional sensitivity to the cost and practicality of the solution(s) arrived at. In this context, while traditional engineering applies physical and mathematical sciences to analyze, design and manufacture inanimate tools, structures and processes, biological engineering uses primarily the rapidly developing body of knowledge known as molecular biology to study and advance applications of organisms and to create biotechnology. This may eventually include the possibility of biologically engineering machines and 3D printing that re-order matter at a molecular scale. Physicist Richard Feynman theorized about the idea of a *medical* use for these biological machines, introduced into the body, to repair or detect damages and infections. . Feynman and Albert Hibbs suggested that it might one day be possible to (as Feynman put it) "swallow the doctor". The idea was discussed in Feynman's 1959 essay *There's Plenty of Room at the Bottom.*[1]

Industrial bio-engineering extends from the creation of artificial organs by technical means or finds ways of growing organs and tissues through the methods of regenerative medicine to compensate reduced or lost physiological functions (Biomedical Engineering) and to develop genetically modified organisms, i.e., agricultural plants and animals as well as the molecular designs of compounds with desired properties (protein engineering, engineering enzymology). In the non-medical aspects of bio-engineering, it is closely related to biotechnology, nanotechnology and 3D printing.

An especially important application is the analysis and cost-effective solution of problems related to human health (human bioengineering), but the field is much more general than that. For example, biomimetics is a branch of biological engineering which strives to find ways in which the structures and functions of living organisms can be used as models for the design and engineering of materials and machines. Systems biology, on the other hand, seeks to exploit the engineer's familiarity with complex artificial systems, and perhaps the concepts used in "reverse engineering", to facilitate the difficult process of recognition of the structure, function, and precise method of operation of complex biological systems.

The differentiation between biological engineering and biomedical engineering can be unclear, as many universities loosely use the terms "bioengineering" and "biomedical engineering" interchangeably.[2] Biomedical engineers are specifically focused on applying biological and other sciences toward medical innovations, whereas biological engineers are focused principally on applying engineering principles to biology - but not necessarily for medical uses. Hence neither "biological" engineering nor "biomedical" engineering is wholly contained within the other, as there can be "non-biological" products for *medical* needs as well as "biological" products for *non-medical* needs (the latter including notably biosystems engineering).

10.1 History

Biological engineering is a science-based discipline founded upon the biological sciences in the same way that chemical engineering, electrical engineering, and mechanical engineering[3] can be based upon chemistry, electricity and magnetism, and classical mechanics, respectively.[4]

Biological engineering can be differentiated from its roots of pure biology or other engineering fields. Biological studies often follow a reductionist approach in viewing a system on its smallest possible scale which naturally leads toward the development of tools like functional genomics. Engineering approaches, using classical design perspectives, are constructionist, building new devices, approaches, and technologies from component parts or concepts. Biological engineering uses both approaches in concert, relying on reductionist approaches to identify, understand, and organize the fundamental units, which are then integrated to generate something new.[5] In addition, because it is an engineering discipline, biological engineering is fundamentally concerned with not just the basic science, but its practical application of the scientific knowledge to solve real-world problems in a cost-effective way.

Although engineered biological systems have been used to manipulate information, construct materials, process chemicals, produce energy, provide food, and help maintain or enhance human health and our environment, our ability to quickly and reliably engineer biological systems that behave as expected is at present less well developed than our mastery over mechanical and electrical systems.[6]

ABET,[7] the U.S.-based accreditation board for engineering B.S. programs, makes a distinction between biomedical engineering and biological engineering, though there is much overlap (see above). Foundational courses are often the same and include thermodynamics, fluid and mechanical dynamics, kinetics, electronics, and materials properties.[8][9] According to Professor Doug Lauffenburger of MIT,[10][11] biological engineering (like biotechnology) has a broader base which applies engineering principles to an enormous range of size and complexities of systems ranging from the molecular level - molecular biology, biochemistry, microbiology, pharmacology, protein chemistry, cytology, immunology, neurobiology and neuroscience (often but not always using biological substances) - to cellular and tissue-based methods (including devices and sensors), whole macroscopic organisms (plants, animals), and up increasing length scales to whole ecosystems.

The word bioengineering was coined by British scientist and broadcaster Heinz Wolff in 1954.[12] The term bioengineering is also used to describe the use of vegetation in civil engineering construction. The term bioengineering may also be applied to environmental modifications such as surface soil protection, slope stabilization, watercourse and shoreline protection, windbreaks, vegetation barriers including noise barriers and visual screens, and the ecological enhancement of an area. The first biological engineering program was created at Mississippi State University in 1967, making it the first biological engineering curriculum in the United States.[13] More recent programs have been launched at MIT [10] and Utah State University.[14]

10.2 Description

Biological engineers or *bio-engineers* are engineers who use the principles of biology and the tools of engineering to create usable, tangible, economically viable products.[15] Biological engineering employs knowledge and expertise from a number of pure and applied sciences,[16] such as mass and heat transfer, kinetics, biocatalysts, biomechanics, bioinformatics, separation and purification processes, bioreactor design, surface science, fluid mechanics, thermodynamics, and polymer science. It is used in the design of medical devices, diagnostic equipment, biocompatible materials, renewable bioenergy, ecological engineering, agricultural engineering, and other areas that improve the living standards of societies.

In general, biological engineers attempt to either mimic biological systems to create products or modify and control biological systems so that they can replace, augment, sustain, or predict chemical and mechanical processes.[17] Bioengineers can apply their expertise to other applications of engineering and biotechnology, including genetic modification of plants and microorganisms, bioprocess engineering, and biocatalysis.

Because other engineering disciplines also address living organisms (e.g., prosthetics in bio-mechanical engineering), the term biological engineering can be applied more broadly to include agricultural engineering and biotechnology, which notably can address non-healthcare objectives as well (unlike biomedical engineering). In fact, many old agricultural engineering departments in universities over the world have rebranded themselves as *agricultural and biological engineering* or *agricultural and biosystems engineering*. Biological engineering is also called *bioengineering* by some colleges, and biomedical engineering is called *bioengineering* by others, and is a rapidly developing field with fluid categorization. Depending on the institution and particular definitional boundaries employed, some major fields of bioengineering may be categorized as (note these may overlap):

- biological systems engineering
- biomedical engineering: biomedical technology, biomedical diagnostics, biomedical therapy, biomechanics, biomaterials;

- genetic engineering (involving both of the above, although in different applications): synthetic biology, horizontal gene transfer;
- bioprocess engineering: bioprocess design, biocatalysis, bioseparation, bioinformatics, bioenergy;
- cellular engineering: cell engineering, tissue engineering, metabolic engineering;
- biomimetics: the use of knowledge gained from reverse engineering evolved living systems to solve difficult design problems in artificial systems.
- bioprinting

10.3 References

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10.4 External links

- Benchling
- Genome Compiler
- Bioengineering Society
- Biomedical Engineering Society
- Institute of Biological Engineering
- Benjoe Institute of Systems Biological Engineering
- American Institute of Medical and Biological Engineering
- American Society of Agricultural and Biological Engineers
- Society for Biological Engineering part of AIChE
- Journal of Biological Engineering, JBE
- Biological Engineering Transactions

Chapter 11

Nanotechnology

For the materials science journal, see Nanotechnology (journal).

Nanotechnology ("**nanotech**") is manipulation of matter on an atomic, molecular, and supramolecular scale. The earliest, widespread description of nanotechnology[1][2] referred to the particular technological goal of precisely manipulating atoms and molecules for fabrication of macroscale products, also now referred to as molecular nanotechnology. A more generalized description of nanotechnology was subsequently established by the National Nanotechnology Initiative, which defines nanotechnology as the manipulation of matter with at least one dimension sized from 1 to 100 nanometers. This definition reflects the fact that quantum mechanical effects are important at this quantum-realm scale, and so the definition shifted from a particular technological goal to a research category inclusive of all types of research and technologies that deal with the special properties of matter which occur below the given size threshold. It is therefore common to see the plural form "nanotechnologies" as well as "nanoscale technologies" to refer to the broad range of research and applications whose common trait is size. Because of the variety of potential applications (including industrial and military), governments have invested billions of dollars in nanotechnology research. Until 2012, through its National Nanotechnology Initiative, the USA has invested 3.7 billion dollars, the European Union has invested 1.2 billion and Japan 750 million dollars.[3]

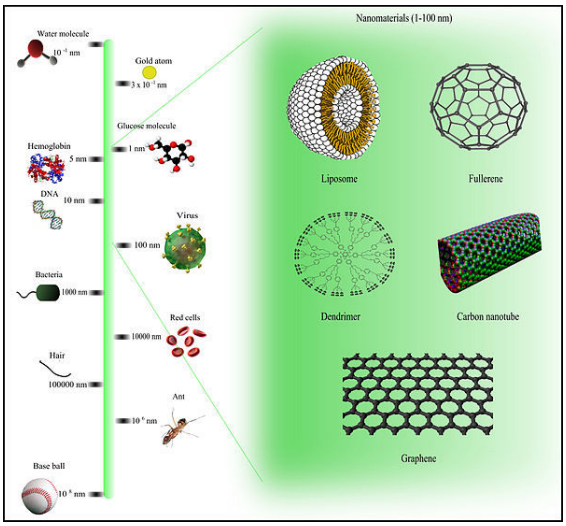
Nanotechnology as defined by size is naturally very broad, including fields of science as diverse as surface science, organic chemistry, molecular biology, semiconductor physics, microfabrication, molecular engineering, etc.[4] The associated research and applications are equally diverse, ranging from extensions of conventional device physics to completely new approaches based upon molecular self-assembly, from developing new materials with dimensions on the nanoscale to direct control of matter on the atomic scale.

Scientists currently debate the future implications of nanotechnology. Nanotechnology may be able to create many new materials and devices with a vast range of applications, such as in nanomedicine, nanoelectronics, biomaterials energy production, and consumer products. On the other hand, nanotechnology raises many of the same issues as any new technology, including concerns about the toxicity and environmental impact of nanomaterials,[5] and their potential effects on global economics, as well as speculation about various doomsday scenarios. These concerns have led to a debate among advocacy groups and governments on whether special regulation of nanotechnology is warranted.

11.1 Origins

Main article: History of nanotechnology

The concepts that seeded nanotechnology were first discussed in 1959 by renowned physicist Richard Feynman in his talk *There's Plenty of Room at the Bottom*, in which he described the possibility of synthesis via direct manipulation of atoms. The term "nano-technology" was first used by Norio Taniguchi in 1974, though it was not widely known.



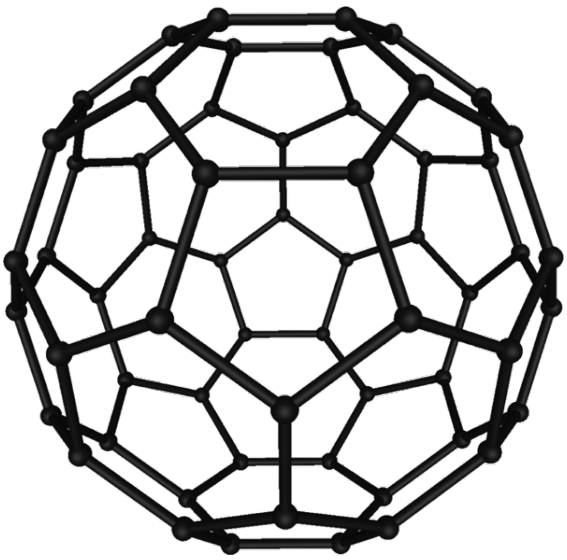
Comparison of Nanomaterials Sizes

Inspired by Feynman's concepts, K. Eric Drexler used the term "nanotechnology" in his 1986 book *Engines of Creation: The Coming Era of Nanotechnology*, which pro-

posed the idea of a nanoscale "assembler" which would be able to build a copy of itself and of other items of arbitrary complexity with atomic control. Also in 1986, Drexler co-founded The Foresight Institute (with which he is no longer affiliated) to help increase public awareness and understanding of nanotechnology concepts and implications.

Thus, emergence of nanotechnology as a field in the 1980s occurred through convergence of Drexler's theoretical and public work, which developed and popularized a conceptual framework for nanotechnology, and high-visibility experimental advances that drew additional wide-scale attention to the prospects of atomic control of matter. In the 1980s, two major breakthroughs sparked the growth of nanotechnology in modern era.

First, the invention of the scanning tunneling microscope in 1981 which provided unprecedented visualization of individual atoms and bonds, and was successfully used to manipulate individual atoms in 1989. The microscope's developers Gerd Binnig and Heinrich Rohrer at IBM Zurich Research Laboratory received a Nobel Prize in Physics in 1986.[6][7] Binnig, Quate and Gerber also invented the analogous atomic force microscope that year.



Buckminsterfullerene C_{60}, also known as the buckyball, is a representative member of the carbon structures known as fullerenes. Members of the fullerene family are a major subject of research falling under the nanotechnology umbrella.

Second, Fullerenes were discovered in 1985 by Harry Kroto, Richard Smalley, and Robert Curl, who together won the 1996 Nobel Prize in Chemistry.[8][9] C_{60} was not initially described as nanotechnology; the term was used regarding subsequent work with related graphene tubes (called carbon nanotubes and sometimes called Bucky tubes) which suggested potential applications for nanoscale electronics and devices.

In the early 2000s, the field garnered increased scientific, political, and commercial attention that led to both controversy and progress. Controversies emerged regarding the definitions and potential implications of nanotechnologies, exemplified by the Royal Society's report on nanotechnology.[10] Challenges were raised regarding the feasibility of applications envisioned by advocates of molecular nanotechnology, which culminated in a public debate between Drexler and Smalley in 2001 and 2003.[11]

Meanwhile, commercialization of products based on advancements in nanoscale technologies began emerging. These products are limited to bulk applications of nanomaterials and do not involve atomic control of matter. Some examples include the Silver Nano platform for using silver nanoparticles as an antibacterial agent, nanoparticle-based transparent sunscreens, carbon fiber strengthening using silica nanoparticles, and carbon nanotubes for stain-resistant textiles.[12][13]

Governments moved to promote and fund research into nanotechnology, such as in the U.S. with the National Nanotechnology Initiative, which formalized a size-based definition of nanotechnology and established funding for research on the nanoscale, and in Europe via the European Framework Programmes for Research and Technological Development.

By the mid-2000s new and serious scientific attention began to flourish. Projects emerged to produce nanotechnology roadmaps[14][15] which center on atomically precise manipulation of matter and discuss existing and projected capabilities, goals, and applications.

11.2 Fundamental concepts

Nanotechnology is the engineering of functional systems at the molecular scale. This covers both current work and concepts that are more advanced. In its original sense, nanotechnology refers to the projected ability to construct items from the bottom up, using techniques and tools being developed today to make complete, high performance products.

One nanometer (nm) is one billionth, or 10^{-9}, of a meter. By comparison, typical carbon-carbon bond lengths, or the spacing between these atoms in a molecule, are in the range 0.12–0.15 nm, and a DNA double-helix has a diameter around 2 nm. On the other hand, the smallest cellular life-forms, the bacteria of the genus *Mycoplasma*, are around 200 nm in length. By convention, nanotechnology is taken as the scale range 1 to 100 nm following the definition used by the National Nanotechnology Initiative in the US. The lower limit is set by the size of atoms (hydrogen has the smallest atoms, which are approximately a quarter of a nm diameter) since nanotechnology must build its devices from atoms and molecules. The upper limit is more or less arbitrary but is around the size below which phenomena not observed in larger structures start to become apparent and can be made use

of in the nano device.[16] These new phenomena make nanotechnology distinct from devices which are merely miniaturised versions of an equivalent macroscopic device; such devices are on a larger scale and come under the description of microtechnology.[17]

To put that scale in another context, the comparative size of a nanometer to a meter is the same as that of a marble to the size of the earth.[18] Or another way of putting it: a nanometer is the amount an average man's beard grows in the time it takes him to raise the razor to his face.[18]

Two main approaches are used in nanotechnology. In the "bottom-up" approach, materials and devices are built from molecular components which assemble themselves chemically by principles of molecular recognition.[19] In the "top-down" approach, nano-objects are constructed from larger entities without atomic-level control.[20]

Areas of physics such as nanoelectronics, nanomechanics, nanophotonics and nanoionics have evolved during the last few decades to provide a basic scientific foundation of nanotechnology.

11.2.1 Larger to smaller: a materials perspective

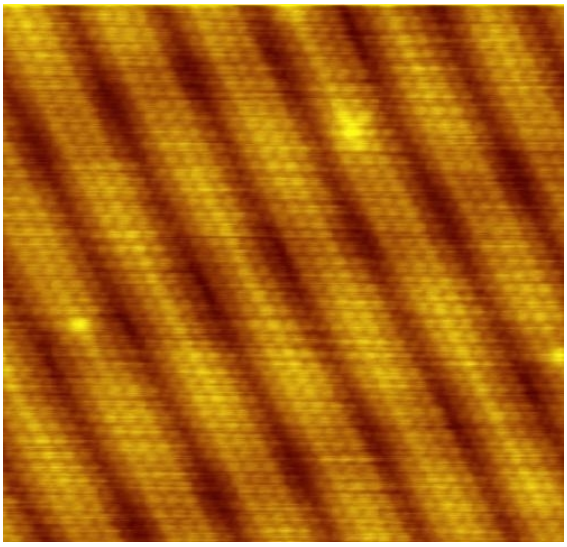


Image of reconstruction on a clean Gold(100) surface, as visualized using scanning tunneling microscopy. The positions of the individual atoms composing the surface are visible.

Main article: Nanomaterials

Several phenomena become pronounced as the size of the system decreases. These include statistical mechanical effects, as well as quantum mechanical effects, for example the "quantum size effect" where the electronic properties of solids are altered with great reductions in particle size. This effect does not come into play by going from macro to micro dimensions. However, quantum effects can become significant when the nanometer size range is reached, typically at distances of 100 nanometers or less, the so-called quantum realm. Additionally, a number of physical (mechanical, electrical, optical, etc.) properties change when compared to macroscopic systems. One example is the increase in surface area to volume ratio altering mechanical, thermal and catalytic properties of materials. Diffusion and reactions at nanoscale, nanostructures materials and nanodevices with fast ion transport are generally referred to nanoionics. *Mechanical* properties of nanosystems are of interest in the nanomechanics research. The catalytic activity of nanomaterials also opens potential risks in their interaction with biomaterials.

Materials reduced to the nanoscale can show different properties compared to what they exhibit on a macroscale, enabling unique applications. For instance, opaque substances can become transparent (copper); stable materials can turn combustible (aluminium); insoluble materials may become soluble (gold). A material such as gold, which is chemically inert at normal scales, can serve as a potent chemical catalyst at nanoscales. Much of the fascination with nanotechnology stems from these quantum and surface phenomena that matter exhibits at the nanoscale.[21]

11.2.2 Simple to complex: a molecular perspective

Main article: Molecular self-assembly

Modern synthetic chemistry has reached the point where it is possible to prepare small molecules to almost any structure. These methods are used today to manufacture a wide variety of useful chemicals such as pharmaceuticals or commercial polymers. This ability raises the question of extending this kind of control to the next-larger level, seeking methods to assemble these single molecules into supramolecular assemblies consisting of many molecules arranged in a well defined manner.

These approaches utilize the concepts of molecular self-assembly and/or supramolecular chemistry to automatically arrange themselves into some useful conformation through a bottom-up approach. The concept of molecular recognition is especially important: molecules can be designed so that a specific configuration or arrangement is favored due to non-covalent intermolecular forces. The Watson–Crick basepairing rules are a direct result of this, as is the specificity of an enzyme being targeted to a single substrate, or the specific folding of the protein itself. Thus, two or more components can be designed to be complementary and mutually attractive so that they make a more complex and useful whole.

Such bottom-up approaches should be capable of producing devices in parallel and be much cheaper than top-down methods, but could potentially be overwhelmed as the size and complexity of the desired assembly increases. Most useful structures require complex and ther-

modynamically unlikely arrangements of atoms. Nevertheless, there are many examples of self-assembly based on molecular recognition in biology, most notably Watson–Crick basepairing and enzyme-substrate interactions. The challenge for nanotechnology is whether these principles can be used to engineer new constructs in addition to natural ones.

11.2.3 Molecular nanotechnology: a long-term view

Main article: Molecular nanotechnology

Molecular nanotechnology, sometimes called molecular manufacturing, describes engineered nanosystems (nanoscale machines) operating on the molecular scale. Molecular nanotechnology is especially associated with the molecular assembler, a machine that can produce a desired structure or device atom-by-atom using the principles of mechanosynthesis. Manufacturing in the context of productive nanosystems is not related to, and should be clearly distinguished from, the conventional technologies used to manufacture nanomaterials such as carbon nanotubes and nanoparticles.

When the term "nanotechnology" was independently coined and popularized by Eric Drexler (who at the time was unaware of an earlier usage by Norio Taniguchi) it referred to a future manufacturing technology based on molecular machine systems. The premise was that molecular scale biological analogies of traditional machine components demonstrated molecular machines were possible: by the countless examples found in biology, it is known that sophisticated, stochastically optimised biological machines can be produced.

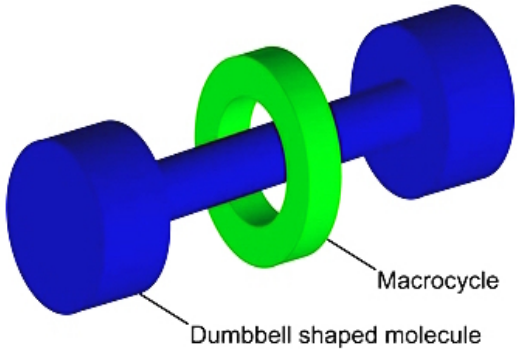
It is hoped that developments in nanotechnology will make possible their construction by some other means, perhaps using biomimetic principles. However, Drexler and other researchers[22] have proposed that advanced nanotechnology, although perhaps initially implemented by biomimetic means, ultimately could be based on mechanical engineering principles, namely, a manufacturing technology based on the mechanical functionality of these components (such as gears, bearings, motors, and structural members) that would enable programmable, positional assembly to atomic specification.[23] The physics and engineering performance of exemplar designs were analyzed in Drexler's book *Nanosystems*.

In general it is very difficult to assemble devices on the atomic scale, as one has to position atoms on other atoms of comparable size and stickiness. Another view, put forth by Carlo Montemagno,[24] is that future nanosystems will be hybrids of silicon technology and biological molecular machines. Richard Smalley argued that mechanosynthesis are impossible due to the difficulties in mechanically manipulating individual molecules.

This led to an exchange of letters in the ACS publication Chemical & Engineering News in 2003.[25] Though biology clearly demonstrates that molecular machine systems are possible, non-biological molecular machines are today only in their infancy. Leaders in research on non-biological molecular machines are Dr. Alex Zettl and his colleagues at Lawrence Berkeley Laboratories and UC Berkeley. They have constructed at least three distinct molecular devices whose motion is controlled from the desktop with changing voltage: a nanotube nanomotor, a molecular actuator,[26] and a nanoelectromechanical relaxation oscillator.[27] See nanotube nanomotor for more examples.

An experiment indicating that positional molecular assembly is possible was performed by Ho and Lee at Cornell University in 1999. They used a scanning tunneling microscope to move an individual carbon monoxide molecule (CO) to an individual iron atom (Fe) sitting on a flat silver crystal, and chemically bound the CO to the Fe by applying a voltage.

11.3 Current research

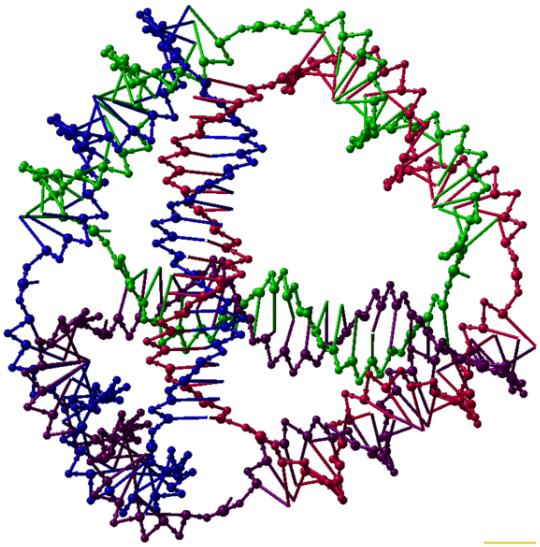


Graphical representation of a rotaxane, useful as a molecular switch.

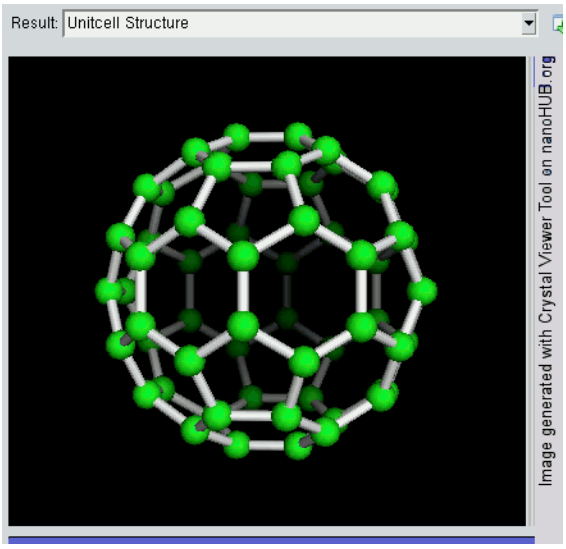
11.3.1 Nanomaterials

The nanomaterials field includes subfields which develop or study materials having unique properties arising from their nanoscale dimensions.[30]

- Interface and colloid science has given rise to many materials which may be useful in nanotechnology, such as carbon nanotubes and other fullerenes, and various nanoparticles and nanorods. Nanomaterials with fast ion transport are related also to nanoionics and nanoelectronics.
- Nanoscale materials can also be used for bulk applications; most present commercial applications of nanotechnology are of this flavor.

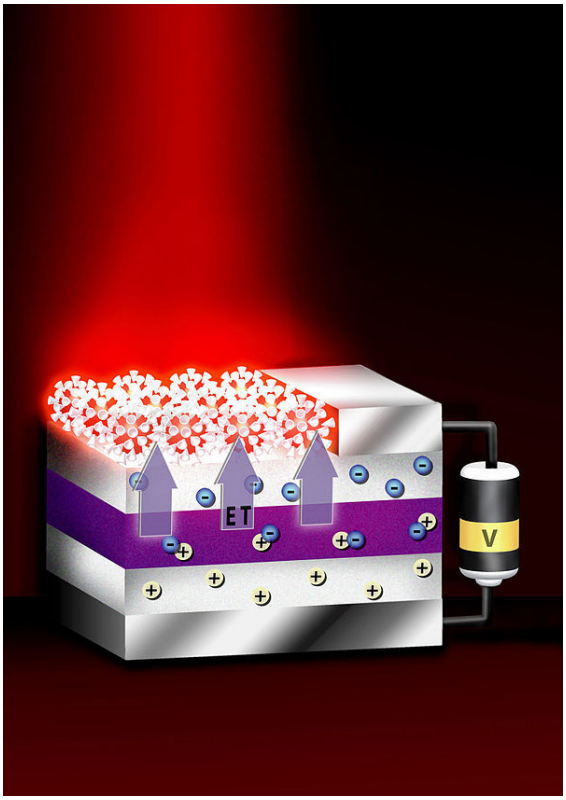


This DNA tetrahedron[28] is an artificially designed nanostructure of the type made in the field of DNA nanotechnology. Each edge of the tetrahedron is a 20 base pair DNA double helix, and each vertex is a three-arm junction.



Rotating view of C_{60}, one kind of fullerene.

- Progress has been made in using these materials for medical applications; see Nanomedicine.
- Nanoscale materials such as nanopillars are sometimes used in solar cells which combats the cost of traditional silicon solar cells.
- Development of applications incorporating semiconductor nanoparticles to be used in the next generation of products, such as display technology, lighting, solar cells and biological imaging; see quantum dots.
- Recent application of nanomaterials include a range of biomedical applications, such as tissue engineering, drug delivery, and biosensors.[31]



This device transfers energy from nano-thin layers of quantum wells to nanocrystals above them, causing the nanocrystals to emit visible light.[29]

11.3.2 Bottom-up approaches

These seek to arrange smaller components into more complex assemblies.

- DNA nanotechnology utilizes the specificity of Watson–Crick basepairing to construct well-defined structures out of DNA and other nucleic acids.
- Approaches from the field of "classical" chemical synthesis (Inorganic and organic synthesis) also aim at designing molecules with well-defined shape (e.g. bis-peptides[32]).
- More generally, molecular self-assembly seeks to use concepts of supramolecular chemistry, and molecular recognition in particular, to cause single-molecule components to automatically arrange themselves into some useful conformation.
- Atomic force microscope tips can be used as a nanoscale "write head" to deposit a chemical upon a surface in a desired pattern in a process called dip pen nanolithography. This technique fits into the larger subfield of nanolithography.

11.3.3 Top-down approaches

These seek to create smaller devices by using larger ones to direct their assembly.

- Many technologies that descended from conventional solid-state silicon methods for fabricating microprocessors are now capable of creating features smaller than 100 nm, falling under the definition of nanotechnology. Giant magnetoresistance-based hard drives already on the market fit this description,[33] as do atomic layer deposition (ALD) techniques. Peter Grünberg and Albert Fert received the Nobel Prize in Physics in 2007 for their discovery of Giant magnetoresistance and contributions to the field of spintronics.[34]
- Solid-state techniques can also be used to create devices known as nanoelectromechanical systems or NEMS, which are related to microelectromechanical systems or MEMS.
- Focused ion beams can directly remove material, or even deposit material when suitable precursor gasses are applied at the same time. For example, this technique is used routinely to create sub-100 nm sections of material for analysis in Transmission electron microscopy.
- Atomic force microscope tips can be used as a nanoscale "write head" to deposit a resist, which is then followed by an etching process to remove material in a top-down method.

11.3.4 Functional approaches

These seek to develop components of a desired functionality without regard to how they might be assembled.

- Magnetic assembly for the synthesis of anisotropic superparamagnetic materials such as recently presented magnetic nanochains.[19]
- Molecular scale electronics seeks to develop molecules with useful electronic properties. These could then be used as single-molecule components in a nanoelectronic device.[35] For an example see rotaxane.
- Synthetic chemical methods can also be used to create synthetic molecular motors, such as in a so-called nanocar.

11.3.5 Biomimetic approaches

- Bionics or biomimicry seeks to apply biological methods and systems found in nature, to the study and design of engineering systems and modern technology. Biomineralization is one example of the systems studied.
- Bionanotechnology is the use of biomolecules for applications in nanotechnology, including use of viruses and lipid assemblies.[36][37] Nanocellulose is a potential bulk-scale application.

11.3.6 Speculative

These subfields seek to anticipate what inventions nanotechnology might yield, or attempt to propose an agenda along which inquiry might progress. These often take a big-picture view of nanotechnology, with more emphasis on its societal implications than the details of how such inventions could actually be created.

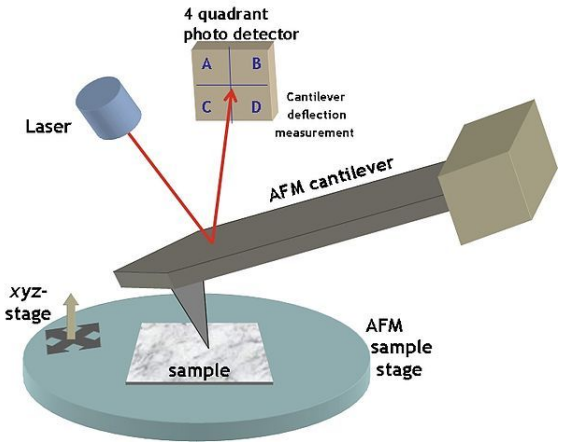
- Molecular nanotechnology is a proposed approach which involves manipulating single molecules in finely controlled, deterministic ways. This is more theoretical than the other subfields, and many of its proposed techniques are beyond current capabilities.
- Nanorobotics centers on self-sufficient machines of some functionality operating at the nanoscale. There are hopes for applying nanorobots in medicine,[38][39][40] but it may not be easy to do such a thing because of several drawbacks of such devices.[41] Nevertheless, progress on innovative materials and methodologies has been demonstrated with some patents granted about new nanomanufacturing devices for future commercial applications, which also progressively helps in the development towards nanorobots with the use of embedded nanobioelectronics concepts.[42][43]
- Productive nanosystems are "systems of nanosystems" which will be complex nanosystems that produce atomically precise parts for other nanosystems, not necessarily using novel nanoscale-emergent properties, but well-understood fundamentals of manufacturing. Because of the discrete (i.e. atomic) nature of matter and the possibility of exponential growth, this stage is seen as the basis of another industrial revolution. Mihail Roco, one of the architects of the USA's National Nanotechnology Initiative, has proposed four states of nanotechnology that seem to parallel the technical progress of the Industrial Revolution, progressing from passive nanostructures to active nanodevices to complex nanomachines and ultimately to productive nanosystems.[44]
- Programmable matter seeks to design materials whose properties can be easily, reversibly and externally controlled though a fusion of information science and materials science.

- Due to the popularity and media exposure of the term nanotechnology, the words picotechnology and femtotechnology have been coined in analogy to it, although these are only used rarely and informally.

11.3.7 Dimensionality in nanomaterials

Nanomaterials can be classified in 0D, 1D, 2D and 3D nanomaterials. The dimensionality play a major role in determining the characteristic of nanomaterials including physical, chemical and biological characteristics. With the decrease in dimensionality, an increase in surface-to-volume ratio is observed. This indicate that smaller dimensional nanomaterials have higher surface area compared to 3D nanomaterials. Recently, two dimensional (2D) nanomaterials are extensively investigated for electronic, biomedical, drug delivery and biosensor applications.

11.4 Tools and techniques



Typical AFM setup. A microfabricated cantilever with a sharp tip is deflected by features on a sample surface, much like in a phonograph but on a much smaller scale. A laser beam reflects off the backside of the cantilever into a set of photodetectors, allowing the deflection to be measured and assembled into an image of the surface.

There are several important modern developments. The atomic force microscope (AFM) and the Scanning Tunneling Microscope (STM) are two early versions of scanning probes that launched nanotechnology. There are other types of scanning probe microscopy. Although conceptually similar to the scanning confocal microscope developed by Marvin Minsky in 1961 and the scanning acoustic microscope (SAM) developed by Calvin Quate and coworkers in the 1970s, newer scanning probe microscopes have much higher resolution, since they are not limited by the wavelength of sound or light.

The tip of a scanning probe can also be used to manipulate nanostructures (a process called positional assembly). Feature-oriented scanning methodology may be a promising way to implement these nanomanipulations in automatic mode.[45][46] However, this is still a slow process because of low scanning velocity of the microscope.

Various techniques of nanolithography such as optical lithography, X-ray lithography dip pen nanolithography, electron beam lithography or nanoimprint lithography were also developed. Lithography is a top-down fabrication technique where a bulk material is reduced in size to nanoscale pattern.

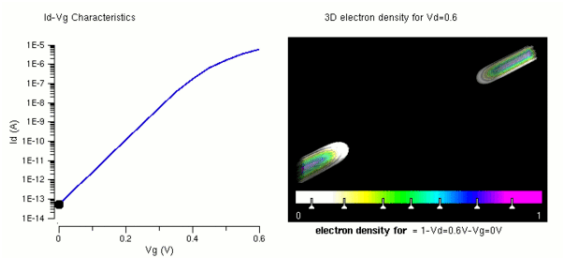
Another group of nanotechnological techniques include those used for fabrication of nanotubes and nanowires, those used in semiconductor fabrication such as deep ultraviolet lithography, electron beam lithography, focused ion beam machining, nanoimprint lithography, atomic layer deposition, and molecular vapor deposition, and further including molecular self-assembly techniques such as those employing di-block copolymers. The precursors of these techniques preceded the nanotech era, and are extensions in the development of scientific advancements rather than techniques which were devised with the sole purpose of creating nanotechnology and which were results of nanotechnology research.[47]

The top-down approach anticipates nanodevices that must be built piece by piece in stages, much as manufactured items are made. Scanning probe microscopy is an important technique both for characterization and synthesis of nanomaterials. Atomic force microscopes and scanning tunneling microscopes can be used to look at surfaces and to move atoms around. By designing different tips for these microscopes, they can be used for carving out structures on surfaces and to help guide self-assembling structures. By using, for example, feature-oriented scanning approach, atoms or molecules can be moved around on a surface with scanning probe microscopy techniques.[45][46] At present, it is expensive and time-consuming for mass production but very suitable for laboratory experimentation.

In contrast, bottom-up techniques build or grow larger structures atom by atom or molecule by molecule. These techniques include chemical synthesis, self-assembly and positional assembly. Dual polarisation interferometry is one tool suitable for characterisation of self assembled thin films. Another variation of the bottom-up approach is molecular beam epitaxy or MBE. Researchers at Bell Telephone Laboratories like John R. Arthur. Alfred Y. Cho, and Art C. Gossard developed and implemented MBE as a research tool in the late 1960s and 1970s. Samples made by MBE were key to the discovery of the fractional quantum Hall effect for which the 1998 Nobel Prize in Physics was awarded. MBE allows scientists to lay down atomically precise layers of atoms and, in the process, build up complex structures. Important for research on semiconductors, MBE is also widely used to make samples and devices for the newly emerging field of spintronics.

However, new therapeutic products, based on responsive nanomaterials, such as the ultradeformable, stress-sensitive Transfersome vesicles, are under development and already approved for human use in some countries.[48]

11.5 Applications



One of the major applications of nanotechnology is in the area of nanoelectronics with MOSFET's being made of small nanowires ~10 nm in length. Here is a simulation of such a nanowire.

Nanostructures provide this surface with superhydrophobicity, which lets water droplets roll down the inclined plane.

Main article: List of nanotechnology applications

As of August 21, 2008, the Project on Emerging Nanotechnologies estimates that over 800 manufacturer-identified nanotech products are publicly available, with new ones hitting the market at a pace of 3–4 per week.[13] The project lists all of the products in a publicly accessible online database. Most applications are limited to the use of "first generation" passive nanomaterials which includes titanium dioxide in sunscreen, cosmetics, surface coatings,[49] and some food products; Carbon allotropes used to produce gecko tape; silver in food packaging, clothing, disinfectants and household appliances; zinc oxide in sunscreens and cosmetics, surface coatings, paints and outdoor furniture varnishes; and cerium oxide as a fuel catalyst.[12]

Further applications allow tennis balls to last longer, golf balls to fly straighter, and even bowling balls to become more durable and have a harder surface. Trousers and socks have been infused with nanotechnology so that they will last longer and keep people cool in the summer. Bandages are being infused with silver nanoparticles to heal cuts faster.[50] Video game consoles and personal computers may become cheaper, faster, and contain more memory thanks to nanotechnology.[51] Nanotechnology may have the ability to make existing medical applications cheaper and easier to use in places like the general practitioner's office and at home.[52] Cars are being manufactured with nanomaterials so they may need fewer metals and less fuel to operate in the future.[53]

Scientists are now turning to nanotechnology in an attempt to develop diesel engines with cleaner exhaust fumes. Platinum is currently used as the diesel engine catalyst in these engines. The catalyst is what cleans the exhaust fume particles. First a reduction catalyst is employed to take nitrogen atoms from NOx molecules in order to free oxygen. Next the oxidation catalyst oxidizes the hydrocarbons and carbon monoxide to form carbon dioxide and water.[54] Platinum is used in both the reduction and the oxidation catalysts.[55] Using platinum though, is inefficient in that it is expensive and unsustainable. Danish company InnovationsFonden invested DKK 15 million in a search for new catalyst substitutes using nanotechnology. The goal of the project, launched in the autumn of 2014, is to maximize surface area and minimize the amount of material required. Objects tend to minimize their surface energy; two drops of water, for example, will join to form one drop and decrease surface area. If the catalyst's surface area that is exposed to the exhaust fumes is maximized, efficiency of the catalyst is maximized. The team working on this project aims to create nanoparticles that will not merge. Every time the surface is optimized, material is saved. Thus, creating these nanoparticles will increase the effectiveness of the resulting diesel engine catalyst—in turn leading to cleaner exhaust fumes—and will decrease cost. If successful, the team hopes to reduce platinum use by 25%.[56]

Nanotechnology also has a prominent role in the fast developing field of Tissue Engineering. When designing scaffolds, researchers attempt to the mimic the nanoscale features of a Cell's microenvironment to direct its differentiation down a suitable lineage.[57] For example, when creating scaffolds to support the growth of bone, researchers may mimic osteoclast resorption pits.[58]

Researchers have successfully used DNA origami-based nanobots capable of carrying out logic functions to achieve targeted drug delivery in cockroaches. It is said that the computational power of these nanobots can be scaled up to that of a Commodore 64.[59]

11.6 Implications

Main article: Implications of nanotechnology

An area of concern is the effect that industrial-scale manufacturing and use of nanomaterials would have on human health and the environment, as suggested by nanotoxicology research. For these reasons, some groups advocate that nanotechnology be regulated by governments. Others counter that overregulation would stifle scientific research and the development of beneficial innovations. Public health research agencies, such as the National Institute for Occupational Safety and Health are actively conducting research on potential health effects stemming from exposures to nanoparticles.[60][61]

Some nanoparticle products may have unintended consequences. Researchers have discovered that bacteriostatic silver nanoparticles used in socks to reduce foot odor are being released in the wash.[62] These particles are then flushed into the waste water stream and may destroy bacteria which are critical components of natural ecosystems, farms, and waste treatment processes.[63]

Public deliberations on risk perception in the US and UK carried out by the Center for Nanotechnology in Society found that participants were more positive about nanotechnologies for energy applications than for health applications, with health applications raising moral and ethical dilemmas such as cost and availability.[64]

Experts, including director of the Woodrow Wilson Center's Project on Emerging Nanotechnologies David Rejeski, have testified[65] that successful commercialization depends on adequate oversight, risk research strategy, and public engagement. Berkeley, California is currently the only city in the United States to regulate nanotechnology;[66] Cambridge, Massachusetts in 2008 considered enacting a similar law,[67] but ultimately rejected it.[68] Relevant for both research on and application of nanotechnologies, the insurability of nanotechnology is contested.[69] Without state regulation of nanotechnology, the availability of private insurance for potential damages is seen as necessary to ensure that burdens are not socialised implicitly.

11.6.1 Health and environmental concerns

Main articles: Nanotoxicology and Pollution from nanomaterials

Nanofibers are used in several areas and in different products, in everything from aircraft wings to tennis rackets. Inhaling airborne nanoparticles and nanofibers may lead to a number of pulmonary diseases, e.g. fibrosis.[70] Researchers have found that when rats breathed in nanoparticles, the particles settled in the brain and lungs, which led to significant increases in biomarkers for inflammation and stress response[71] and that nanoparticles induce skin aging through oxidative stress in hairless mice.[72][73]

A video on the health and safety implications of nanotechnology

A two-year study at UCLA's School of Public Health found lab mice consuming nano-titanium dioxide showed DNA and chromosome damage to a degree "linked to all the big killers of man, namely cancer, heart disease, neurological disease and aging".[74]

A major study published more recently in Nature Nanotechnology suggests some forms of carbon nanotubes – a poster child for the "nanotechnology revolution" – could be as harmful as asbestos if inhaled in sufficient quantities. Anthony Seaton of the Institute of Occupational Medicine in Edinburgh, Scotland, who contributed to the article on carbon nanotubes said "We know that some of them probably have the potential to cause mesothelioma. So those sorts of materials need to be handled very carefully."[75] In the absence of specific regulation forthcoming from governments, Paull and Lyons (2008) have called for an exclusion of engineered nanoparticles in food.[76] A newspaper article reports that workers in a paint factory developed serious lung disease and nanoparticles were found in their lungs.[77][78][79][80]

11.7 Regulation

Main article: Regulation of nanotechnology

Calls for tighter regulation of nanotechnology have occurred alongside a growing debate related to the human health and safety risks of nanotechnology.[81] There is significant debate about who is responsible for the regulation of nanotechnology. Some regulatory agencies currently cover some nanotechnology products and processes (to varying degrees) – by "bolting on" nanotechnology to existing regulations – there are clear gaps in these regimes.[82] Davies (2008) has proposed a regulatory road map describing steps to deal with these shortcomings.[83]

Stakeholders concerned by the lack of a regulatory framework to assess and control risks associated with the release of nanoparticles and nanotubes have drawn parallels with bovine spongiform encephalopathy ("mad cow"

disease), thalidomide, genetically modified food,[84] nuclear energy, reproductive technologies, biotechnology, and asbestosis. Dr. Andrew Maynard, chief science advisor to the Woodrow Wilson Center's Project on Emerging Nanotechnologies, concludes that there is insufficient funding for human health and safety research, and as a result there is currently limited understanding of the human health and safety risks associated with nanotechnology.[85] As a result, some academics have called for stricter application of the precautionary principle, with delayed marketing approval, enhanced labelling and additional safety data development requirements in relation to certain forms of nanotechnology.[86][87]

The Royal Society report[10] identified a risk of nanoparticles or nanotubes being released during disposal, destruction and recycling, and recommended that "manufacturers of products that fall under extended producer responsibility regimes such as end-of-life regulations publish procedures outlining how these materials will be managed to minimize possible human and environmental exposure" (p. xiii).

The Center for Nanotechnology in Society has found that people respond to nanotechnologies differently, depending on application – with participants in public deliberations more positive about nanotechnologies for energy than health applications – suggesting that any public calls for nano regulations may differ by technology sector.[64]

11.8 See also

Main article: Outline of nanotechnology

- Bionanoscience
- Carbon nanotube
- Energy applications of nanotechnology
- Gold nanobeacon
- Gold nanoparticle
- List of emerging technologies
- List of nanotechnology organizations
- List of software for nanostructures modeling
- Magnetic nanochains
- Materiomics
- Nano-thermite
- Molecular design software
- Molecular mechanics
- Nanobiotechnology
- Nanoelectromechanical relay
- Nanoengineering
- Nanofluidics
- NanoHUB
- Nanometrology
- Nanoscale networks
- Nanotechnology education
- Nanotechnology in fiction
- Nanotechnology in water treatment
- Nanoweapons
- National Nanotechnology Initiative
- Self-assembly of nanoparticles
- Top-down and bottom-up
- Translational research
- Wet nanotechnology

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11.10 External links

- Nanotechnology at DMOZ
- What is Nanotechnology? (A Vega/BBC/OU Video Discussion).

Chapter 12

Autonomous car

For the wider application of artificial intelligence to automobiles, see Unmanned ground vehicle and Vehicular automation.

Navlab autonomous cars 1 through 5. NavLab 1 (farthest in photo) was started in 1984 and completed in 1986. Navlab 5 (closest vehicle), finished in 1995, was the first car to drive coast-to-coast (USA) autonomously .

An **autonomous car** (also known as a **driverless car**, **auto**,[1] **self-driving car**,[2] **robotic car**[3]) is a vehicle that is capable of sensing its environment and navigating without human input.[4] Many such vehicles are being developed, but as of February 2017 automated cars permitted on public roads are not yet fully autonomous. They all require a human driver at the wheel who is ready at a moment's notice to take control of the vehicle.

Autonomous cars use a variety of techniques to detect their surroundings, such as radar, laser light, GPS, odometry, and computer vision. Advanced control systems interpret sensory information to identify appropriate navigation paths, as well as obstacles and relevant signage.[5][6] Autonomous cars have control systems that are capable of analyzing sensory data to distinguish between different cars on the road, which is very useful in planning a path to the desired destination.[7]

Some demonstrative systems, precursory to autonomous cars, date back to the 1920s and 1930s. The first self-sufficient (and therefore, truly autonomous) cars appeared in the 1980s, with Carnegie Mellon University's Navlab and ALV projects in 1984 and Mercedes-Benz and Bundeswehr University Munich's Eureka Prometheus Project in 1987. A major milestone was achieved in 1995, with CMU's NavLab 5 completing the first autonomous coast-to-coast drive of the United States. Of the 2,849 miles between Pittsburgh, PA and San Diego, CA, 2,797 miles were autonomous (98.2%), completed with an average speed of 63.8 miles per hour (102.3 km/h).[8][9][10][11] Since then, numerous major companies and research organizations have developed working prototype autonomous vehicles.

Junior, a robotic Volkswagen Passat, in a parking lot at Stanford University in October 2009.

Among the potential benefits of autonomous cars is a significant reduction in traffic collisions;[12] the resulting injuries; and related costs, including a lower need for insurance. Autonomous cars are also predicted to offer major increases in traffic flow;[13] enhanced mobility for children, the elderly,[14] disabled and poor people; the relief of travelers from driving and navigation chores; lower fuel consumption; significantly reduced needs for parking space in cities;[15] a reduction in crime;[16] and the facilitation of different business models for mobility as a service, especially those involved in the sharing economy.[17][18]

Among the main obstacles to widespread adoption of autonomous vehicles, in addition to the technological challenges, are disputes concerning liability; the time period needed to turn an existing stock of vehicles from non-autonomous to autonomous; resistance by individuals to forfeit control of their cars; consumer concern about the

safety of driverless cars; implementation of legal framework and establishment of government regulations for self-driving cars; risk of loss of privacy and security concerns, such as hackers or terrorism; concerns about the resulting loss of driving-related jobs in the road transport industry; and risk of increased suburbanization as driving becomes faster and less onerous without proper public policies in place to avoid more urban sprawl. Many of these issues are due to the fact that Autonomous Things such as autonomous vehicles (and self-navigating drones) are allowing, for the first time, the computers to roam freely, with all the related safety and security concerns.

12.1 Autonomous vs. automated

Autonomous means having the power for self-governance.[19] Many historical projects related to vehicle autonomy have in fact only been *automated* (made to be *automatic*) due to a heavy reliance on artificial hints in their environment, such as magnetic strips. Autonomous control implies good performance under significant uncertainties in the environment for extended periods of time and the ability to compensate for system failures without external intervention.[19] As can be seen from many projects mentioned, it is often suggested to extend the capabilities of an autonomous car by implementing communication networks both in the immediate vicinity (for collision avoidance) and far away (for congestion management). By bringing in these outside influences in the decision process, some would no longer regard the car's behavior or capabilities as autonomous; for example Wood et al. (2012) writes "This Article generally uses the term 'autonomous,' instead of the term 'automated.'" The term "autonomous" was chosen "because it is the term that is currently in more widespread use (and thus is more familiar to the general public). However, the latter term is arguably more accurate. 'Automated' connotes control or operation by a machine, while 'autonomous' connotes acting alone or independently. Most of the vehicle concepts (that we are currently aware of) have a person in the driver's seat, utilize a communication connection to the Cloud or other vehicles, and do not independently select either destinations or routes for reaching them. Thus, the term 'automated' would more accurately describe these vehicle concepts".[20]

12.2 Classification

A classification system based on six different levels (ranging from none to fully automated systems) was published in 2014 by SAE International, an automotive standardization body, as J3016, Taxonomy and Definitions for Terms Related to On-Road Motor Vehicle Automated Driving Systems.[23][24] This classification system

The aim of the Volvo Drive Me project, which is using Volvo S60 test vehicles, is to develop SAE level 4 cars. According to CNET journalist Tim Stevens, the Volvo S60 Drive Me autonomous test vehicle is considered "Level 3 autonomous driving", apparently referring to the now defunct NHTSA classification system levels. [21] [22]

is based on the amount of driver intervention and attentiveness required, rather than the vehicle capabilities, although these are very closely related. In the United States in 2013, the National Highway Traffic Safety Administration (NHTSA) released a formal classification system,[25] but abandoned this system when it adopted the SAE standard in September 2016.

SAE automated vehicle classifications:

- Level 0: Automated system issues warnings but has no vehicle control.
- Level 1 ("hands on"): Driver and automated system shares control over the vehicle. An example would be be Adaptive Cruise Control (ACC) where the driver controls steering and the automated system controls speed. Using Parking Assistance, steering is automated while speed is manual. The driver must be ready to retake full control at any time. Lane Keeping Assistance (LKA) Type II is a further example of level 1 self driving.
- Level 2 ("hands off"): The automated system takes full control of the vehicle (accelerating, braking, and steering). The driver must monitor the driving and be prepared to immediately intervene at any time if the automated system fails to respond properly.
- Level 3 ("eyes off"): The driver can safely turn their attention away from the driving tasks, i.e. the driver can do texting or watch a movie. The vehicle will handle situations that call for an immediate response, like emergency braking. The driver must still be prepared to intervene within some limited time, specified by the manufacturer, when called upon by the vehicle to do so.
- Level 4 ("mind off"): As level 3, but no driver attention is ever required for safety, i.e. the driver may

safely go to sleep or leave the driver's seat. Self driving is supported only in limited areas (geofenced) or under special circumstances, like traffic jams. Outside of theses areas or circumstances, the vehicle must be able to safely abort the trip, i.e. park the car, if the driver does not retake control.

- Level 5 ("wheel optional"): No human intervention is required. An example would be a robot taxi.

12.3 Technology

Modern self-driving cars generally use Bayesian Simultaneous localization and mapping (SLAM) algorithms, which fuse data from multiple sensors and an off-line map into current location estimates and map updates. SLAM with DATMO is a variant developed by researcher now at Google which also handles detection and tracking of other moving objects such as cars and pedestrians. Simpler systems may use roadside real-time locating system (RTLS) beacon systems to aid localisation. Typical sensors include lidar and stereo vision, GPS and IMU. Visual object recognition uses machine vision including neural networks. Educator Udacity is developing an open-source software stack.

12.4 Testing

Testing vehicles with varying degrees of autonomy can be done physically, in closed environments,[26] on public roads (where permitted, typically with a license or permit[27] or adhering to a specific set of operating principles[28]) or virtually, i.e. in computer simulations.

When driven on public roads, the vehicles require at least one person to monitor their proper operation and "take over" when needed. Three of the best-known testing programs are:

- Google - these cars are tested primarily in suburban neighborhoods at slow speeds and run automatically less than 80% of their time. The test driver takes over 20% of the time.

- Tesla - although capable of fully autonomous travel on highways and many urban situations, the manufacturer requires the human driver to remain alert and ready to take over at any moment.

- Uber - their so-called "driverless cars" when tested in California on 2016 carried two people to run them - one behind the wheel as a test driver

12.5 History

Main article: History of autonomous cars

Experiments have been conducted on automating cars

General Motors' Firebird II was described as having an "electronic brain" that allowed it to move into a lane with a metal conductor and follow it along.

The TRL's modified 1960 Citroën DS19 to be automatically controlled at the Science Museum, London.

since at least the 1920s;[29] promising trials took place in the 1950s and work has proceeded since then. The first self-sufficient and truly autonomous cars appeared in the 1980s, with Carnegie Mellon University's Navlab[30] and ALV[31][32] projects in 1984 and Mercedes-Benz and Bundeswehr University Munich's EUREKA Prometheus Project[33] in 1987. Since then, numerous major companies and research organizations have developed working prototype autonomous vehicles, including Mercedes-Benz, General Motors, Continental Automotive Systems, IAV, Autoliv Inc., Bosch, Nissan, Renault, Toyota, Audi, Hyundai Motor Company, Volvo, Tesla Motors, Peugeot, Local Motors, AKKA Technologies, Vislab from University of Parma, Oxford University and Google.[33][34][35][36][37][38][39][40][41][42] In July 2013, Vislab demonstrated BRAiVE, a vehicle that moved autonomously on a mixed traffic route open to public traffic.[43] In 2015, five US states (Nevada, Florida, California, Virginia, and Michigan) together with Washington, D.C. allowed the testing of fully autonomous cars on public roads.[44] While autonomous

cars have generally been tested in regular weather on normal roads, Ford has been testing its autonomous cars on snow-covered roads.[45]

12.6 Transport systems

In Europe, cities in Belgium, France, Italy and the UK are planning to operate transport systems for driverless cars,[46][47][48] and Germany, the Netherlands, and Spain have allowed testing robotic cars in traffic. In 2015, the UK Government launched public trials of the LUTZ Pathfinder driverless pod in Milton Keynes.[49] Since Summer 2015 the French government allowed PSA Peugeot-Citroen to make trials in real conditions in the Paris area. The experiments will be extended to other French cities like Bordeaux and Strasbourg by 2016.[50] The alliance between the French companies THALES and Valeo (provider of the first self-parking car system that equips Audi and Mercedes premi) is also testing its own driverless car system.[51] New Zealand is also planning to use Autonomous Vehicles to solve its public transport problems in Tauranga and Christchurch.[52][53][54][55]

12.7 Potential advantages

Among the anticipated benefits of automated cars is the potential reduction in traffic collisions (and resulting deaths and injuries and costs), caused by human-driver errors, such as delayed reaction time, tailgating, rubbernecking, and other forms of distracted or aggressive driving.[12][17][18][56] Consulting firm McKinsey & Company estimated that widespread use of autonomous vehicles could "eliminate 90% of all auto accidents in the United States, prevent up to US$190 billion in damages and health-costs annually and save thousands of lives."[57]

If a human driver isn't required, automated cars could also reduce labor costs;[58][59] relieve travelers from driving and navigation chores, thereby replacing behind-the-wheel commuting hours with more time for leisure or work;[12][56] and also would lift constraints on occupant ability to drive, distracted and texting while driving, intoxicated, prone to seizures, or otherwise impaired.[60][61][14] For the young, the elderly, people with disabilities, and low-income citizens, autonomous cars could provide enhance mobility.[62][63][64]

Additional advantages could include higher speed limits;[65] smoother rides;[66] and increased roadway capacity; and minimized traffic congestion, due to decreased need for safety gaps and higher speeds.[67][68] Currently, maximum controlled-access highway throughput or capacity according to the U.S. Highway Capacity Manual is about 2,200 passenger vehicles per hour per lane, with about 5% of the available road space is taken up by cars. According to a study by researchers at Columbia University, autonomous cars could increase capacity by 273% (~8,200 cars per hour per lane). The study also estimated that with 100% connected vehicles using vehicle-to-vehicle communication, capacity could reach 12,000 passenger vehicles per hour (up 445% from 2,200 pc/h per lane) traveling safely at 120 km/h (75 mph) with a following gap of about 6 m (20 ft) of each other. Currently, at highway speeds drivers keep between 40 to 50 m (130 to 160 ft) away from the car in front. These increases in highway capacity could have a significant impact in traffic congestion, particularly in urban areas, and even effectively end highway congestion in some places.[69]

There would also be an improved ability to manage traffic flow,[13] combined with less need for traffic police, vehicle insurance;[58] or even road signage, since automated cars could receive necessary communication electronically (although roadway signage may still be needed for any human drivers on the road).[70][71][72] Reduced traffic congestion and the improvements in traffic flow due to widespread use of autonomous cars will also translate into better fuel efficiency.[64][73][74]

Widespread adoption of autonomous cars could reduce the needs of road and parking space in urban areas, freeing scarce land for other uses such as parks, public spaces, retail outlets, housing, and other social uses. Some academics think it could also contribute, along with automated mass transit, to make dense cities much more efficient and livable.[64][75][76][77]

The vehicles' increased awareness could reduce car theft,[16] while the removal of the steering wheel—along with the remaining driver interface and the requirement for any occupant to assume a forward-facing position—would give the interior of the cabin greater ergonomic flexibility. Large vehicles, such as motorhomes, would attain appreciably enhanced ease of use.[78]

When used for carsharing, the total number of cars is reduced.[79] Furthermore, new business models (such as mobility as a service) can develop, which aim to be cheaper than car ownership by removing the cost of the driver.[80] Finally, the robotic car could drive unoccupied to wherever it is required, such as to pick up passengers or to go in for maintenance (eliminating redundant passengers).[68][81][82]

12.8 Potential obstacles

In spite of the various benefits to increased vehicle automation, some foreseeable challenges persist, such as disputes concerning liability,[83][84] the time needed to turn the existing stock of vehicles from nonautonomous to autonomous,[85] resistance by individuals to forfeit control of their cars,[86] customer concern about the safety of driverless cars,[87] and the implementation of legal

framework and establishment of government regulations for self-driving cars.[88] Other obstacles could be missing driver experience in potentially dangerous situations,[89] ethical problems in situations where an autonomous car's software is forced during an unavoidable crash to choose between multiple harmful courses of action,[90][91][92] and possibly insufficient Adaptation to Gestures and non-verbal cues by police and pedestrians.[93]

Possible technological obstacles for autonomous cars are:

- Software reliability.[94]
- Artificial Intelligence still isn't able to function properly in chaotic inner city environments[95]
- A car's computer could potentially be compromised, as could a communication system between cars.[96][97][98][99][100]
- Susceptibility of the car's sensing and navigation systems to different types of weather or deliberate interference, including jamming and spoofing.[93]
- Autonomous cars may require very high-quality specialised maps[101] to operate properly. Where these maps may be out of date, they would need to be able to fall back to reasonable behaviors.[93][102]
- Competition for the radio spectrum desired for the car's communication.[103]
- Field programmability for the systems will require careful evaluation of product development and the component supply chain.[100]
- Current road infrastructure may need changes for autonomous cars to function optimally.[104]

12.9 Potential disadvantages

See also: Computer security § Automobiles

A direct impact of widespread adoption of autonomous vehicles is the loss of driving-related jobs in the road transport industry.[58][59][105] There could be resistance from professional drivers and unions who are threatened by job losses.[106] In addition, there could be job losses in public transit services and crash repair shops. The automobile insurance industry might suffer as the technology makes certain aspects of these occupations obsolete.[64]

Potential loss of privacy and risks of hacking. Sharing of information through V2V (Vehicle to Vehicle) and V2I (Vehicle to Infrastructure) protocols.[107][108] There is also the risk of terrorist attacks. Self-driving cars could potentially be loaded with explosives and used as bombs.[109]

The lack of stressful driving, more productive time during the trip, and the potential savings in travel time and cost could become an incentive to live far away from cities, where land is cheaper, and work in the city's core, thus increasing travel distances and inducing more urban sprawl, more fuel consumption and an increase in the carbon footprint of urban travel.[110][111] There is also the risk that traffic congestion might increase, rather than decrease.[64] Appropriate public policies and regulations, such as zoning, pricing, and urban design are required to avoid the negative impacts of increased suburbanization and longer distance travel.[64][111]

Research shows that drivers in autonomous cars react later when they have to intervene in a critical situation, compared to if they were driving manually.[112]

12.10 Safety record

12.10.1 Tesla Autopilot

Main article: Crash incidents with Tesla Autopilot

In mid-October 2015 Tesla Motors rolled out version 7 of their software in the U.S. that included Tesla Autopilot capability.[113] On 9 January 2016, Tesla rolled out version 7.1 as an over-the-air update, adding a new "summon" feature that allows cars to self-park at parking locations without the driver in the car.[114] Tesla's autonomous driving features are ahead of others in the industry, and can be classified as somewhere between level 2 and level 3 under the U.S. Department of Transportation's National Highway Traffic Safety Administration (NHTSA) five levels of vehicle automation. At this level the car can act autonomously but requires the full attention of the driver, who must be prepared to take control at a moment's notice.[115][116][117] Autopilot should be used only on limited-access highways, and sometimes it will fail to detect lane markings and disengage itself. In urban driving the system will not read traffic signals or obey stop signs. The system also does not detect pedestrians or cyclists.[118]

Tesla Model S Autopilot system is suitable only on limited-access highways not for urban driving. Among other limitations, Autopilot can not detect pedestrians or cyclists.[118]

The first fatal accident involving a vehicle being driven by itself took place in Williston, Florida on 7 May 2016 while a Tesla Model S electric car was engaged in Autopilot mode. The occupant was killed in a crash with an 18-wheel tractor-trailer. On 28 June 2016 the National Highway Traffic Safety Administration (NHTSA) opened a formal investigation into the accident working with the Florida Highway Patrol. According to the NHTSA, preliminary reports indicate the crash occurred when the tractor-trailer made a left turn in front of the Tesla at an intersection on a non-controlled access highway, and the car failed to apply the brakes. The car continued to travel after passing under the truck's trailer.[119][120] The NHTSA's preliminary evaluation was opened to examine the design and performance of any automated driving systems in use at the time of the crash, which involved a population of an estimated 25,000 Model S cars.[121] On 8 July 2016, the NHTSA requested Tesla Motors provide the agency detailed information about the design, operation and testing of its Autopilot technology. The agency also requested details of all design changes and updates to Autopilot since its introduction, and Tesla's planned updates schedule for the next four months.[122]

According to Tesla, "neither autopilot nor the driver noticed the white side of the tractor-trailer against a brightly lit sky, so the brake was not applied." The car attempted to drive full speed under the trailer, "with the bottom of the trailer impacting the windshield of the Model S." Tesla also stated that this was Tesla's first known autopilot death in over 130 million miles (208 million km) driven by its customers with Autopilot engaged. According to Tesla there is a fatality every 94 million miles (150 million km) among all type of vehicles in the U.S.[119][120][123] Although this number also includes fatalities of the crashes, for example, of motorcycle driver with stationary objects or pedestrians.[124][125]

In July 2016 the U.S. National Transportation Safety Board (NTSB) opened a formal investigation into the fatal accident while the Autopilot was engaged. The NTSB is an investigative body that only has the power to make policy recommendations. An agency spokesman said "It's worth taking a look and seeing what we can learn from that event, so that as that automation is more widely introduced we can do it in the safest way possible.".[126] In January 2017, the NTSB released the report that concluded Tesla was not at fault; the investigation revealed that the Tesla car crash rate dropped by 40 percent after Autopilot was installed.[127]

According to Tesla, starting 19 October 2016, all Tesla cars are built with hardware to allow full self-driving capability at the highest safety level (SAE Level 5).[128] The hardware includes eight surround cameras and twelve ultrasonic sensors, in addition to the forward-facing radar with enhanced processing capabilities.[129] The system will operate in "shadow mode" (processing without taking action) and send data back to Tesla to improve its abilities until the software is ready for deployment via over-the-air upgrades.[130] After the required testing, Tesla hopes to enable full self-driving by the end of 2017 under certain conditions.

12.10.2 Google self-driving car

Main article: Google self-driving car

In August 2012, Google announced that their self-driving car had completed over 300,000 autonomous-driving miles (500,000 km) accident-free, typically having about a dozen cars on the road at any given time, and were starting to test them with single drivers instead of in pairs.[131] In late-May 2014, Google revealed a new prototype of its driverless car, which had no steering wheel, gas pedal, or brake pedal, and was fully autonomous.[132] As of March 2016, Google had test-driven their fleet of driverless cars in autonomous mode a total of 1,500,000 mi (2,400,000 km).[133] In December 2016, Alphabet (Google's parent company) announced that the self-driving car technology would be spun-off to a new company called *Waymo*.[134][135]

Google's in-house driverless car

Based on Google's own accident reports, their test cars have been involved in 14 collisions, of which other drivers were at fault 13 times. It was not until 2016 that the car's software caused a crash.[136]

In June 2015, Google founder Sergey Brin confirmed that there had been 12 collisions as of that date, eight of which involved being rear-ended at a stop sign or traffic light, two in which the vehicle was side-swiped by another driver, one in which another driver rolled through a stop sign, and one where a Google employee was controlling the car manually.[137] In July 2015, three Google employees suffered minor injuries when the self-driving car they were riding in was rear-ended by a car whose driver failed to brake at a traffic light. This was the first time that a self-driving car collision resulted in injuries.[138] On 14 February 2016 a Google self-driving car attempted to avoid sandbags blocking its path. During the maneuver it struck a bus. Google addressed the crash, saying "In this case, we clearly bear some responsibility, because if our car hadn't moved there wouldn't have been

a collision."[139][140] Google characterized the crash as a misunderstanding and a learning experience.[136]

12.10.3 Uber

In March 2017, a self-driving Uber car was involved in an accident in Tempe, Arizona when another car failed to yield, resulting in the Uber vehicle flipping over.[141]

12.11 Policy implications

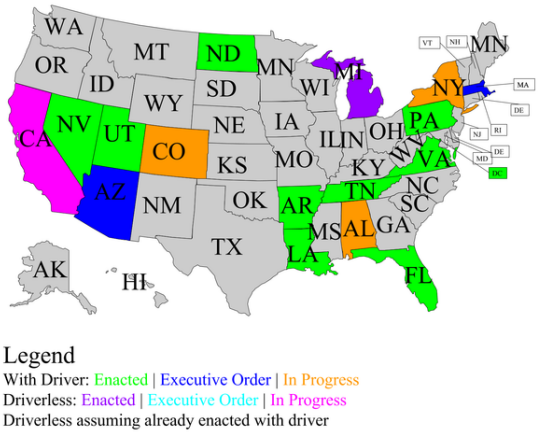
If fully autonomous cars become commercially available, they have the potential to be a disruptive innovation with major implications for society. The likelihood of widespread adoption is still unclear, but if they are used on a wide scale, policy makers face a number of unresolved questions about their effects.[104]

One fundamental question is about their effect on travel behavior. Some people believe that they will increase car ownership and car use because it will become easier to use them and they will ultimately be more useful.[104] This may in turn encourage urban sprawl and ultimately total private vehicle use. Others argue that it will be easier to share cars and that this will thus discourage outright ownership and decrease total usage, and make cars more efficient forms of transportation in relation to the present situation.[142]

Other disruptive effects will come from the use of autonomous vehicles to carry goods. **Self-driving vans** have the potential to make home deliveries significantly cheaper, transforming retail commerce and possibly rendering hypermarkets and supermarkets redundant. As of right now the U.S. Government defines automation into six levels, starting at level zero which means the human driver does everything and ending with level five, the automated system performs all the driving tasks. Also under the current law, manufacturers bear all the responsibility to self-certify vehicles for use on public roads. This means that currently as long as the vehicle is compliant within the regulatory framework, there are no specific federal legal barriers to a highly automated vehicle being offered for sale. Iyad Rahwan, an associate professor in the MIT Media lab said, "Most people want to live in a world where cars will minimize casualties, but everyone wants their own car to protect them at all costs." Furthermore, industry standards and best practice are still needed in systems before they can be considered reasonably safe under real-world conditions.[143]

12.11.1 Legislation

In the United States, state vehicle codes generally do not envisage — but do not necessarily prohibit — highly automated vehicles.[144] To clarify the legal status of and

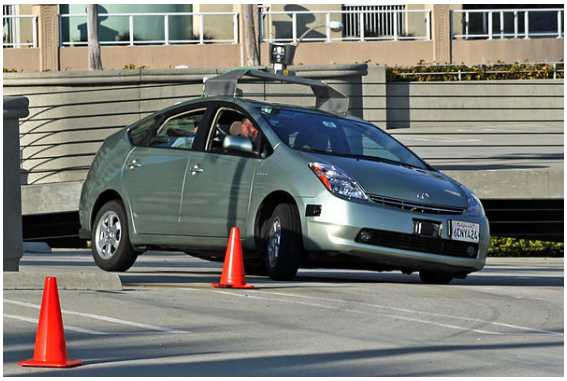


U.S. states that allow driverless cars public road testing as of 2016.

otherwise regulate such vehicles, several states have enacted or are considering specific laws.[145] In 2016, 7 states (Nevada, California, Florida, Michigan, Hawaii, Washington, and Tennessee), along with the District of Columbia, have enacted laws for autonomous vehicles. After the first fatal accident by Tesla's Autopilot system, revising laws or standards for autonomous car is carefully discussed globally.

In September 2016, the US National Economic Council and Department of Transportation released federal standards that describe how automated vehicles should react if their technology fails, how to protect passenger privacy, and how riders should be protected in the event of an accident. The new federal guidelines are meant to avoid a patchwork of state laws, while avoiding being so overbearing as to stifle innovation.[146]

In June 2011, the Nevada Legislature passed a law to authorize the use of autonomous cars. Nevada thus became the first jurisdiction in the world where autonomous vehicles might be legally operated on public roads. According to the law, the Nevada Department of Motor Vehicles (NDMV) is responsible for setting safety and performance standards and the agency is responsible for designating areas where autonomous cars may be tested.[147][148][149] This legislation was supported by Google in an effort to legally conduct further testing of its Google driverless car.[150] The Nevada law defines an autonomous vehicle to be "a motor vehicle that uses artificial intelligence, sensors and global positioning system coordinates to drive itself without the active intervention of a human operator." The law also acknowledges that the operator will not need to pay attention while the car is operating itself. Google had further lobbied for an exemption from a ban on distracted driving to permit occupants to send text messages while sitting behind the wheel, but this did not become law.[150][151][152] Furthermore, Nevada's regulations require a person behind the wheel and one in the passenger's seat during tests.[153]



A Toyota Prius modified by Google to operate as a driverless car.

In 2013, the government of the United Kingdom permitted the testing of autonomous cars on public roads.[154] Prior to this, all testing of robotic vehicles in the UK had been conducted on private property.[154]

In 2014 the Government of France announced that testing of autonomous cars on public roads would be allowed in 2015. 2000 km of road would be opened through the national territory, especially in Bordeaux, in Isère, Île-de-France and Strasbourg. At the 2015 ITS World Congress, a conference dedicated to intelligent transport systems, the very first demonstration of autonomous vehicles on open road in France was carried out in Bordeaux in early October 2015.[155]

In spring of 2015, the Federal Department of Environment, Transport, Energy and Communications in Switzerland (UVEK) allowed Swisscom to test a driverless Volkswagen Passat on the streets of Zurich.[156]

On 19 February 2016, Assembly Bill No. 2866 was introduced in California that would allow completely autonomous vehicles to operate on the road, including those without a driver, steering wheel, accelerator pedal, or brake pedal. The Bill states the Department of Motor Vehicles would need to comply with these regulations by 1 July 2018 for these rules to take effect. This bill has yet to pass the house of origin.[157]

In 2016, the Singapore Land Transit Authority in partnership with UK automotive supplier Delphi Automotive Plc will launch preparations for a test run of a fleet of automated taxis for an on-demand autonomous cab service to take effect in 2017.[158]

In September 2016, the U.S. Department of Transportation released its Federal Automated Vehicles Policy,[159] and California published discussions on the subject in October 2016.[160]

In December 2016, the California Department of Motor Vehicles ordered Uber to remove its self driving vehicles from the road in response to two red-light violations. Uber immediately blamed the violations on "human-error", and has suspended the drivers.[161]

12.12 Vehicular communication systems

Main article: Vehicular communication systems

Individual vehicles may benefit from information obtained from other vehicles in the vicinity, especially information relating to traffic congestion and safety hazards. Vehicular communication systems use vehicles and roadside units as the communicating nodes in a peer-to-peer network, providing each other with information. As a cooperative approach, vehicular communication systems can allow all cooperating vehicles to be more effective. According to a 2010 study by the National Highway Traffic Safety Administration, vehicular communication systems could help avoid up to 79 percent of all traffic accidents.[162]

In 2012, computer scientists at the University of Texas in Austin began developing smart intersections designed for autonomous cars. The intersections will have no traffic lights and no stop signs, instead using computer programs that will communicate directly with each car on the road.[163]

Among connected cars, an unconnected one is the weakest link and will be increasingly banned from busy high-speed roads, predicted a Helsinki think tank in January 2016.[164]

12.13 Public opinion surveys

In a 2011 online survey of 2,006 US and UK consumers by Accenture, 49% said they would be comfortable using a "driverless car".[165]

A 2012 survey of 17,400 vehicle owners by J.D. Power and Associates found 37% initially said they would be interested in purchasing a fully autonomous car. However, that figure dropped to 20% if told the technology would cost $3,000 more.[166]

In a 2012 survey of about 1,000 German drivers by automotive researcher Puls, 22% of the respondents had a positive attitude towards these cars, 10% were undecided, 44% were skeptical and 24% were hostile.[167]

A 2013 survey of 1,500 consumers across 10 countries by Cisco Systems found 57% "stated they would be likely to ride in a car controlled entirely by technology that does not require a human driver", with Brazil, India and China the most willing to trust autonomous technology.[168]

In a 2014 US telephone survey by Insurance.com, over three-quarters of licensed drivers said they would at least consider buying a self-driving car, rising to 86% if car insurance were cheaper. 31.7% said they would not continue to drive once an autonomous car was available instead.[169]

In a February 2015 survey of top auto journalists, 46% predict that either Tesla or Daimler will be the first to the market with a fully autonomous vehicle, while (at 38%) Daimler is predicted to be the most functional, safe, and in-demand autonomous vehicle.[170]

In 2015 a questionnaire survey by Delft University of Technology explored the opinion of 5,000 people from 109 countries on automated driving. Results showed that respondents, on average, found manual driving the most enjoyable mode of driving. 22% of the respondents did not want to spend any money for a fully automated driving system. Respondents were found to be most concerned about software hacking/misuse, and were also concerned about legal issues and safety. Finally, respondents from more developed countries (in terms of lower accident statistics, higher education, and higher income) were less comfortable with their vehicle transmitting data.[171]

In 2016, a survey in Germany examined the opinion of 1,603 people, who were representative in terms of age, gender, and education for the German population, towards partially, highly, and fully automated cars. Results showed that men and women differ in their willingness to use them. Men felt less anxiety and more joy towards automated cars, whereas women showed the exact opposite. The gender difference towards anxiety was especially pronounced between young men and women but decreased with participants' age.[172]

In 2016, a PwC survey, in the United States, showing the opinion of 1,584 people, highlights that "66 percent of respondents said they think autonomous cars are probably smarter than the average human driver". People are still worried about safety and mostly the fact of having the car hacked. Nevertheless, only 13% of the interviewees see no advantages in this new kind of cars.[173]

12.14 Moral issues

With the emergence of autonomous cars, there are various ethical issues arising. While morally, the introduction of autonomous vehicles to the mass market seems inevitable due to a reduction of crashes by up to 90%[174] and their accessibility to disabled, elderly, and young passengers, there still remain some ethical issues that have not yet been fully solved. Those include, but are not limited to: The moral, financial, and criminal responsibility for crashes, the decisions a car is to make right before a (fatal) crash, privacy issues, and potential job loss.

There are different opinions on who should be held liable in case of a crash, in particular with people being hurt. Many experts see the car manufacturers themselves responsible for those crashes that occur due to a technical malfunction or misconstruction.[175] Besides the fact that the car manufacturer would be the source of the problem in a situation where a car crashes due to a technical issue, there is another important reason why car manufacturers could be held responsible: it would encourage them to innovate and heavily invest into fixing those issues, not only due to protection of the brand image, but also due to financial and criminal consequences. However, there are also voices that argue those using or owning the vehicle should be held responsible since they lastly know the risk that involves using such a vehicle. Experts suggest introducing a tax or insurances that would protect owners and users of autonomous vehicles of claims made by victims of an accident.[175] Other possible parties that can be held responsible in case of a technical failure include software engineers that programmed the code for the autonomous operation of the vehicles, and suppliers of components of the AV.[176]

Taking aside the question of legal liability and moral responsibility, the question arises how autonomous vehicles should be programmed to behave in an emergency situation where either passengers or other traffic participants are endangered. A very visual example of the moral dilemma that a software engineer or car manufacturer might face in programming the operating software is described in an ethical thought experiment, the trolley problem: a conductor of a trolley has the choice of staying on the planned track and running over 5 people, or turn the trolley onto a track where it would only kill one person, assuming there is no traffic on it.[177] There are two main considerations that need to be addressed. First, on what moral basis would the decisions an autonomous vehicle would have to make be based on. Second, how could those be translated into software code. Researchers have suggested, in particular, two ethical theories to be applicable to the behavior of autonomous vehicles in cases of emergency: deontology and utilitarianism.[178] Asimov's three laws of robotics are a typical example of deontological ethics. The theory suggests that an autonomous car needs to follow strict written-out rules that it needs to follow in any situation. Utilitarianism suggests the idea that any decision must be made based on the goal to maximize utility. This needs a definition of utility which could be maximizing the number of people surviving in a crash. Critics suggest that autonomous vehicles should adapt a mix of multiple theories to be able to respond morally right in the instance of a crash.[178]

Privacy-related issues arise mainly from the interconnectivity of autonomous cars, making it just another mobile device that can gather any information about an individual. This information gathering ranges from tracking of the routes taken, voice recording, video recording, preferences in media that is consumed in the car, behavioral patterns, to many more streams of information.[179][180]

The implementation of autonomous vehicles to the mass market might cost up to 5 million jobs in the US alone, making up almost 3% of the workforce.[181] Those jobs include drivers of taxis, buses, vans, trucks, and e-hailing vehicles. Many industries, such as the auto insurance industry are indirectly affected. This industry alone generates an annual revenue of about $220 billions, support-

ing 277,000 jobs.[182] To put this into perspective – this is about the number of mechanical engineering jobs.[183] The potential loss of a majority of those jobs due to an estimated decline of accidents by up to 90% will have a tremendous impact on those individuals involved.[184] However, new jobs will be created, e.g. due to a higher demand for programmers to program the necessary software.

12.15 In fiction

Minority Report's *Lexus 2054 on display in Paris, France in October 2002.*

12.15.1 In anime

- The *éX-Driver* anime series features autonomous electric-powered vehicles driven by Artificial Intelligences (AIs). These sometimes malfunction or are taken over by malicious users, requiring interception and intervention by éX-Drivers operating manually controlled gas-powered vehicles

12.15.2 In film

- Dudu, a VW Beetle, features in a 1971 to 1978 German series of movies similar to Disney's Herbie, but with an electronic brain. (Herbie, also a Beetle, was depicted as an anthropomorphic car with its own spirit.)
- The Stephen King book and eponymous movie adaptation, *Christine* (1983), feature a sentient, autonomous car as the title character.
- In the film *Who Framed Roger Rabbit* (1988), starring Bob Hoskins, the character Benny the Cab, a sentient taxicab, drives on his own.
- In the film *Batman* (1989), starring Michael Keaton, the Batmobile is shown to be able to drive to Batman's current location with some navigation commands from Batman and possibly some autonomy.
- The film *Total Recall* (1990), starring Arnold Schwarzenegger, features taxis called *Johnny Cabs* controlled by artificial intelligence in the car or the android occupants.
- The film *Demolition Man* (1993), starring Sylvester Stallone and set in 2032, features vehicles that can be self-driven or commanded to "Auto Mode" where a voice-controlled computer operates the vehicle.
- The film *Timecop* (1994), starring Jean-Claude Van Damme, set in 2004 and 1994, has autonomous cars.
- Another Arnold Schwarzenegger movie, *The 6th Day* (2000), features an autonomous car commanded by Michael Rapaport.
- The film *Minority Report* (2002), set in Washington, D.C. in 2054, features an extended chase sequence involving autonomous cars. The vehicle of protagonist John Anderton is transporting him when its systems are overridden by police in an attempt to bring him into custody.
- The film Terminator 3: Rise of the Machines (2003), during an automobile chase scene; emergency vehicles are taken control by the T-X Terminator in an attempt to kill John Connor and Kate Brewster who is played by Claire Danes.
- The film, *The Incredibles* (2004), Mr. Incredible makes his car autonomous for him while it changes him into his supersuit when driving to save a cat from a tree.

I, Robot's *Audi RSQ at CeBIT in March 2005.*

- The film *I, Robot* (2004), set in Chicago in 2035, features autonomous vehicles driving on highways, allowing the car to travel safer at higher speeds than if manually controlled. The option to manually operate the vehicles is available.

12.15.3 In literature

Intelligent or self-driving cars are a common theme in science fiction literature. Examples include:

- In Isaac Asimov's science-fiction short story, "Sally" (first published May–June 1953), autonomous cars have "positronic brains" and communicate via honking horns and slamming doors, and save their human caretaker.
- Peter F. Hamilton's *Commonwealth Saga* series features intelligent or self-driving vehicles.
- In Robert A Heinlein's novel, *The Number of the Beast* (1980), Zeb Carter's driving and flying car "Gay Deceiver" is at first semi-autonomous and later, after modifications by Zeb's wife Deety, becomes sentient and capable of fully autonomous operation.
- In Edizioni Piemme's series *Geronimo Stilton*, a robotic vehicle called "Solar" is in the 54th book.
- Alastair Reynolds' series, *Revelation Space*, features intelligent or self-driving vehicles.
- In Daniel Suarez' novels *Daemon* (2006) and *Freedom™* (2010) driverless cars and motorcycles are used for attacks in a software-based open-source warfare. The vehicles are modified for this using 3D printers and distributed manufacturing[185] and are also able to operate as swarms.

12.15.4 In television

- "CSI: Cyber" Season 2, episode 6, *Gone in 60 Seconds*, features three seemingly normal customized vehicles, a 2009 Nissan Fairlady Z Roadster, a BMW M3 E90 and a Cadillac CTS-V, and one stock luxury BMW 7-series, being remote-controlled by a computer hacker.
- "Handicar", season 18, episode 4 of 2014 TV series *South Park* features a Japanese autonomous car that takes part in the *Wacky Races*-style car race.
- KITT, the Pontiac Trans Am in the 1982 TV series *Knight Rider*, was sentient and autonomous.
- "Driven", series 4 episode 11 of the 2006 TV series *NCIS* features a robotic vehicle named "Otto," part of a high-level project of the Department of Defense, which causes the death of a Navy Lieutenant, and then later almost kills Abby.
- The TV series "Viper" features a silver/grey armored assault vehicle, called *The Defender*, which masquerades as a flame-red 1992 Dodge Viper RT/10 and later as a 1998 cobalt blue Dodge Viper GTS. The vehicle's sophisticated computer systems allow it to be controlled via remote on some occasions.
- "Black Mirror" episode "Hated in the Nation" briefly features a self-driving SUV with a touchscreen interface on the inside.
- *Bull* has a show discussing the effectiveness and safety of Self Driving cars in an episode call E.J.[186]

12.16 See also

- Automated guideway transit
- Automatic train operation
- Automobile safety
- Automotive navigation system
- Autopilot
- Autotech
- Connected car
- Dutch Automated Vehicle Initiative
- Death by GPS
- Driverless tractor
- Elevator operator
- Hybrid navigation
- Intelligent transportation system
- Mobility as a service (transport)
- Personal rapid transit
- Technological unemployment
- Unmanned ground vehicle
- Unmanned aerial vehicle / Drone
- Vehicle infrastructure integration
- Vehicular automation
- Vision processing unit

12.16.1 Manufacturers

- Mobileye
- Tesla
- Waymo

12.16.2 Autonomous driving functions

- Measurement of Assured Clear Distance Ahead
- Autonomous cruise control system
- Automatic parking
- Electronic stability control
- Lane Keep Assist
- Precrash system
- Automated platooning

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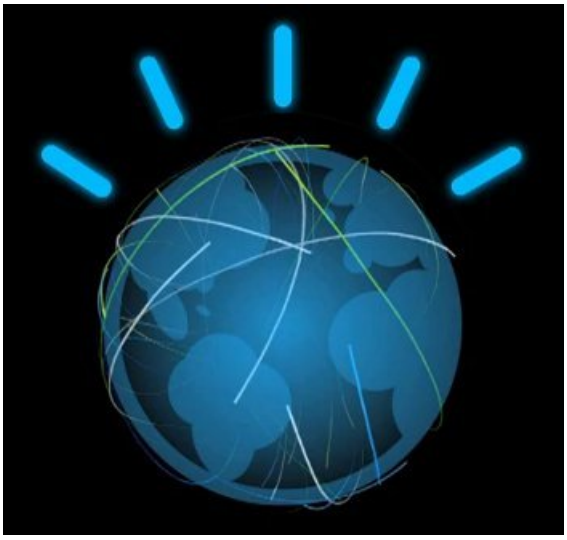
Chapter 13

Watson (computer)

"IBM Watson" redirects here. For the IBM laboratory, see Thomas J. Watson Research Center.

Watson is a question answering computer system capa-



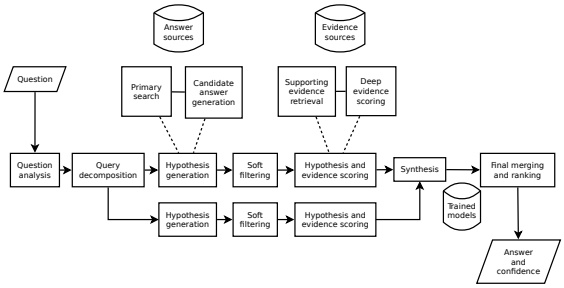
Watson's avatar, inspired by the IBM "smarter planet" logo[1]

ble of answering questions posed in natural language,[2] developed in IBM's DeepQA project by a research team led by principal investigator David Ferrucci.[3] Watson was named after IBM's first CEO, industrialist Thomas J. Watson.[4][5] The computer system was specifically developed to answer questions on the quiz show *Jeopardy!*[6] In 2011, Watson competed on *Jeopardy!* against former winners Brad Rutter and Ken Jennings.[4][7] Watson received the first place prize of $1 million.[8]

Watson had access to 200 million pages of structured and unstructured content consuming four terabytes of disk storage[9] including the full text of Wikipedia,[10] but was not connected to the Internet during the game.[11][12] For each clue, Watson's three most probable responses were displayed on the television screen. Watson consistently outperformed its human opponents on the game's signaling device, but had trouble in a few categories, notably those having short clues containing only a few words.

In February 2013, IBM announced that Watson software system's first commercial application would be for utilization management decisions in lung cancer treatment at Memorial Sloan Kettering Cancer Center, New York City, in conjunction with health insurance company WellPoint.[13] IBM Watson's former business chief, Manoj Saxena, says that 90% of nurses in the field who use Watson now follow its guidance.[14]

13.1 Description



The high-level architecture of IBM's DeepQA used in Watson[15]

Watson is a question answering (QA) computing system that IBM built to apply advanced natural language processing, information retrieval, knowledge representation, automated reasoning, and machine learning technologies to the field of open domain question answering.[2]

> The key difference between QA technology and document search is that document search takes a keyword query and returns a list of documents, ranked in order of relevance to the query (often based on popularity and page ranking), while QA technology takes a question expressed in natural language, seeks to understand it in much greater detail, and returns a precise answer to the question.[16]

According to IBM, "more than 100 different techniques are used to analyze natural language, identify sources, find and generate hypotheses, find and score evidence, and merge and rank hypotheses."[17]

13.1.1 Software

Watson uses IBM's DeepQA software and the Apache UIMA (Unstructured Information Management Architecture) framework. The system was written in various languages, including Java, C++, and Prolog, and runs on the SUSE Linux Enterprise Server 11 operating system using Apache Hadoop framework to provide distributed computing.[9][18][19]

13.1.2 Hardware

The system is workload-optimized, integrating massively parallel POWER7 processors and built on IBM's *DeepQA* technology,[20] which it uses to generate hypotheses, gather massive evidence, and analyze data.[2] Watson employs a cluster of ninety IBM Power 750 servers, each of which uses a 3.5 GHz POWER7 eight-core processor, with four threads per core. In total, the system has 2,880 POWER7 processor threads and 16 terabytes of RAM.[20]

According to John Rennie, Watson can process 500 gigabytes, the equivalent of a million books, per second.[21] IBM's master inventor and senior consultant, Tony Pearson, estimated Watson's hardware cost at about three million dollars.[22] Its Linpack performance stands at 80 TeraFLOPs, which is about half as fast as the cut-off line for the Top 500 Supercomputers list.[23] According to Rennie, all content was stored in Watson's RAM for the Jeopardy game because data stored on hard drives would be too slow to be competitive with human Jeopardy champions.[21]

13.1.3 Data

The sources of information for Watson include encyclopedias, dictionaries, thesauri, newswire articles, and literary works. Watson also used databases, taxonomies, and ontologies. Specifically, DBPedia, WordNet, and Yago were used.[24] The IBM team provided Watson with millions of documents, including dictionaries, encyclopedias, and other reference material that it could use to build its knowledge.[12]

13.2 Operation

Watson parses questions into different keywords and sentence fragments in order to find statistically related phrases.[12] Watson's main innovation was not in the creation of a new algorithm for this operation but rather its ability to quickly execute hundreds of proven language analysis algorithms simultaneously to find the correct answer.[12][26] The more algorithms that find the same answer independently the more likely Watson is to be correct.[12] Once Watson has a small number of potential solutions, it is able to check against its database to ascertain whether the solution makes sense.[12]

13.2.1 Comparison with human players

Ken Jennings, Watson, and Brad Rutter in their Jeopardy! *exhibition match*

Watson's basic working principle is to parse keywords in a clue while searching for related terms as responses. This gives Watson some advantages and disadvantages compared with human *Jeopardy!* players.[27] Watson has deficiencies in understanding the contexts of the clues. As a result, human players usually generate responses faster than Watson, especially to short clues.[12] Watson's programming prevents it from using the popular tactic of buzzing before it is sure of its response.[12] Watson has consistently better reaction time on the buzzer once it has generated a response, and is immune to human players' psychological tactics, such as jumping between categories on every clue.[12][28]

In a sequence of 20 mock games of *Jeopardy*, human participants were able to use the average six to seven seconds that Watson needed to hear the clue and decide whether to signal for responding.[12] During that time, Watson also has to evaluate the response and determine whether it is sufficiently confident in the result to signal.[12] Part of the system used to win the *Jeopardy!* contest was the electronic circuitry that receives the "ready" signal and then examined whether Watson's confidence level was great enough to activate the buzzer. Given the speed of this circuitry compared to the speed of human reaction times, Watson's reaction time was faster than the human contestants except when the human anticipated (instead of reacted to) the ready signal.[29] After signaling, Watson speaks with an electronic voice and gives the responses in *Jeopardy!*'s question format.[12] Watson's voice was synthesized from recordings that actor Jeff Woodman made for an IBM text-to-speech program in 2004.[30]

The *Jeopardy!* staff used different means to notify Watson and the human players when to buzz,[29] which was critical in many rounds.[28] The humans were notified by a light, which took them tenths of a second to perceive.[31][32] Watson was notified by an electronic signal and could activate the buzzer within about eight

milliseconds.[33] The humans tried to compensate for the perception delay by anticipating the light,[34] but the variation in the anticipation time was generally too great to fall within Watson's response time.[28] Watson did not attempt to anticipate the notification signal.[32][34]

13.3 History

13.3.1 Development

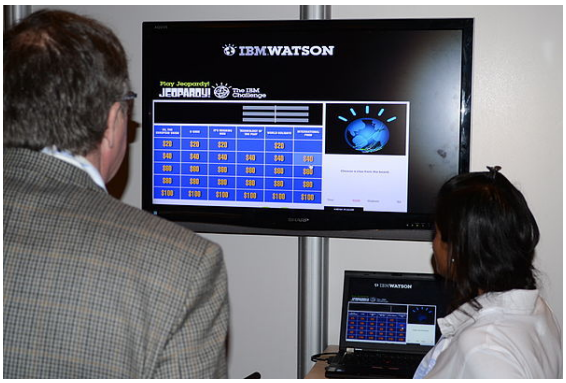
Since Deep Blue's victory over Garry Kasparov in chess in 1997, IBM had been on the hunt for a new challenge. In 2004, IBM Research manager Charles Lickel, over dinner with coworkers, noticed that the restaurant they were in had fallen silent. He soon discovered the cause of this evening hiatus: Ken Jennings, who was then in the middle of his successful 74-game run on *Jeopardy!*. Nearly the entire restaurant had piled toward the televisions, mid-meal, to watch the phenomenon. Intrigued by the quiz show as a possible challenge for IBM, Lickel passed the idea on, and in 2005, IBM Research executive Paul Horn backed Lickel up, pushing for someone in his department to take up the challenge of playing *Jeopardy!* with an IBM system. Though he initially had trouble finding any research staff willing to take on what looked to be a much more complex challenge than the wordless game of chess, eventually David Ferrucci took him up on the offer.[35] In competitions managed by the United States government, Watson's predecessor, a system named Piquant, was usually able to respond correctly to only about 35% of clues and often required several minutes to respond.[36][37][38] To compete successfully on *Jeopardy!*, Watson would need to respond in no more than a few seconds, and at that time, the problems posed by the game show were deemed to be impossible to solve.[12]

In initial tests run during 2006 by David Ferrucci, the senior manager of IBM's Semantic Analysis and Integration department, Watson was given 500 clues from past *Jeopardy!* programs. While the best real-life competitors buzzed in half the time and responded correctly to as many as 95% of clues, Watson's first pass could get only about 15% correct. During 2007, the IBM team was given three to five years and a staff of 15 people to solve the problems.[12] By 2008, the developers had advanced Watson such that it could compete with *Jeopardy!* champions.[12] By February 2010, Watson could beat human *Jeopardy!* contestants on a regular basis.[39]

Although the system is primarily an IBM effort, Watson's development involved faculty and graduate students from Rensselaer Polytechnic Institute, Carnegie Mellon University, University of Massachusetts Amherst, the University of Southern California's Information Sciences Institute, the University of Texas at Austin, the Massachusetts Institute of Technology, and the University of Trento,[15] as well as students from New York Medical College.[40]

13.3.2 *Jeopardy!*

Preparation



Watson demo at an IBM booth at a trade show

In 2008, IBM representatives communicated with *Jeopardy!* executive producer Harry Friedman about the possibility of having Watson compete against Ken Jennings and Brad Rutter, two of the most successful contestants on the show, and the program's producers agreed.[12][41] Watson's differences with human players had generated conflicts between IBM and *Jeopardy!* staff during the planning of the competition.[27] IBM repeatedly expressed concerns that the show's writers would exploit Watson's cognitive deficiencies when writing the clues, thereby turning the game into a Turing test. To alleviate that claim, a third party randomly picked the clues from previously written shows that were never broadcast.[27] *Jeopardy!* staff also showed concerns over Watson's reaction time on the buzzer. Originally Watson signaled electronically, but show staff requested that it press a button physically, as the human contestants would.[42] Even with a robotic "finger" pressing the buzzer, Watson remained faster than its human competitors. Ken Jennings noted, "If you're trying to win on the show, the buzzer is all", and that Watson "can knock out a microsecond-precise buzz every single time with little or no variation. Human reflexes can't compete with computer circuits in this regard."[28][34][43] Stephen Baker, a journalist who recorded Watson's development in his book *Final Jeopardy*, reported that the conflict between IBM and *Jeopardy!* became so serious in May 2010 that the competition was almost canceled.[27] As part of the preparation, IBM constructed a mock set in a conference room at one of its technology sites to model the one used on *Jeopardy!*. Human players, including former *Jeopardy!* contestants, also participated in mock games against Watson with Todd Alan Crain of *The Onion* playing host.[12] About 100 test matches were conducted with Watson winning 65% of the games.[44]

To provide a physical presence in the televised games, Watson was represented by an "avatar" of a globe, inspired by the IBM "smarter planet" symbol. Jennings described the computer's avatar as a "glowing blue ball

criss-crossed by 'threads' of thought—42 threads, to be precise",[25] and stated that the number of thought threads in the avatar was an in-joke referencing the significance of the number 42 in Douglas Adams' *Hitchhiker's Guide to the Galaxy*.[25] Joshua Davis, the artist who designed the avatar for the project, explained to Stephen Baker that there are 36 triggerable states that Watson was able to use throughout the game to show its confidence in responding to a clue correctly; he had hoped to be able to find forty-two, to add another level to the *Hitchhiker's Guide* reference, but he was unable to pinpoint enough game states.[45]

A practice match was recorded on January 13, 2011, and the official matches were recorded on January 14, 2011. All participants maintained secrecy about the outcome until the match was broadcast in February.[46]

Practice match

In a practice match before the press on January 13, 2011, Watson won a 15-question round against Ken Jennings and Brad Rutter with a score of $4,400 to Jennings's $3,400 and Rutter's $1,200, though Jennings and Watson were tied before the final $1,000 question. None of the three players responded incorrectly to a clue.[47]

First match

The first round was broadcast February 14, 2011, and the second round, on February 15, 2011. The right to choose the first category had been determined by a draw won by Rutter.[48] Watson, represented by a computer monitor display and artificial voice, responded correctly to the second clue and then selected the fourth clue of the first category, a deliberate strategy to find the Daily Double as quickly as possible.[49] Watson's guess at the Daily Double location was correct. At the end of the first round, Watson was tied with Rutter at $5,000; Jennings had $2,000.[48]

Watson's performance was characterized by some quirks. In one instance, Watson repeated a reworded version of an incorrect response offered by Jennings. (Jennings said "What are the '20s?" in reference to the 1920s. Then Watson said "What is 1920s?") Because Watson could not recognize other contestants' responses, it did not know that Jennings had already given the same response. In another instance, Watson was initially given credit for a response of "What is leg?" after Jennings incorrectly responded "What is: he only had one hand?" to a clue about George Eyser (the correct response was, "What is: he's missing a leg?"). Because Watson, unlike a human, could not have been responding to Jennings's mistake, it was decided that this response was incorrect. The broadcast version of the episode was edited to omit Trebek's original acceptance of Watson's response.[50] Watson also demonstrated complex wagering strategies on the Daily Doubles, with one bet at $6,435 and another at $1,246.[51] Gerald Tesauro, one of the IBM researchers who worked on Watson, explained that Watson's wagers were based on its confidence level for the category and a complex regression model called the Game State Evaluator.[52]

Watson took a commanding lead in Double Jeopardy!, correctly responding to both Daily Doubles. Watson responded to the second Daily Double correctly with a 32% confidence score.[51]

Although it wagered only $947 on the clue, Watson was the only contestant to miss the Final Jeopardy! response in the category U.S. CITIES ("Its largest airport was named for a World War II hero; its second largest, for a World War II battle"). Rutter and Jennings gave the correct response of Chicago, but Watson's response was "What is Toronto?????"[51][53][54] Ferrucci offered reasons why Watson would appear to have guessed a Canadian city: categories only weakly suggest the type of response desired, the phrase "U.S. city" did not appear in the question, there are cities named Toronto in the U.S., and Toronto in Ontario has an American League baseball team.[55] Dr. Chris Welty, who also worked on Watson, suggested that it may not have been able to correctly parse the second part of the clue, "its second largest, for a World War II battle" (which was not a standalone clause despite it following a semicolon, and required context to understand that it was referring to a second-largest *airport*).[56] Eric Nyberg, a professor at Carnegie Mellon University and a member of the development team, stated that the error occurred because Watson does not possess the comparative knowledge to discard that potential response as not viable.[54] Although not displayed to the audience as with non-Final Jeopardy! questions, Watson's second choice was Chicago. Both Toronto and Chicago were well below Watson's confidence threshold, at 14% and 11% respectively. (This lack of confidence was the reason for the multiple question marks in Watson's response.)

The game ended with Jennings with $4,800, Rutter with $10,400, and Watson with $35,734.[51]

Second match

During the introduction, Trebek (a Canadian native) joked that he had learned Toronto was a U.S. city, and Watson's error in the first match prompted an IBM engineer to wear a Toronto Blue Jays jacket to the recording of the second match.[57]

In the first round, Jennings was finally able to choose a Daily Double clue,[58] while Watson responded to one Daily Double clue incorrectly for the first time in the Double Jeopardy! Round.[59] After the first round, Watson placed second for the first time in the competition after Rutter and Jennings were briefly successful in increasing their dollar values before Watson could respond.[59][60] Nonetheless, the final result ended with a victory for Wat-

son with a score of $77,147, besting Jennings who scored $24,000 and Rutter who scored $21,600.[61]

Final outcome

The prizes for the competition were $1 million for first place (Watson), $300,000 for second place (Jennings), and $200,000 for third place (Rutter). As promised, IBM donated 100% of Watson's winnings to charity, with 50% of those winnings going to World Vision and 50% going to World Community Grid.[62] Similarly, Jennings and Rutter donated 50% of their winnings to their respective charities.[63]

In acknowledgment of IBM and Watson's achievements, Jennings made an additional remark in his Final Jeopardy! response: "I for one welcome our new computer overlords", echoing a similar memetic reference to the episode "Deep Space Homer" on *The Simpsons*, in which TV news presenter Kent Brockman speaks of welcoming "our new insect overlords".[64][65] Jennings later wrote an article for *Slate*, in which he stated

> IBM has bragged to the media that Watson's question-answering skills are good for more than annoying Alex Trebek. The company sees a future in which fields like medical diagnosis, business analytics, and tech support are automated by question-answering software like Watson. Just as factory jobs were eliminated in the 20th century by new assembly-line robots, Brad and I were the first knowledge-industry workers put out of work by the new generation of 'thinking' machines. 'Quiz show contestant' may be the first job made redundant by Watson, but I'm sure it won't be the last.[25]

Philosophy

Philosopher John Searle argues that Watson—despite impressive capabilities—cannot actually think.[66] Drawing on his Chinese room thought experiment, Searle claims that Watson, like other computational machines, is capable only of manipulating symbols, but has no ability to understand the meaning of those symbols; however, Searle's experiment has its detractors.[67]

Match against members of the United States Congress

On February 28, 2011, Watson played an untelevised exhibition match of *Jeopardy!* against members of the United States House of Representatives. In the first round, Rush D. Holt, Jr. (D-NJ, a former *Jeopardy!* contestant), who was challenging the computer with Bill Cassidy (R-LA, later Senator from Louisiana), led with Watson in second place. However, combining the scores between all matches, the final score was $40,300 for Watson and $30,000 for the congressional players combined.[68]

IBM's Christopher Padilla said of the match, "The technology behind Watson represents a major advancement in computing. In the data-intensive environment of government, this type of technology can help organizations make better decisions and improve how government helps its citizens."[68]

13.4 Current and future applications

According to IBM, "The goal is to have computers start to interact in natural human terms across a range of applications and processes, understanding the questions that humans ask and providing answers that humans can understand and justify."[39] It has been suggested by Robert C. Weber, IBM's general counsel, that Watson may be used for legal research.[69] The company also intends to use Watson in other information-intensive fields, such as telecommunications, financial services, and government.[70]

Watson is based on commercially available IBM Power 750 servers that have been marketed since February 2010. IBM also intends to market the DeepQA software to large corporations, with a price in the millions of dollars, reflecting the $1 million needed to acquire a server that meets the minimum system requirement to operate Watson. IBM expects the price to decrease substantially within a decade as the technology improves.[12]

Commentator Rick Merritt said that "there's another really important reason why it is strategic for IBM to be seen very broadly by the American public as a company that can tackle tough computer problems. A big slice of [IBM's profit] comes from selling to the U.S. government some of the biggest, most expensive systems in the world."[71]

In 2013, it was reported that three companies were working with IBM to create apps embedded with Watson technology. Fluid is developing an app for retailers, one called "The North Face", which is designed to provide advice to online shoppers. Welltok is developing an app designed to give people advice on ways to engage in activities to improve their health. MD Buyline is developing an app for the purpose of advising medical institutions on equipment procurement decisions.[72][73]

In November 2013, IBM announced it would make Watson's API available to software application providers, enabling them to build apps and services that are embedded with Watson's capabilities. To build out its base of partners who create applications on the Watson platform, IBM consults with a network of venture capital firms, which advise IBM on which of their portfolio companies may be a logical fit for what IBM calls the Watson Ecosys-

tem. Thus far, roughly 800 organizations and individuals have signed up with IBM, with interest in creating applications that could use the Watson platform.[74]

On January 30, 2013, it was announced that Rensselaer Polytechnic Institute would receive a successor version of Watson, which would be housed at the Institute's technology park and be available to researchers and students.[75] By summer 2013, Rensselaer had become the first university to receive a Watson computer.[76]

On February 6, 2014, it was reported that IBM plans to invest $100 million in a 10-year initiative to use Watson and other IBM technologies to help countries in Africa address development problems, beginning with healthcare and education.[77]

On June 3, 2014, three new Watson Ecosystem partners were chosen from more than 400 business concepts submitted by teams spanning 18 industries from 43 countries. "These bright and enterprising organizations have discovered innovative ways to apply Watson that can deliver demonstrable business benefits", said Steve Gold, vice president, IBM Watson Group. The winners were Majestyk Apps with their adaptive educational platform, FANG (Friendly Anthropomorphic Networked Genome);[78][79] Red Ant with their retail sales trainer;[80] and GenieMD[81] with their medical recommendation service.[82]

On July 9, 2014, Genesys Telecommunications Laboratories announced plans to integrate Watson to improve their customer experience platform, citing the sheer volume of customer data to analyze is staggering.[83]

Watson has been integrated with databases including *Bon Appétit* magazine to perform a recipe generating platform.[84]

Watson is being used by Decibel, a music discovery startup, in its app MusicGeek which uses the supercomputer to provide music recommendations to its users. The use of the artificial intelligence of Watson has also been found in hospitality industry. GoMoment uses Watson for its Rev1 app, which gives hotel staff a way to quickly respond to questions from guests.[85] Arria NLG has built an app that helps energy companies stay within regulatory guidelines, making it easier for managers to make sense of thousands of pages of legal and technical jargon.

OmniEarth, Inc. uses Watson computer vision services to analyze satellite and aerial imagery, along with other municipal data, to infer water usage on a property-by-property basis, helping water districts in drought-stricken California improve water conservation efforts.[86]

In September 2016, Condé Nast has started using IBM's Watson to help build and strategize social influencer campaigns for brands. Using software built by IBM and Influential, Condé Nast's clients will be able to know which influencer's demographics, personality traits and more best align with a marketer and the audience it is targeting.[87]

13.4.1 Healthcare

In healthcare, Watson's natural language, hypothesis generation, and evidence-based learning capabilities are being investigated to see how Watson may contribute to clinical decision support systems for use by medical professionals.[88] To aid physicians in the treatment of their patients, once a physician has posed a query to the system describing symptoms and other related factors, Watson first parses the input to identify the most important pieces of information; then mines patient data to find facts relevant to the patient's medical and hereditary history; then examines available data sources to form and test hypotheses;[88] and finally provides a list of individualized, confidence-scored recommendations.[89] The sources of data that Watson uses for analysis can include treatment guidelines, electronic medical record data, notes from physicians and nurses, research materials, clinical studies, journal articles, and patient information.[88] Despite being developed and marketed as a "diagnosis and treatment advisor", Watson has never been actually involved in the medical diagnosis process, only in assisting with identifying treatment options for patients who have already been diagnosed.[90]

In February 2011, it was announced that IBM would be partnering with Nuance Communications for a research project to develop a commercial product during the next 18 to 24 months, designed to exploit Watson's clinical decision support capabilities. Physicians at Columbia University would help to identify critical issues in the practice of medicine where the system's technology may be able to contribute, and physicians at the University of Maryland would work to identify the best way that a technology like Watson could interact with medical practitioners to provide the maximum assistance.[91]

In September 2011, IBM and WellPoint announced a partnership to utilize Watson's data crunching capability to help suggest treatment options to physicians.[92] Then, in February 2013, IBM and WellPoint gave Watson its first commercial application, for utilization management decisions in lung cancer treatment at Memorial Sloan–Kettering Cancer Center.[13]

IBM announced a partnership with Cleveland Clinic in October 2012. The company has sent Watson to the Cleveland Clinic Lerner College of Medicine of Case Western Reserve University, where it will increase its health expertise and assist medical professionals in treating patients. The medical facility will utilize Watson's ability to store and process large quantities of information to help speed up and increase the accuracy of the treatment process. "Cleveland Clinic's collaboration with IBM is exciting because it offers us the opportunity to teach Watson to 'think' in ways that have the potential to make it a powerful tool in medicine", said C. Martin Harris, MD, chief information officer of Cleveland Clinic.[93]

In 2013, IBM and MD Anderson Cancer Center began

a pilot program to further the center's "mission to eradicate cancer".[94][95] However, after spending $62 million, the project did not meet its goals and it has been put on hold.[96]

On February 8, 2013, IBM announced that oncologists at the Maine Center for Cancer Medicine and Westmed Medical Group in New York have started to test the Watson supercomputer system in an effort to recommend treatment for lung cancer.[97]

On July 29, 2016, IBM and Manipal Hospitals[98][99][100](a leading hospital chain in India), announced launch of IBM Watson for Oncology, for cancer patients. This product provides information and insights to physicians and cancer patients to help them identify personalized, evidence-based cancer care options. Manipal Hospitals is the second hospital[101] in the world to adopt this technology and first in the world to offer it to patients online as an expert second opinion through their website.[98][102]

On January 7, 2017, IBM and Fukoku Mutual Life Insurance entered into a contract for IBM to deliver analysis to compensation payouts via its IBM Watson Explorer AI, this resulted in the loss of 34 jobs and the company said it would speed up compensation payout analysis via analysing claims and medical record and increase productivity by 30%. The company also said it would save ¥140m in running costs.[103]

13.4.2 IBM Watson Group

On January 9, 2014 IBM announced it was creating a business unit around Watson, led by senior vice president Michael Rhodin.[104] IBM Watson Group will have headquarters in New York's Silicon Alley and will employ 2,000 people. IBM has invested $1 billion to get the division going. Watson Group will develop three new cloud-delivered services: Watson Discovery Advisor, Watson Engagement Advisor, and Watson Explorer. Watson Discovery Advisor will focus on research and development projects in pharmaceutical industry, publishing, and biotechnology, Watson Engagement Advisor will focus on self-service applications using insights on the basis of natural language questions posed by business users, and Watson Explorer will focus on helping enterprise users uncover and share data-driven insights based on federated search more easily.[104] The company is also launching a $100 million venture fund to spur application development for "cognitive" applications. According to IBM, the cloud-delivered enterprise-ready Watson has seen its speed increase 24 times over—a 2,300 percent improvement in performance, and its physical size shrank by 90 percent—from the size of a master bedroom to three stacked pizza boxes.[104] IBM CEO Virginia Rometty said she wants Watson to generate $10 billion in annual revenue within ten years.[105]

13.4.3 Chatterbot

Watson is being used via IBM partner program as a Chatterbot to provide the conversation for children's toys.[106]

13.4.4 Teaching Assistant

Ashok Goel, professor at Georgia Tech, used Watson to create a virtual Teaching Assistant to assist students in his class.[107] Initially, Goel did not reveal the nature of "Jill", which was created with the help of a few students and IBM. Jill answered questions where it had a 97% certainty of an accurate answer, with the remainder being answered by human assistants.

The research group of Sabri Pllana developed an assistant for learning parallel programming using the IBM Watson [108]. A survey with a number of novice parallel programmers at the Linnaeus University indicated that such assistant will be welcome by students that learn parallel programming.

13.4.5 Weather forecasting

In August 2016, IBM announced it would be using Watson for weather forecasting.[109] Specifically, the company announced they would use Watson to analyze data from over 200,000 Weather Underground personal weather stations, and data from other sources, as a part of project Deep Thunder.[110]

13.4.6 Tax Preparation

On February 5–6, 2017, tax preparation company H&R Block will begin nationwide use of a Watson-based program to enhance their client experience.[111]

13.5 See also

- Blue Gene
- Commonsense knowledge (artificial intelligence)
- Strong AI
- Tech companies in the New York metropolitan area
- Wolfram Alpha

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- DeepQA homepage
- About Watson on Jeopardy.com
- Smartest Machine on Earth (PBS NOVA documentary about the making of Watson)
- Power Systems
- The Watson Trivia Challenge. *The New York Times*. June 16, 2010.
- This is Watson - IBM Journal of Research and Development (published by the IEEE)

13.8.1 J! Archive

- *Jeopardy!* Show #6086 - Game 1, Part 1
- *Jeopardy!* Show #6087 - Game 1, Part 2
- *Jeopardy!* Show #6088 - Game 2

13.8.2 Videos

- PBS NOVA documentary on the making of Watson
- Building Watson – A Brief Overview of the DeepQA Project on YouTube (21:42), IBMLabs
- How Watson Answers a Question on YouTube
- David Ferrucci, Dan Cerutti and Ken Jennings on IBM's Watson at Singularity Summit 2011 on YouTube
- A Computer Called Watson on YouTube - November 15, 2011, David Ferrucci at Computer History Museum, alternate
- IBM Watson and the Future of Healthcare on YouTube - 2012

- IBM Watson-Introduction and Future Applications on YouTube - IBM at EDGE 2012
- IBM Watson for Healthcare on YouTube - Martin Kohn, 2013
- Jeopardy! IBM Watson day 3 (2011). Retrieved July 26, 2012 on YouTube
- IBM Watson playlist, IBMLabs Watson playlist

Chapter 14

AlphaGo

AlphaGo logo

AlphaGo is a narrow AI, computer program developed by Alphabet Inc.'s Google DeepMind in London to play the board game Go.[1] In October 2015, it became the first Computer Go program to beat a human professional Go player without handicaps on a full-sized 19×19 board.[2][3] In March 2016, it beat Lee Sedol in a five-game match, the first time a computer Go program has beaten a 9-dan professional without handicaps.[4] Although it lost to Lee Sedol in the fourth game, Lee resigned the final game, giving a final score of 4 games to 1 in favour of AlphaGo. In recognition of beating Lee Sedol, AlphaGo was awarded an honorary 9-dan by the Korea Baduk Association. It was chosen by *Science* as one of the Breakthrough of the Year runners-up on 22 December 2016.[5]

AlphaGo's algorithm uses a Monte Carlo tree search to find its moves based on knowledge previously "learned" by machine learning, specifically by an artificial neural network (a deep learning method) by extensive training, both from human and computer play.

14.1 History and competitions

Go is considered much more difficult for computers to win than other games such as chess, because its much larger branching factor makes it prohibitively difficult to use traditional AI methods such as alpha–beta pruning, tree traversal and heuristic search.[2][6]

Almost two decades after IBM's computer Deep Blue beat world chess champion Garry Kasparov in the 1997 match, the strongest Go programs using artificial intelligence techniques only reached about amateur 5-dan level,[7] and still could not beat a professional Go player without handicaps.[2][3][8] In 2012, the software program Zen, running on a four PC cluster, beat Masaki Takemiya (9p) two times at five and four stones handicap.[9] In 2013, Crazy Stone beat Yoshio Ishida (9p) at four-stones handicap.[10]

According to AlphaGo's David Silver, the AlphaGo research project was formed around 2014 to test how well a neural network using deep learning can compete at Go.[11] AlphaGo represents a significant improvement over previous Go programs. In 500 games against other available Go programs, including Crazy Stone and Zen,[12] AlphaGo running on a single computer won all but one.[13] In a similar matchup, AlphaGo running on multiple computers won all 500 games played against other Go programs, and 77% of games played against AlphaGo running on a single computer. The distributed version in October 2015 was using 1,202 CPUs and 176 GPUs.[7]

14.1.1 Match against Fan Hui

In October 2015, the distributed version of AlphaGo defeated the European Go champion Fan Hui,[14] a 2-dan (out of 9 dan possible) professional, five to zero.[3][15] This was the first time a computer Go program had beaten a professional human player on a full-sized board without handicap.[16] The announcement of the news was delayed until 27 January 2016 to coincide with the publication of a paper in the journal *Nature*[7] describing the algorithms used.[3]

14.1.2 Match against Lee Sedol

Main article: AlphaGo versus Lee Sedol

AlphaGo played South Korean professional Go player Lee Sedol, ranked 9-dan, one of the best players at Go,[8] with five games taking place at the Four Seasons Hotel in Seoul, South Korea on 9, 10, 12, 13, and 15 March 2016,[17][18] which were video-streamed live.[19] Aja Huang, a DeepMind team member and amateur 6-dan Go player, placed stones on the Go board for AlphaGo, which ran through Google's cloud computing with its servers located in the United States.[20] The match used Chinese rules with a 7.5-point komi, and each side

had two hours of thinking time plus three 60-second byoyomi periods.[21] The version of AlphaGo playing against Lee used a similar amount of computing power as was used in the Fan Hui match.[22] The Economist reported that it used 1,920 CPUs and 280 GPUs.[23]

At the time of play, Lee Sedol had the second-highest number of Go international championship victories in the world.[24] While there is no single official method of ranking in international Go, some sources ranked Lee Sedol as the fourth-best player in the world at the time.[25][26] AlphaGo was not specifically trained to face Lee.[27]

The first three games were won by AlphaGo following resignations by Lee Sedol.[28][29] However, Lee Sedol beat AlphaGo in the fourth game, winning by resignation at move 180. AlphaGo then continued to achieve a fourth win, winning the fifth game by resignation.[30]

The prize was $1 million USD. Since AlphaGo won four out of five and thus the series, the prize will be donated to charities, including UNICEF.[31] Lee Sedol received $150,000 for participating in all five games and an additional $20,000 for his win.[21]

On June 29th, at a presentation held at a University in the Netherlands, Aja Huang, one of the Deep Mind team, revealed that it had rectified the problem that occurred during the 4th game of the match between AlphaGo and Lee Sedol, and that after move 78 (which was dubbed the "hand of God" by many professionals), it would play accurately and maintain Black's advantage, since before the error which resulted in the loss, AlphaGo was leading throughout the game and Lee's move was not credited as the one which won the game, but caused the program's computing powers to be diverted and confused. Aja Huang explained that AlphaGo's policy network of finding the most accurate move order and continuation did not precisely guide AlphaGo to make the correct continuation after move 78, since its value network did not determine Lee Sedol's 78th move as being the most likely, and therefore when the move was made AlphaGo could not make the right adjustment to the logical continuation.[32]

14.1.3 Unofficial online matches in late 2016 to early 2017

On December 29 in 2016, a new account named "Magist" from South Korea began to play games with professional players on the Tygem server. It changed its account name to "Master" on 30 December, then moved to the FoxGo server on 1 January 2017. On 4 January, DeepMind confirmed that the "Magister" and the "Master" were both played by an updated version of AlphaGo.[33][34] As of 5 January 5 2017, AlphaGo's online record was 60 wins and 0 losses,[35] including three victories over Go's top ranked player, Ke Jie,[36] who had been quietly briefed in advance that Master was a version of AlphaGo.[35] After losing to Master, Gu Li offered a bounty of 100,000 yuan (14,400 USD) to the first human player who could defeat Master.[34] Master played at the pace of 10 games per day. Many quickly suspected it to be an AI player due to little or no resting between games. Its adversaries included many world champions such as Ke Jie, Park Jeong-hwan, Yuta Iyama, Tuo Jiaxi, Mi Yuting, Shi Yue, Chen Yaoye, Li Qincheng, Gu Li, Chang Hao, Tang Weixing, Fan Tingyu, Zhou Ruiyang, Jiang Weijie, Chou Chun-hsun, Kim Ji-seok, Kang Dong-yun, Park Yeong-hun, and Won Seong-jin; national champions or world championship runners-up such as Lian Xiao, Tan Xiao, Meng Tailing, Dang Yifei, Huang Yunsong, Yang Dingxin, Gu Zihao, Shin Jinseo, Cho Han-seung, and An Sungjoon. All 60 games except one were fast paced games with three 20 or 30 seconds byo-yomi. Master offered to extend the byo-yomi to one minute when playing with Nie Weiping due to his old age. After winning its 59th game Master revealed itself in the chatroom to be controlled by Dr. Aja Huang of the DeepMind team,[37] then changed its nationality to United Kingdom. After these games were completed, the co-founder of Google DeepMind, Demis Hassabis said in a tweet "we're looking forward to playing some official, full-length games later [2017] in collaboration with Go organizations and experts".[33][34]

Human players tend to make more mistakes in fast paced online games than in full-length tournament games due to short response time. It isn't definitively known whether AlphaGo will succeed as well in tournaments as it has online.[34] However, Go experts are extremely impressed by AlphaGo's performance and by its nonhuman play style; Ke Jie stated that "After humanity spent thousands of years improving our tactics, computers tell us that humans are completely wrong... I would go as far as to say not a single human has touched the edge of the truth of Go."[35]

14.1.4 Wuzhen Future of Go Summit

Main article: Future of Go Summit

In late May 2017, AlphaGo will play several exhibition games in Wuzhen, including:[38]

- A best of 3 match versus world number 1, Ke Jie
- AlphaGo versus a collaborating team of top Chinese professionals
- Pair Go: human plus AlphaGo versus human plus AlphaGo

14.2 Hardware

An early version of AlphaGo was tested on hardware with various numbers of CPUs and GPUs, running in asynchronous or distributed mode. Two seconds of thinking

time was given to each move. The resulting Elo ratings are listed below.[7] In the matches with more time per move higher ratings are achieved.

In May 2016, Google unveiled its own proprietary hardware "tensor processing units", which it stated had already been deployed in multiple internal projects at Google, including the AlphaGo match against Lee Sedol.[39][40]

14.3 Algorithm

As of 2016, AlphaGo's algorithm uses a combination of machine learning and tree search techniques, combined with extensive training, both from human and computer play. It uses Monte Carlo tree search, guided by a "value network" and a "policy network," both implemented using deep neural network technology.[2][7] A limited amount of game-specific feature detection preprocessing (for example, to highlight whether a move matches a nakade pattern) is applied to the input before it is sent to the neural networks.[7]

The system's neural networks were initially bootstrapped from human gameplay expertise. AlphaGo was initially trained to mimic human play by attempting to match the moves of expert players from recorded historical games, using a database of around 30 million moves.[14] Once it had reached a certain degree of proficiency, it was trained further by being set to play large numbers of games against other instances of itself, using reinforcement learning to improve its play.[2] To avoid "disrespectfully" wasting its opponent's time, the program is specifically programmed to resign if its assessment of win probability falls beneath a certain threshold; for the March 2016 match against Lee, the resignation threshold was set to 20%.[41]

14.4 Style of play

Toby Manning, the match referee for AlphaGo vs. Fan Hui, has described the program's style as "conservative".[42] AlphaGo's playstyle strongly favours greater probability of winning by fewer points over lesser probability of winning by more points.[11] Its strategy of maximising its probability of winning is distinct from what human players tend to do which is to maximise territorial gains, and explains some of its odd-looking moves.[43]

14.5 Responses to 2016 victory against Lee Sedol

14.5.1 AI community

AlphaGo's March 2016 victory was a major milestone in artificial intelligence research.[44] Go had previously been regarded as a hard problem in machine learning that was expected to be out of reach for the technology of the time.[44][45][46] Most experts thought a Go program as powerful as AlphaGo was at least five years away;[47] some experts thought that it would take at least another decade before computers would beat Go champions.[7][48][49] Most observers at the beginning of the 2016 matches expected Lee to beat AlphaGo.[44]

With games such as checkers (that has been "solved" by the Chinook draughts player team), chess, and now Go won by computers, victories at popular board games can no longer serve as major milestones for artificial intelligence in the way that they used to. Deep Blue's Murray Campbell called AlphaGo's victory "the end of an era... board games are more or less done and it's time to move on."[44]

When compared with Deep Blue or with Watson, AlphaGo's underlying algorithms are potentially more general-purpose, and may be evidence that the scientific community is making progress towards artificial general intelligence.[11][50] Some commentators believe AlphaGo's victory makes for a good opportunity for society to start discussing preparations for the possible future impact of machines with general purpose intelligence. (As noted by entrepreneur Guy Suter, AlphaGo itself only knows how to play Go, and doesn't possess general purpose intelligence: "[It] couldn't just wake up one morning and decide it wants to learn how to use firearms"[44]) In March 2016, AI researcher Stuart Russell stated that "AI methods are progressing much faster than expected, (which) makes the question of the long-term outcome more urgent," adding that "in order to ensure that increasingly powerful AI systems remain completely under human control... there is a lot of work to do."[51] Some scholars, such as Stephen Hawking, warned (in May 2015 before the matches) that some future self-improving AI could gain actual general intelligence, leading to an unexpected AI takeover; other scholars disagree: AI expert Jean-Gabriel Ganascia believes that "Things like 'common sense'... may never be reproducible",[52] and says "I don't see why we would speak about fears. On the contrary, this raises hopes in many domains such as health and space exploration."[51] Computer scientist Richard Sutton "I don't think people should be scared... but I do think people should be paying attention."[53]

14.5.2 Go community

Go is a popular game in China, Japan and Korea, and the 2016 matches were watched by perhaps a hundred million people worldwide.[44][54] Many top Go players characterized AlphaGo's unorthodox plays as seemingly-questionable moves that initially befuddled onlookers, but

made sense in hindsight:[48] "All but the very best Go players craft their style by imitating top players. AlphaGo seems to have totally original moves it creates itself."[44] AlphaGo appeared to have unexpectedly become much stronger, even when compared with its October 2015 match[55] where a computer had beat a Go professional for the first time ever without the advantage of a handicap.[56] The day after Lee's first defeat, Jeong Ahram, the lead Go correspondent for one of South Korea's biggest daily newspapers, said "Last night was very gloomy... Many people drank alcohol."[57] The Korea Baduk Association, the organization that oversees Go professionals in South Korea, awarded AlphaGo an honorary 9-dan title for exhibiting creative skills and pushing forward the game's progress.[58]

China's Ke Jie, an 18-year-old generally recognized as the world's best Go player,[25][59] initially claimed that he would be able to beat AlphaGo, but declined to play against it for fear that it would "copy my style".[59] As the matches progressed, Ke Jie went back and forth, stating that "it is highly likely that I (could) lose" after analysing the first three matches,[60] but regaining confidence after AlphaGo displayed flaws in the fourth match.[61]

Toby Manning, the referee of AlphaGo's match against Fan Hui, and Hajin Lee, secretary general of the International Go Federation, both reason that in the future, Go players will get help from computers to learn what they have done wrong in games and improve their skills.[56]

After game two, Lee said he felt "speechless": "From the very beginning of the match, I could never manage an upper hand for one single move. It was AlphaGo's total victory."[62] Lee apologized for his losses, stating after game three that "I misjudged the capabilities of AlphaGo and felt powerless."[44] He emphasized that the defeat was "Lee Se-dol's defeat" and "not a defeat of mankind".[27][52] Lee said his eventual loss to a machine was "inevitable" but stated that "robots will never understand the beauty of the game the same way that we humans do."[52] Lee called his game four victory a "priceless win that I (would) not exchange for anything."[27]

14.6 Similar systems

Facebook has also been working on their own Go-playing system *darkforest*, also based on combining machine learning and tree search.[42][63] Although a strong player against other computer Go programs, as of early 2016, it had not yet defeated a professional human player.[64] darkforest has lost to CrazyStone and Zen and is estimated to be of similar strength to CrazyStone and Zen.[65]

DeepZenGo, a system developed with support from video-sharing website Dwango and the University of Tokyo, lost 2-1 in November 2016 to Go master Cho Chikun, who holds the record for the largest number of Go title wins in Japan.[66][67]

14.7 Example game

AlphaGo (white) v. Tang Weixing (31 December 2016), AlphaGo won by resignation. White 36 was widely praised.

14.8 See also

- AlphaGo versus Lee Sedol
- Glossary of artificial intelligence
- Go and mathematics
- Deep Blue (chess computer)
- Chinook (draughts player), draughts playing program
- TD-Gammon, backgammon neural network

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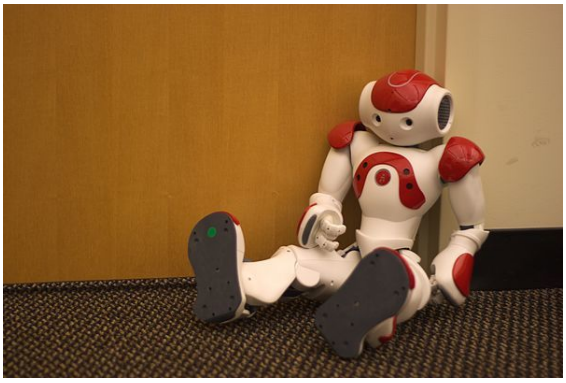
14.10 External links

- Official website
- AlphaGo wiki at Sensei's Library, including links to AlphaGo games

Chapter 15

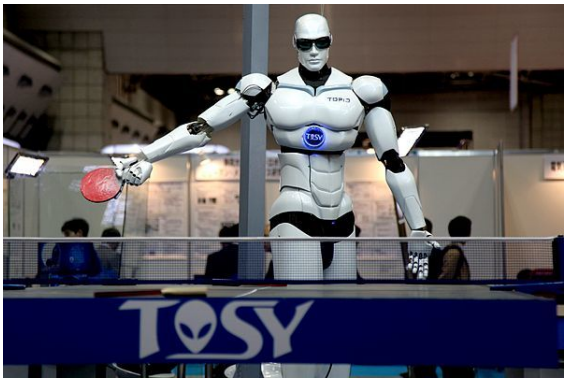
Humanoid robot

A **humanoid robot** is a robot with its body shape built to resemble the human body. The design may be for functional purposes, such as interacting with human tools and environments, for experimental purposes, such as the study of bipedal locomotion, or for other purposes. In general, humanoid robots have a torso, a head, two arms, and two legs, though some forms of humanoid robots may model only part of the body, for example, from the waist up. Some humanoid robots also have heads designed to replicate human facial features such as eyes and mouths. Androids are humanoid robots built to aesthetically resemble humans.



Nao is a robot created for companionship. It also competes in the RoboCup soccer championship.

15.1 Purpose



TOPIO, a humanoid robot, played ping pong at Tokyo International Robot Exhibition (IREX) 2009.[1][2]

Enon was created to be a personal assistant. It is self-guiding and has limited speech recognition and synthesis. It can also carry things.

Humanoid robots are now used as a research tool in several scientific areas.

Researchers need to understand the human body structure and behavior (biomechanics) to build and study humanoid robots. On the other side, the attempt to the simulation of the human body leads to a better understanding of it. Human cognition is a field of study which is focused on how humans learn from sensory information in order to acquire perceptual and motor skills. This knowledge is used to develop computational models of human behavior and it has been improving over time.

It has been suggested that very advanced robotics will

facilitate the enhancement of ordinary humans. See transhumanism.

Although the initial aim of humanoid research was to build better orthosis and prosthesis for human beings, knowledge has been transferred between both disciplines. A few examples are: powered leg prosthesis for neuromuscularly impaired, ankle-foot orthosis, biological realistic leg prosthesis and forearm prosthesis.

Besides the research, humanoid robots are being developed to perform human tasks like personal assistance, where they should be able to assist the sick and elderly, and dirty or dangerous jobs. Regular jobs like being a receptionist or a worker of an automotive manufacturing line are also suitable for humanoids. In essence, since they can use tools and operate equipment and vehicles designed for the human form, humanoids could theoretically perform any task a human being can, so long as they have the proper software. However, the complexity of doing so is immense.

They are becoming increasingly popular for providing entertainment too. For example, Ursula, a female robot, sings, play music, dances, and speaks to her audiences at Universal Studios. Several Disney attractions employ the use of animatrons, robots that look, move, and speak much like human beings, in some of their theme park shows. These animatrons look so realistic that it can be hard to decipher from a distance whether or not they are actually human. Although they have a realistic look, they have no cognition or physical autonomy. Various humanoid robots and their possible applications in daily life are featured in an independent documentary film called *Plug & Pray*, which was released in 2010.

Humanoid robots, especially with artificial intelligence algorithms, could be useful for future dangerous and/or distant space exploration missions, without having the need to turn back around again and return to Earth once the mission is completed.

15.2 Sensors

A sensor is a device that measures some attribute of the world. Being one of the three primitives of robotics (besides planning and control), sensing plays an important role in robotic paradigms.

Sensors can be classified according to the physical process with which they work or according to the type of measurement information that they give as output. In this case, the second approach was used.

15.2.1 Proprioceptive sensors

Proprioceptive sensors sense the position, the orientation and the speed of the humanoid's body and joints.

In human beings the otoliths and semi-circular canals (in the inner ear) are used to maintain balance and orientation. In addition humans use their own proprioceptive sensors (e.g. touch, muscle extension, limb position) to help with their orientation._ Humanoid robots use accelerometers to measure the acceleration, from which velocity can be calculated by integration; tilt sensors to measure inclination; force sensors placed in robot's hands and feet to measure contact force with environment; position sensors, that indicate the actual position of the robot (from which the velocity can be calculated by derivation) or even speed sensors.

15.2.2 Exteroceptive sensors

An artificial hand holding a lightbulb

Arrays of tactels can be used to provide data on what has been touched. The Shadow Hand uses an array of 34 tactels arranged beneath its polyurethane skin on each finger tip.[3] Tactile sensors also provide information about forces and torques transferred between the robot and other objects.

Vision refers to processing data from any modality which uses the electromagnetic spectrum to produce an image.

In humanoid robots it is used to recognize objects and determine their properties. Vision sensors work most similarly to the eyes of human beings. Most humanoid robots use CCD cameras as vision sensors.

Sound sensors allow humanoid robots to hear speech and environmental sounds, and perform as the ears of the human being. Microphones are usually used for this task.

15.3 Actuators

Actuators are the motors responsible for motion in the robot.

Humanoid robots are constructed in such a way that they mimic the human body, so they use actuators that perform like muscles and joints, though with a different structure. To achieve the same effect as human motion, humanoid robots use mainly rotary actuators. They can be either electric, pneumatic, hydraulic, piezoelectric or ultrasonic.

Hydraulic and electric actuators have a very rigid behavior and can only be made to act in a compliant manner through the use of relatively complex feedback control strategies. While electric coreless motor actuators are better suited for high speed and low load applications, hydraulic ones operate well at low speed and high load applications.

Piezoelectric actuators generate a small movement with a high force capability when voltage is applied. They can be used for ultra-precise positioning and for generating and handling high forces or pressures in static or dynamic situations.

Ultrasonic actuators are designed to produce movements in a micrometer order at ultrasonic frequencies (over 20 kHz). They are useful for controlling vibration, positioning applications and quick switching.

Pneumatic actuators operate on the basis of gas compressibility. As they are inflated, they expand along the axis, and as they deflate, they contract. If one end is fixed, the other will move in a linear trajectory. These actuators are intended for low speed and low/medium load applications. Between pneumatic actuators there are: cylinders, bellows, pneumatic engines, pneumatic stepper motors and pneumatic artificial muscles.

15.4 Planning and control

In planning and control, the essential difference between humanoids and other kinds of robots (like industrial ones) is that the movement of the robot has to be human-like, using legged locomotion, especially biped gait. The ideal planning for humanoid movements during normal walking should result in minimum energy consumption, as it does in the human body. For this reason, studies on dynamics and control of these kinds of structures become more and more important.

The question of walking biped robots stabilization on the surface is of great importance. Maintenance of the robot's gravity center over the center of bearing area for providing a stable position can be chosen as a goal of control.[4]

To maintain dynamic balance during the walk, a robot needs information about contact force and its current and desired motion. The solution to this problem relies on a major concept, the Zero Moment Point (ZMP).

Another characteristic of humanoid robots is that they move, gather information (using sensors) on the "real world" and interact with it. They don't stay still like factory manipulators and other robots that work in highly structured environments. To allow humanoids to move in complex environments, planning and control must focus on self-collision detection, path planning and obstacle avoidance.

Humanoids do not yet have some features of the human body. They include structures with variable flexibility, which provide safety (to the robot itself and to the people), and redundancy of movements, i.e. more degrees of freedom and therefore wide task availability. Although these characteristics are desirable to humanoid robots, they will bring more complexity and new problems to planning and control. The field of whole-body control deals with these issues and addresses the proper coordination of numerous degrees of freedom, e.g. to realize several control tasks simultaneously while following a given order of priority.[5]

15.5 Timeline of developments

15.6 See also

Template:Working of robots

15.7 Notes

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15.10 External links

- Humanoid Robots' jobs in Japan
- Ulrich Hottelet: Albert is not happy - How robots learn to live with people, African Times, June 2009

15.11 Text and image sources, contributors, and licenses

15.11.1 Text

- **Fourth Industrial Revolution** *Source:* https://en.wikipedia.org/wiki/Fourth_Industrial_Revolution?oldid=770763390 *Contributors:* PRehse, Lostintealand, ONUnicorn, LeeColleton, Qwfp, MatthewVanitas, Yobot, AnomieBOT, BobKilcoyne, Diannaa, BG19bot, Killer Moff, Mikeh101, Fixuture, Mecorbin08 and Marknoa

- **Artificial intelligence** *Source:* https://en.wikipedia.org/wiki/Artificial_intelligence?oldid=776335115 *Contributors:* AxelBoldt, TwoOneTwo, The Cunctator, Derek Ross, WojPob, Sodium, Lee Daniel Crocker, Brion VIBBER, Mav, Bryan Derksen, Robert Merkel, Zundark, The Anome, Koyaanis Qatsi, Taw, RK, Andre Engels, Poiman, Arvindn, Toby Bartels, Dlloader~enwiki, MadSurgeon, M~enwiki, Little guru, ChangChienFu, Axon, Ellmist, Imran, Heron, Ryguasu, Mintguy, Netesq, KF, Tzartzam, Olivier, Chuq, Stevertigo, Hfastedge, Frecklefoot, Edward, AdSR, D, JohnOwens, Michael Hardy, EvanProdromou, Oliver Pereira, Lexor, David Martland, Nixdorf, Liftarn, Gabbe, Bobby D. 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Spencer, DHN-bot~enwiki, Darth Panda, WikiPedant, Zsinj, Pegua, Can't sleep, clown will eat me, Erayman64, Onorem, MJBurrage, JonHarder, EvelinaB, Nunocordeiro, RedHillian, Edivorce, Normxxx, Memming, Edans, COMPFUNK2, Freek Verkerk, PrometheusX303, Jaibe, Shadow1, Richard001, Taggart Transcontinental, NapoleonB, Freemarket, Kleuske, Lacatosias, StephenReed, Jon Awbrey, Metamagician3000, Salamurai, LeoNomis, Curly Turkey, Ck lostsword, Pilotguy, Kukini, Ohconfucius, Dankonikolic, William conway bcc, Nishkid64, Baby16, Harryboyles, Titus III, John, Jonrgrover, AmiDaniel, Geoinline, Yan Kuligin, Madhukaleeckal, Tazmaniacs, Gobonobo, Disavian, NewTestLeper79, ChaoticLogic, Chessmaniac, Goodnightmush, IronGargoyle, Ripe, Mr. Vernon, A. Parrot, Newkidd11, Special-T, WMod-NS, Owlbuster, Mr Stephen, Dicklyon, Emurph, Daphne A, Dee Jay Randall, Wega14, AdultSwim, Condem, Glen Pepicelli, Zapvet, Digsdirt, Nabeth, Peyre, Caiaffa, Andreworkney, Hu12, Burto88, Levineps, Vespine, Yodin, Clarityfiend, Sierkejd, Joseph Solis in Australia, Ralf Klinkenberg, Snoutholder, Igoldste, Rnb, Wfructose, Marysunshine, Dream land2080, Tawkerbot2, Dlohcierekim, Chris55, GerryWolff, Eastlaw, Myncknm, 8754865, Rahuldharmani, CRGreathouse, CmdrObot, Eggman64, Wafulz, Makeemlighter, Discordant~enwiki, Mudd1, Ruslik0, El aprendelenguas, ShelfSkewed, Pgr94, MeekMark, Casper2k3, Fordmadoxfraud, Myasuda, Livingston7, Abdullahazzam, Gregbard, Shanoman, Cydebot, AndyPardoe, Peripitus, Abeg92, Besieged, Beta Trom, Peterdjones, Kaldosh, Gogo Dodo, Corpx, Ivant, Rzwitserloot, JamesLucas, Julian Mendez, Josephorourke, LaserBeams, WikiNing, Robertinventor, Bubba2323, Bryan Seecrets, Bitsmart, Gimmetrow, PamD, Michael Fourman, Thijs!bot, Epbr123, Biruitorul, Mercury~enwiki, ConceptExp, Daniel, Hervegirod, Sagaciousuk, N5iln, Mojo Hand, Atamyrat~enwiki, Headbomb, Marek69, Zzthex, GTof~enwiki, Mailseth, I already forgot, David D., Mschures, Mac-steele, AntiVandalBot, Tabortiger, Luna Santin, Seaphoto, Opelio, Prolog, 17Drew, Nosirrom, Mary Mark Ockerbloom, Jj137, Ykalyan, TurntableX, Science History, Theropod-X, Lfstevens, Spinningobo, Myanw, Steelpillow, MikeLynch, JAnDbot, Jimothytrotter, MattBan, MTuffield, Barek, Sarnholm, MER-C, CosineKitty, Mrsolutions, Schlegel, The Transhumanist, Davespice, 100110100,

Greensburger, TAnthony, .anacondabot, Acroterion, Wasell, Coffee2theorems, Magioladitis, Bongwarrior, VoABot II, Cobratom, Farquaadhnchmn, Gammy, Redaktor, Tedickey, Johannes Simon, Tremilux, Rootxploit, Cic, Crunchy Numbers, Nposs, BatteryIncluded, Robotman1974, ArthurWeasley, Johnkoza1992, Jroudh, Allstarecho, Adamreiswig, Wookiee cheese, Joydurgin, Siddharthsk2000, Dane, Talon Artaine, DerHexer, Tommy Herbert, TheRanger, Drm310, Francob, MartinBot, IanElmore, Bradgib, ARCG, Naohiro19, Rettetast, Bissinger, Drewmutt, Keith D, Mschel, Kostisl, CommonsDelinker, Amareshjoshi, KTo288, Lilac Soul, LedgendGamer, Mausy5043, Shellwood, Pacas, J.delanoy, JuniorMonkey, Trusilver, Anandcv, Gustavo1255, Richiekim, Jiuguang Wang, Uncle Dick, Theo Mark, Yonidebot, Benscripps, Laurusnobilis, Jkaplan, Dispenser, Eric Mathews Technology, DarkGhost08, Ignatzmice, Touisiau, Tdewey, Pogowitwiz, Mikael Häggström, Ypetrachenko, Tarotcards, Topazxx, ColinClark, AntiSpamBot, Zubenelgenubi, Tobias Kuhn, 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Blackshadow153, Viskonsas, WBTtheFROG, Yintan, Soler97, Grundle2600, Purbo T, DavidBourguignon, Yungjibbz, Mr.Z-bot, Toddst1, Wadeduck, Flyer22 Reborn, Darth Chyrsaor, Jojalozzo, Taemyr, Arthur Smart, Oxymoron83, Ioverka, Scorpion451, Ddxc, Harry-, MiNombreDeGuerra, Steven Crossin, Lightmouse, Yankee-Bravo, Xobritbabeox10, RyanParis, Svick, Smallclone2, Firefly4342, CharlesGillingham, Macduffman, Wyckster, Voices cray, Searchmaven, Cheesefondue, Neo., Denisarona, Finetooth, Emptymountains, ImageRemovalBot, Hpdl, Elassint, ClueBot, Fribbler, Rumping, Prohlep, Avenged Eightfold, The Thing That Should Not Be, Logperson, Ezavarei, Ndenison, Unbuttered Parsnip, Willingandable, Grantbow, Drmies, VQuakr, Mild Bill Hiccup, Malignedtruth, Boing! said Zebedee, Mayfly may fly, Niceguyedc, Nappy1020, Arne Heise, Neverquick, Thomas Kist, Yakota21, Pooya.babahajyani, Time for action, Jdzarlino, Excirial, Gnome de plume, Hezarfenn, Vivio Testarossa, Thunderhippo, Nayanraut, Xklsv, NuclearWarfare, Arjayay, Jotterbot, Iohannes Animosus, Sebaldusadam, Renamed user 3, Mr.Sisgay, Mullhawk, Chaosdruid, Aitias, EPIC MASTER, Ranjithsutari, Scalhotrod, Qwfp, Johnuniq, HumphreyW, Apparition11, Sparkygravity, MasterOfHisOwnDomain, Escientist, XLinkBot, AgnosticPreachersKid, Basploeger, Sgunteratparamus.k12.nj.us, Spitfire, Pichpich, Alex naish, Rror, Ost316, Libcub, Dheer7c, Noctibus, Jhorthos, Thede, Truthnlove, D.M. from Ukraine, Addbot, Barsoomian, DOI bot, Guoguo12, Kimveale, Betterusername, Ashish krazzy, Coolcatfish, AndrewHZ, DougsTech, Elsendero, TutterMouse, CanadianLinuxUser, Leszek Jańczuk, Fluffernutter, Damiens.rf, Me pras, Sebastian scha., Looie496, MrOllie, Aykantspel, LaaknorBot, Nuclear Treason, The world deserves the truth, Glane23, Neonorange, AndersBot, Favonian, Kyle1278, LinkFA-Bot, Rbalcke, AgadaUrbanit, Tassedethe, Brianjfox, Jan eissfeldt, Ricvelozo, Jarble, KarenEdda, Ben Ben, Luckas-bot, PetroKonashevich, Yobot, Worldbruce, Themfromspace, Ptbotgourou, Fraggle81, 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Mschuldt, Atultherajput, Glacialfox, Peter Baum, Devonmann101, Avery.mabojie, Wannabemodel, Maarten Rail, BattyBot, StarryGrandma, Simbara, Yeedle, E prosser, Varagrawal, Cyberbot II, Ideafarmcity, Brookeweiner, Fireboy3015, Psych2012Joordens, Marktindal, IjonTichyIjonTichy, RichardKPSun, Dexbot, FoCuSandLeArN, Oritnk, Pintoch, Acrognale, Vincenzo1492, Lugia2453, Sly1993, Mark Bao, Iskand26, SFK2, Dineshhi, Yassu66, Henrifrischborno, Chaoren Lin, Zziccardi, Me, Myself, and I are Here, Reatlas, Samee, Joeinwiki, Phamnhatkhanh, Faizan, ChassonR, Epicgenius, Newtesteditor, Allaroundtheworld123, TheFrog001, Amandapan1, Snatoon, Michipedian, Melonkelon, Kingfaj, Silas Ropac, Weightlessjapan1337, Spacepub, Vbrm, Satassi, Jiayuliu, Tentinator, Rosenblumb1, Kogmaw, Syntaxerrorz, Msundqvist, EvergreenFir, Shrikarsan, Master of Time, Mamadoutadioukone, Chris troutman, Laper1900, Rolf h nelson, Gaurang2904, Riddhi-gupta, Babitaarora, Megerler, IWishIHadALife, Orion dude, Mrm7171, MarinMersenne, ????, Aniruddhmanishpatel, Mandruss, Ginsuloft, Mintiematt, Aubreybardo, Kind Tennis Fan, Francois-Pier, FockeWulf FW 190, EmmaLiverpool, Healybd, Bojo1498, Cows12345, Zourcilleux, Fixuture, TimoHonkelaEnglish, Mellon2030, Lakun.patra, Balaji4894, 7Sidz, FelixRosch, Wyn.junior, JacwanaKL, ????, Lovkal, 22merlin, MadScientistX11, Yoshi24517, Rim sim, Hnchinmaya, Georgopa, Monkbot, Patient Zero, Lucyloo10, SantiLak, Jfishel, TheQ Editor, Kinetic37, YdJ, T lanuza, BioMeow, Ozdigennaro, Madan Pokharel, Deonikar, Pbravo2, Dodynamic, Evolutionvisions, Wstevens2090, Zeus000000, TranquilHope, KH-1, Charmingpianist, ChamithN, Feynman1918, Shrestha sumit, Yoon Aris, Crystallizedcarbon, Dorianluparu, Junbibi, Pythagoros, SpRu01, Comp-heur-intel, Praneshyadav1, ???, Kethrus, Kmp302, NotTheFakeJTP, Govindaharihari, Zabshk, ScrapIronIV, KayleighwilliamsLS, Iazyges, Easeit7, Devsaw, Zortwort, Illiteration, Spectrum629, CV9933, Miguelsnchz723, Newwikieditor678, KenTancwell, Demdim0, Amccann421, Eobasanya, KasparBot, Pianophage, Csisawesome, Pmaiden, Συντάκτης Βικιλεξικό, Ray engh 302, Tiger7890, Vahagn125, My Chemistry romantic, Skyshines, Andyjin2002, Aviartm, CAPTAIN RAJU, Babymissfortune, ProgrammingGeek, Chhana Tlau, AndyTheDurb,

FiendYT, Sanket Edits Wiki, CLCStudent, Rhinopuss, Mdtrotter, Kksouvik007, Hddty., Simplexity22, Fd1193, DatGuy, Ameotf, Qzd, InfoPurist, Shade1400, AdWomanMan, InternetArchiveBot, Buffer king, Entranced98, Aeylyeaelle, Ayylmaoayylmao123456, Mythili Murugan, Account creation error11,422,951, 23brinslow, Estay14, 9066subham, Mathpriest, Cammymac15, GreenC bot, AbduallahYousafzai, Austinmyleslee, Aaaaaaaaaarrrfff, Longisquama, Robot psychiatrist, D412TH V4D312, Fmadd, Frugal fisherman, Tariq al sama, RunnyAmiga, Communitarian703, JKRLife, Bear-rings, Jmcgnh, Motivação, Hacker Mr Common Sense, Findtime, GamerCat2016, Hyksandra, Legohero111111, Turkofusion, Bender the Bot, Raul negrete, L3X1, Trevornessel, Charvey1597, Kimjeo42, Ozogjess, Aios3837, Drycroft4, Seohub, Selichm, Johnmaini, Iadmc, DanielSmallwood, JueLinLi, Jamie Grant, FriyMan, Laurdecl, Eddy Tor, Sunnychiuka, Dmdaleva, Lolwasson, Helloiambob27, Natialexx, Tylerbishopezoic, Kannanfire, Codonologist, Perpnation, Uy87t76tyutyutuygiuyt, Devin Ledoux, DavidRemigioReis, Akkaneror, Imjustheretohelp, Tankst, Luz.imprezi, GoPats and Anonymous: 1805

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Garcia, Iot coi, Fixuture, DPY81, Kevalsingh, Wyn.junior, Rotunda2013, Wbakeriii, Tazi Mehdi, Yoshi24517, RicardoCuevasGarcia, Lagoset, Posicks, Wikideas1, Gramamoo, Monkbot, Stefenev, Mikedeanklein, Jechma, Hooobron, Sofia Koutsouveli, Acrypter, Sightestrp, Busybi, KaiserKIS, JezGrove, Avidwriterforever, Elgrancid, Nataliard, Mr.freely, Chwagen, NMI-John-Moor, Scienceteacher6410, Drudgeart, Ccofrnzl, Thetechgirl, Oiyarbepsy, Sarasedgewick, Dgund, Xorain, Scoutsoutrecon, Gkort23, Vidyasnap, Cosimomalesci, NotJim99, OdinS Rafael, Mdaliakhtar, Casjonker, Edavinmccoy, Nikhil.sharma2301, Joe00961, Gonzalo.massa, Dwheedon, Fellmark, Wendyavis, TLCNET14, SoSivr, Mehdi.moh, Sanjeev.rawat86, Mtiber, HelpUsStopSpam, Calippoy, Androslaxbos, Jordan.Manser, Liiqi1991, KasparBot, Anaalpoel, MusikBot, Kuzu bhai 2015, HakanIST, Gooser, Jinco, Quackriot, Srednuas Lenoroc, Esthan, Boanuge, NarayanaMoorthy01, LGB2015, Tushar 10, InternetGuru, Ciudadania Digital, CAPTAIN RAJU, Christophe3d, Peppy Paneer, Singh.shivsantosh, Muzithebunny, Majora, Wirelessiot, Marissabell, Robvank, Goutham reddy konduru, U L T R O N97, Utkarshagarwal39, Rpk2014, Flamingo 666, Xelkman, Manojbcs, Yigal59, ElizaLepine, Ishan2708, GerryAsher, Pinchast, DatGuy, Harys32, Suro16, Entranced98, Mclarkk, Farooq-i-Azam, Davidworking2016, Jayleeshanghai, Ppv999, Chillatulit, Navin kumar jha, Christie.Oliver, Bytesock, Dpaul34, Adam1brownell, Kuhnbnhob, Dudesrvgone, Tani.oliver, Katienguyen2016, Isxnuur, Smarty39, Rakesh800, Statliner, Hiteshiot, Future hindrix, JannahTepace, Neeraj08, Hyksandra, Fan3ezie, NotnotaBeacon, Emir of Wikipedia, LorenSorenson, Shaulzo, Bender the Bot, SallyEgan, Burne16, Mehuljain19, Acelesti, JohnHowes, Mecorbin08, Nick1234509876, Lahiru Seneviratne, Abdulsamiayoubi, Justeditingtoday, Enriko Sebastiano, Yellow Diamond, Elenafell, Nikolaylechev, Elizkerimova, Srikanth9700, Ophé8291, Theyoungeditor123, Newpassages145, EE Researcher, IoTian, Scenesdream, Μπάμπης Κανδής, Linuxeros, Abdullah003, Andreas manolis, DashaMaks, Prity c and Anonymous: 472
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Tollsjo, Jtmac24, Dac28, Omnipaedista, Mmm72392, Big balls man 1, Treflipit23, Wet dog fur, Amaury, Doulos Christos, Sumankumardutta, Mgjdelgr, Green Cardamom, Zhenjun hu, Llypde, Bambuway, Citation bot 1, Ntse, Saul Greenberg, I dream of horses, Tom.Reding, Calmer Waters, Serols, Haramire, Olly1988, Dac04, Brightonr, Gamewizard71, Tanzz, Twistor96, Trappist the monk, Lotje, Vipinrajd, Peeweeherman22, Tushar858, Adonovan0, Amkilpatrick, The cuhjnts jot., Diannaa, Fireyair, TrevorRW83, Reach Out to the Truth, TimKasoar, Keegscee, DARTH SIDIOUS 2, Fredwrigley, RjwilmsiBot, NameIsRon, Brteag00, LcawteHuggle, John of Reading, Immunize, Supahshadow, Look2See1, Ajraddatz, Razor2988, Minimac's Clone, Solarra, Atavism, Wikipelli, Dcirovic, K6ka, Lucas Thoms, Illegitimate Barrister, Jahub, Mar4d, Everard Proudfoot, Elektrik Shoos, H3llBot, Mcmatter, Tolly4bolly, GeorgeBarnick, Donner60, Rangoon11, NTox, Nofatlandshark, Wcfios, Sven Manguard, 28bot, Rocketrod1960, ClueBot NG, CocuBot, Jamw23, 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Granger, Martarius, Sfan00 IMG, ClueBot, Mariordo, Noveleric, Willingandable, Drmies, Frmorrison, LUUSAP, Excirial, Syslord2k, Rhododendrites, Sun Creator, Arjayay, Gesundheit, Herr Pfeffer, VsevolodKrolikov, Chaosdruid, Chiu.au, Dmm1169, Christian.fritz, XLinkBot, Stickee, Sakura Cartelet, Rollerc24, Duffbeerforme, Wyatt915, Addbot, Paper Luigi, IterisWebmaster, Kongr43gpen, Fgnievinski, Blethering Scot, IRISHwiki15, MrOllie, Tassedethe, Lightbot, Willondon, Jarble, Gnubo, Narayan, Yobot, Timothyhouse1, Synchronism, AnomieBOT, DemocraticLuntz, Archon 2488, Jim1138, Piano non troppo, Materialscientist, Danno uk, Citation bot, Quebec99, LilHelpa, Txrhino, Drilnoth, DataWraith, MakeBelieveMonster, Jsharpminor, The Evil IP address, Durus, DaleDe, Rudimae, GliderMaven, Calimar300, FrescoBot, Fortdj33, Delhi3, Dr.sliderule, Gripper101, Galmicmi, DrilBot, Pinethicket, LittleWink, Jonesey95, MJ94, Ohtavala, Horst-schlaemma, Henrikfagrell, Trappist the monk, Jordgette, Kaplanke, Barry Pearson, Diablanco, Diannaa, Roland Richter, Mean as custard, RjwilmsiBot, Semmendinger, CarSafety, Epdennis, DASHBot, TGCP, John of Reading, Aelbler, Saharawiki, Lucien504, Zollerriia, Nuujinn, Dewritech, Epsiloner, Klbrain, Greenwayfriend, Tommy2010, K6ka, Ickenham 47, H3llBot, Emeuwese, OnePt618, Tolly4bolly, Vwlstud, TyA, Brandmeister, Gsarwa, Donner60, EvenGreenerFish, 1234456556BK, Morgengave, Anthonytordillos, Gerd Kraemer, Targaryen, 28bot, Jhabdas, ClueBot NG, Michaelmas1957, Gareth Griffith-Jones, MelbourneStar, Doug Grinbergs, Quaber, Wisejhyun, Tabletrack, Frietjes, Luca Ghio, Danim, Helpful Pixie Bot, Fainna, Camdoodlebop, Festermunk, BG19bot, Virtualerian, Mohamed CJ, Pacerier, Tekvie, John Yannis, SodaAnt, 612.354.oxy8, 220 of Borg, Comfr, Samwalton9, BattyBot, Cyberbot II, ChrisGualtieri, Jules Brunet, Arcandam, Khazar2, Cwobeel, Z11o22, Mogism, 331dot, MWright96, Win0922, Alyosha kzov, GSonia, Merxistan, Epicgenius, Chessrat, AndiDC, CsDix, Distelfinck, Jamesmcmahon0, Petemclaren, Jodosma, JamesMoose, Tentinator, Everymorning, Richardbishop, Johnjegan, Jenloe, Ashnap, Mpho1, DavidLeighEllis, ArmbrustBot, Dtruong87, Koza1983, Jwratner1, Bussakendle, YiFeiBot, PatrickHoefler, Krishna006, InAndOutLand, Conversar, Annesowolff, Stamptrader, Joosqo1, Habarithor, Fixuture, Ufranke, ???, Anyrandomperson12345, Pat power11, Lagoset, Monkbot, JRElings, Appirion, Epiphanize101, PaperWario, Shultz the Editor, Duncan C Colman, Huge Efner, CerealKillerYum, NQ, Seen a Mike, Pcdevries, KH-1, Greshthegreat, Ryanhoyingho, TJH2018, Jaidude00, Deepiceman, EoRdE6, ThePenultimateOne, Dokhue, Dtran16, Wheeler2014, Kixean777, Bronze2018, Absolutelypuremilk, Inyouchuu shoku, Jimmy2X, SouthBundy, Timothyjosephwood, Automan84, Etadesse, Fritz3721, Suddha Swattwa Chaudhuri, Btechf, Acbraughlerauthor, Frasercl, Saddiqueimran, CAPTAIN RAJU, Pranay anumula, Qeef, Pithy Francoln, UpsandDowns1234, Rezarch1, CLCStudent, Baboubably, Dorianinou, Mfarukh, Segundo A P, Curro2, Peashooter666, Artcrimes80, TrumpTrump, Chillatulit, Cookiemonster022, Fmadd, Shajeeh-ul-Hassan, Calvalvz1, BeefBurgur, Abbottsford, 1618033golden, Dopyslide123, Indatawetrust, Seba5tien, Bender the Bot, Timot2016, Skar3000, ArticlesMe, Rob (Wiki Ed), Evolution101, Russes1, Michaelrubino27, Mrcdivaio, T`swift`rocks and Anonymous: 471

- **Watson (computer)** *Source:* https://en.wikipedia.org/wiki/Watson_(computer)?oldid=775246295 *Contributors:* William Avery, Kku, Ixfd64, Dcljr, Julesd, Bevo, Denelson83, Dimadick, Ke4roh, Postdlf, Rfc1394, Rhombus, Timrollpickering, Graeme Bartlett, Peruvianllama, Jason Quinn, Edcolins, Grassferry49, Paulscrawl, Szcz, Urhixidur, Robin klein, Klemen Kocjancic, Thorwald, Vsmith, Bender235, Mind the gap, Bobo192, Viriditas, Alansohn, Gary, Diego Moya, Hoary, Mailer diablo, Melaen, Dismas, Falcorian, Richard Arthur Norton (1958-), Mindmatrix, Robert K S, Bkwillwm, Waldir, John Hubbard, Mandarax, Jan.bannister, Ashmoo, Graham87, BD2412, Qwertyus, Drbogdan, Nightscream, Koavf, Rogerd, Mfwills, OneWeirdDude, Nneonneo, Bubba73, AySz88, Jpom, Joedeshon, DVdm, Bgwhite, Aussie Evil, RussBot, Arado, Bhny, Anomalocaris, Darker Dreams, Nick, Corevette, Tim Parenti, CWenger, Back ache, ViperSnake151, Finell, SmackBot, McGeddon, Yamaguchi??, Gilliam, Master Jay, Shaggorama, Hankejh, Emufarmers, RayAYang, Toughpigs, Cybercobra, Chris3145, Dreadstar, Andrew c, The PIPE, Soap, Khazar, JoshuaZ, Minna Sora no Shita, The Man in Question, Stwalkerster, Sinistrum, Jonbsails, Noleander, Ahhwhereami, SubSeven, PaulGS, Theflyer, Chickenmonkey, Nomader, The Letter J, Chris55, Patrickwooldridge, Godgundam10, J Milburn, Raysonho, Addict 2006, Jim101, Xose.vazquez, Pgr94, Krauss, Reywas92, Ipsingh, Gogo Dodo, Myscrnnm, Daniel J. Leivick, DumbBOT, Teratornis, Wikid77, N5iln, Marek69, Dawkeye, Dawnseeker2000, Quiddlet, Fru1tbat, Normanmargolus, ThomasO1989, Gavia immer, Nyttend, Seleucus, Lilac Soul, J.delanoy, Edgeweyes, Jesant13, Tdadamemd, DarkFalls, McSly, Mikael Häggström, Tarinth, NewEnglandYankee, 83d40m, Olegwiki, Larryisgood, Saraleerd, Ddbruce, Oshwah, Sroc, Jenseits~enwiki, Anonymous Dissident, Thrawn562, IronMaidenRocks, Jackfork, Raryel, Weetjesman, Falcon8765, Vchimpanzee, Logan, MattW93, Rontrigger, Tomalak geretkal, Ivan Štambuk, Roesser, Grundle2600, Arthur Smart, Doctorfluffy, Airhogs777, Sbaker8380, AlanUS, CharlesGillingham, ImageRemovalBot, Martarius, Freebullets, UKoch, Piledhigheranddeeper, Takeaway, Jusdafax, Tarijanel, Eustress, LobStoR, Lx 121, XLinkBot, Ost316, MystBot, Addbot, M.nelson, Rich jj, Fluffernutter, Drbobpgh, Redsoxfan1, LaaknorBot, TySoltaur, Chzz, Jasper Deng, Gnubo, Luckas-bot, Yobot, Amirobot, AnomieBOT, Unicyclehusby, Tucoxn, Materialscientist, Rabimba, Xqbot, Smallman12q, Tktru, LucienBOT, Hosszuka, Pokyrek, DivineAlpha, Apexwm, Pinethicket, Abductive, The.megapode, Hoo man, Serols, Jandalhandler, Beao, Kgrad, FoxBot, ConcernedVancouverite, Vrenator, Mean as custard, RjwilmsiBot, J36miles, Whywhenwhohow, EmausBot, WikitanvirBot, Gfoley4, Angrytoast, Dewritech, GoingBatty, 19maxx, Curlydudermb, ZéroBot, Prayerfortheworld, Chire, Medeis, Sir Nils, PJCT, OnePt618, Lokpest, Demiurge1000, SuaveDan, MainFrame, ChuispastonBot, Ihardlythinkso, Matthewrbowker, Hoverflyz, 0wendy33, Xanchester, ClueBot NG, Michaelmas1957, Jolio81, Samwell Pinkus, Onyx321, Brainnews, Liseavery, Snotbot, TheExtraEditor, A wild Rattata, SethAllen623, Cheng, Geekman314, Enfcer, Ilikeducktape, Castncoot, Semerick, Erikbird, Gonfaloniere,

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- **AlphaGo** *Source:* https://en.wikipedia.org/wiki/AlphaGo?oldid=775993964 *Contributors:* The Anome, Nealmcb, William M. Connolley, Evercat, Charles Matthews, Thue, Betterworld, Blainster, Giftlite, Beland, Mike Rosoft, R6144, Bender235, SnowFire, Diego Moya, LearnMore, Lightkey, Runtime, GregorB, Nanami Kamimura, Leeyc0, Bubba73, Tone, Katpatuka, Paul Magnussen, Johndburger, Crandles, Mysterius, Slashme, Clpo13, Skizzik, Marc Kupper, Neo-Jay, George Ho, Ladislav Mecir, Bwarne, Jtm71, Vasiliy Faronov, Valoem, JRSpriggs, Banedon, Mudd1, MaxEnt, DumbBOT, Narayanese, Tewapack, Janviermichelle, Yellowdesk, JamesBWatson, A3nm, Alexei Kopylov, Maproom, Doub, Oshwah, Jobu0101, Natg 19, Thanatos666, Hzh, SethT, Tsarnick, Another Believer, Tayste, Download, Yobot, AnomieBOT, Tino, Jolly Janner, Trafford09, Nagualdesign, Merlin G., Zetifree, Phoenix7777, Kdmjf12000, Rafalq, Tbhotch, Koppapa, Tuankiet65, Primefac, Dcirovic, Aeonx, Draconicfire, Tipanverella, Brandmeister, Widr, Arg342, Sn1per, Corn cheese, Cirolchou, Rolf h nelson, Comp.arch, Dough34, Fixuture, Sebbe D, WillemienH, DBW99, The Average Wikipedian, JrRong, Aogaeru4, Perl coder, Danny81299, Tralala0, Srednuas Lenoroc, Theoriginalandrewia, M-Tails-P, Zamaster4536, EtherealGate, Jeje1991, Joshualouie711, Yanksmarks, ArguMentor, Eltoder, Emotionalllama, JJBers, Swaggydxd, Treenogh, Unknownmen2000, Avast Security Internet, Whazzzup421, TheCoverUp, R0N HER0, Tekodian, Fmadd, Hyksandra, Bender the Bot, NPalgan2, Acopyeditor, Apollo The Logician, JerryCheng21 and Anonymous: 88

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