past 4.5 billion years would be due to and contained within this modest carapace. For example, the limited dynamic range of mercurian topography, detailed in Zuber *et al.*, may stem from the lack of a deep mantle and deep-mantle processes.

But there's more. The moment of inertia of the outer solid layer is also high, giving an average density near $3650\ \mathrm{kg\ m^{-3}}$ for the layer, appreciably higher than that of Earth's upper mantle (about $3400\ \mathrm{kg\ m^{-3}}$). This is all the more remarkable given the paucity of iron and titanium in Mercury's surface volcanic rocks (*13*, *14*) [rocks whose elemental compositions have at long last been revealed by MESSENGER's x-ray spectrometer (*14*), now that the Sun has become active again]. Low-iron volcanic rocks imply low-iron, and thus low-density, mantle source rocks, making it very difficult to explain the overall high density. Smith *et al.* appeal to experimental results on highly chemically reduced metallic melts (*15*) and the compositions of the highly reduced enstatite chondrite meteorite clan (*10*, *11*). Cooling sulfide liquid, if sufficiently sulfur-rich, may not freeze out an inner core of solid iron (as thought to be occurring on Earth), but may plate out a layer of less dense iron sulfide to the base of the rock mantle (see the figure). The thickness of this "anticrust" may rival or exceed that of the traditional surface crust (lower-density rocks) (*4*).

Smith *et al.* rightly point out that such a basal sulfide layer, if real, could profoundly affect the external expression of Mercury's magnetic field. It may also have important (if subtle) geological and geophysical effects, especially if it is of nonuniform thickness (which might be generated by impact basin formation or mantle convection). Using the topography in Zuber *et al.*, Smith *et al.* apply their gravity data to show that Mercury's surface crust likely thins toward the north pole. Mercury's northern polar region is also low-standing and a site of particularly extensive (but ancient) lava flooding. Although the present outline of the northern polar plains is ragged, such expanses of smooth plains on other planets (Procellarum on the Moon and Borealis on Mars) have inspired speculations of formative mega-impacts. In Mercury's case, and whatever their origin, the low-lying northern plains may now sit close to the geographic pole because of polar wander of Mercury's outer shell (*4*). Planetary scientists will begin to consider how the anticrust might have affected this and other processes. And they will have help—the MESSENGER mission has been extended, and the BepiColombo mission will be launched in a few years.

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COMPUTER SCIENCE

Beyond Turing's Machines

Whether all types of computation—including that of our own minds—can be modeled as computer programs remains an open question.

Andrew Hodges

In marking Alan Turing's centenary, it's worth asking what was his most fundamental achievement and what he left for future science to take up when he took his own life in 1954. His success in World War II, as the chief scientific figure in the British cryptographic effort, with hands-on responsibility for the Atlantic naval conflict, had a great and immediate impact. But in its ever-growing influence since that time, the principle of the universal machine, which Turing published in 1937 (*1*), beats even this.

When, in 1945, he used his wartime technological knowledge to design a first digital computer, it was to make a practical version of that universal machine (*2*). All computing has followed his lead. Defining a universal machine rests on one idea, essential to Turing's mathematical proof in 1936, but quite counter-intuitive, and bearing no resemblance to the large practical calculators of the 1930s. It put logic, not arithmetic, in the driving seat. This central observation is that instructions are themselves a form of data. This vital idea was exploited by Turing immediately in his detailed plan of 1945. The computer he planned would allow instructions to operate on instructions to produce new instructions. The logic of software takes charge of computing. As Turing explained, all known processes could now be encoded, and all could be run on a single machine. The process of encodement could itself be automated and made user-friendly, using any logical language you liked. This approach went far beyond the vision of others at the time.

Even more fundamental than the universal machine is the concept of computability that Turing defined in 1936. His first step was to ask for a precise definition of "mechanical process," and he proceeded by analyzing what it means for someone to follow a rule. In modern terms, "anything that can be done by a computer program" was his answer, with the invention of the computer as a by-product. This leaves open the question of whether such an analysis would include absolutely everything that a material system (including brains) might be able to achieve. Ever since 1936, this nagging question has been on the agenda, and it is still there.

In 1939, Turing suggested that mathematical steps that are not rule-following, and so not computable, could be identified with mental "intuition" (*3*). However, he gave no discussion of whether the human brain was actually embodying uncomputable physical processes. Wartime experience led Turing in a different direction. His brilliant codebreaking algorithms, outdoing human guessing, stimulated the conviction that all mental operations must be computable, including those functions of the mind not apparently following methodical rules. His 1950 paper (*4*), most famous for the wit of the Turing test of intelligence (*5*), also included a careful discussion of computability. It set out a basic argument that if the brain's action is computable, then it can be implemented on a computer, this

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being a universal machine. In defending this point of view, Turing referred to what would now be called chaotic effects in the brain and argued that these did not prevent computer simulation. Notably, at this time Turing was also founding a new branch of mathematical biology: He was applying the insights of an applied mathematician who was also one of the first to use a computer for simulating physical systems.

In 1951, however, Turing gave a radio talk with a different take on this question, suggesting that the nature of quantum mechanics might make simulation of the physical brain impossible. This consideration can be traced back in Turing's thought to 1932, when he first studied the axioms of quantum mechanics [see (*6*)]. Turing then took up renewed interest in quantum theory and noted a problem about the observation of quantum systems (now known as the quantum Zeno effect). With his death, this train of thought was lost, but the serious question of relating computation to fundamental physics has remained.

Since the 1980s, quantum computing has given a practical technological arena in which computation and quantum physics interact excitingly, but it has not yet changed Turing's picture of what is computable. There are also many thought-experiment models that explore what it would mean to go beyond the limits of the computable. Some rather trivially require that machine components could operate with boundless speed or allow unlimited accuracy of measurement. Others probe more deeply into the nature of the physical world. Perhaps the best-known body of ideas is that of Roger Penrose (*7*). These draw strongly on the very thing that motivated Turing's early work—the relationship of mental operations to the physical brain. They imply that uncomputable physics is actually fundamental to physical law and oblige a radical reformulation of quantum mechanics.

Superficially, any such theory contradicts the line that Turing put forward after 1945. But more deeply, anything that brings together the fundamentals of logical and physical description is part of Turing's legacy. He was most unusual in disregarding lines between mathematics, physics, biology, technology, and philosophy. In 1945, it was of immediate practical concern to him that physical media could be found to embody the 0-or-1 logical states needed for the practical construction of a computer. But his work always pointed to the more abstract problem of how those discrete states are embodied in the continuous world. The problem remains: Does computation with discrete symbols give a complete account of the physical world? If it does, how can we make this connection manifest? If it does not, where does computation fail, and what would this tell us about fundamental science?

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COMPUTER SCIENCE

Dusting Off the Turing Test

Robert M. French

Revolutionary advances in data capture, storage, retrieval, and analysis revive questions raised by the Turing test.

Hold up both hands and spread your fingers apart. Now put your palms together and fold your two middle fingers down till the knuckles on both fingers touch each other. While holding this position, one after the other, open and close each pair of opposing fingers by an inch or so. Notice anything? Of course you did. But could a computer without a body and without human experiences ever answer that question or a million others like it? And even if recent revolutionary advances in collecting, storing, retrieving, and analyzing data lead to such a computer, would this machine qualify as "intelligent"?

Just over 60 years ago, Alan Turing published a paper on a simple, operational test for machine intelligence that became one of the most highly cited papers ever written (*1*). Turing, whose 100th birthday is celebrated this year, made seminal contributions to the mathematics of automated computing, helped the Allies win World War II by breaking top-secret German codes, and built a forerunner of the modern computer (*2*). His test, today called the Turing test, was the first operational definition of machine intelligence. It posits putting a computer and a human in separate rooms and connecting them by teletype to an external interrogator, who is free to ask any imaginable questions of either entity. The computer aims to fool the interrogator into believing it is the human; the human must convince the interrogator that he/she is the human. If the interrogator cannot determine which is the real human, the computer will be judged to be intelligent.

In the early days of artificial intelligence (AI), the Turing test was held up by many as the true litmus test for computational intelligence (*3*, *4*). However, workers in AI gradually came to realize that human cognition emerges from a web of explicit, knowledge-based processes and automatic, intuitive, "subcognitive" processes (*5*), the latter deriving largely from humans' direct interaction with the world. It was argued, therefore, that by tapping into this subcognitive substrate—something a disembodied computer did not have—a clever interrogator could unfailingly distinguish a computer from a person (*6*). By 1995, most serious researchers in AI had stopped talking about machines passing Turing's original, teletype-based test (*7*), let alone harder versions involving testing visual, auditory, and object-manipulation abilities (*8*). The Turing

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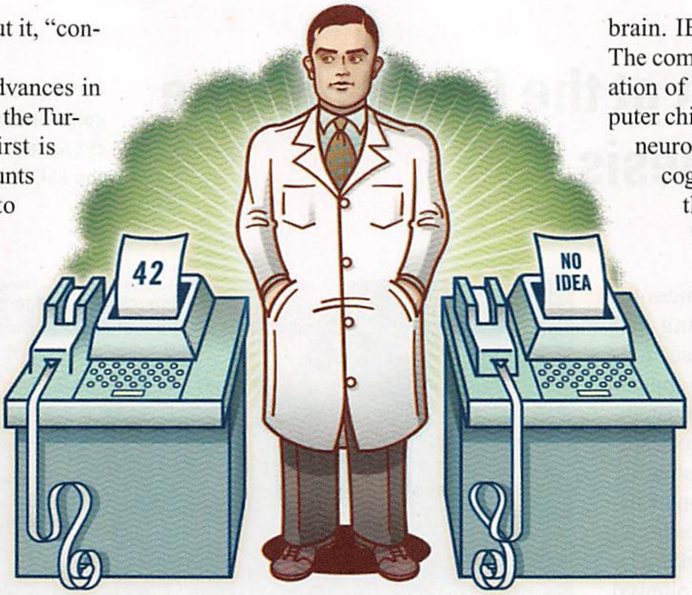
test had been, as one researcher put it, "consigned to history" (*9*).

However, two revolutionary advances in information technology may bring the Turing test out of retirement. The first is the ready availability of vast amounts of raw data—from video feeds to complete sound environments, and from casual conversations to technical documents on every conceivable subject. The second is the advent of sophisticated techniques for collecting, organizing, and processing this rich collection of data. Two deep questions for AI arise from this new technology. The first is whether this wealth of data, appropriately processed, could be used by a machine to pass an unrestricted Turing test. The second question, first asked by Turing, is whether a machine that had passed the Turing test using this technology would necessarily be intelligent.



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Suppose, for a moment, that all the words you have ever spoken, heard, written, or read, as well as all the visual scenes and all the sounds you have ever experienced, were recorded and accessible, along with similar data for hundreds of thousands, even millions, of other people. Ultimately, tactile, and olfactory sensors could also be added to complete this record of sensory experience over time. Researchers at the cutting edge of today's computer industry think that this kind of life-experience recording will become commonplace in the not-too-distant future (*10*). Recently, a home fully equipped with cameras and audio equipment continuously recorded the life of an infant from birth to age three, amounting to ~200,000 hours of audio and video recordings, representing 85% of the child's waking experience (*11*, *12*).

Assume also that the software exists to catalog, analyze, correlate, and cross-link everything in this sea of data. These data and the capacity to analyze them appropriately could allow a machine to answer heretofore computer-unanswerable questions that tap into facts derived from our embodiment or from our subcognitive associative networks, like the finger experiment that began this article or like asking native English speakers whether the neologism "Flugblogs" would be a better name for a start-up computer company or for air-filled bags that you tie on your feet for walking across swamps (*6*). Someone, somewhere has almost certainly done the finger experiment and may well have posted their observations about it to the Internet—or will do so after reading this article—and this information would be accessible to a data-gathering Web crawler. By extension, if a complete record of the sensory input that produced your own subcognitive network over your lifetime were available to a machine, is it so far-fetched to think that the machine might be able to use that data to construct a cognitive and subcognitive network similar to your own? Similar enough, that is, to pass the Turing test.

Computers are already extremely good at collecting and analyzing data from 8 billion (and counting) Web pages, document databases, TV programs, Twitter feeds, etc. (*13*). In early 2011, IBM's Watson (*14*), a 2880-processor, 80-teraflop (i.e., 80 trillion operations/s) computing behemoth with 15 terabytes of RAM, won a *Jeopardy* challenge against two of the best *Jeopardy* players in history. Watson's success was attributable, at least in part, to its meticulous study of *Jeopardy*-like answers and questions, but its performance was nevertheless astounding (*15*). How much would be required to retool Watson for a no-holds-barred Turing test?

The real challenge is not to store countless petabytes (1 million gigabytes) of information, but to selectively retrieve and analyze that information in real time. The human brain processes data in a highly efficient manner, requiring little energy and relying on a densely interconnected network of ~100 billion relatively slow and imprecise neurons. It is still not known to what extent the mechanisms of neuronal firing and the patterns of neuronal interconnectivity are optimal for the analysis of the data stored in the brain. IBM is betting that it just might be. The company recently unveiled a new generation of experimental "neurosynaptic" computer chips, based on principles that underlie neurons, with which they hope to design cognitive computers that will "emulate the brain's abilities for perception, action and cognition" (*16*).

Yes, you say, but data-crunching computers will never be able to think about their own thoughts, which in the final analysis is what makes us human. But there is nothing stopping the computer's data-analysis processes, themselves, from also being data for the machine. Programs already exist that self-monitor their own data processing (*17*).

All of this brings us squarely back to the question first posed by Turing at the dawn of the computer age, one that has generated a flood of philosophical and scientific commentary ever since. No one would argue that computer-simulated chess playing, regardless of how it is achieved, is not chess playing. Is there something fundamentally different about computer-simulated intelligence?

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CELL BIOLOGY

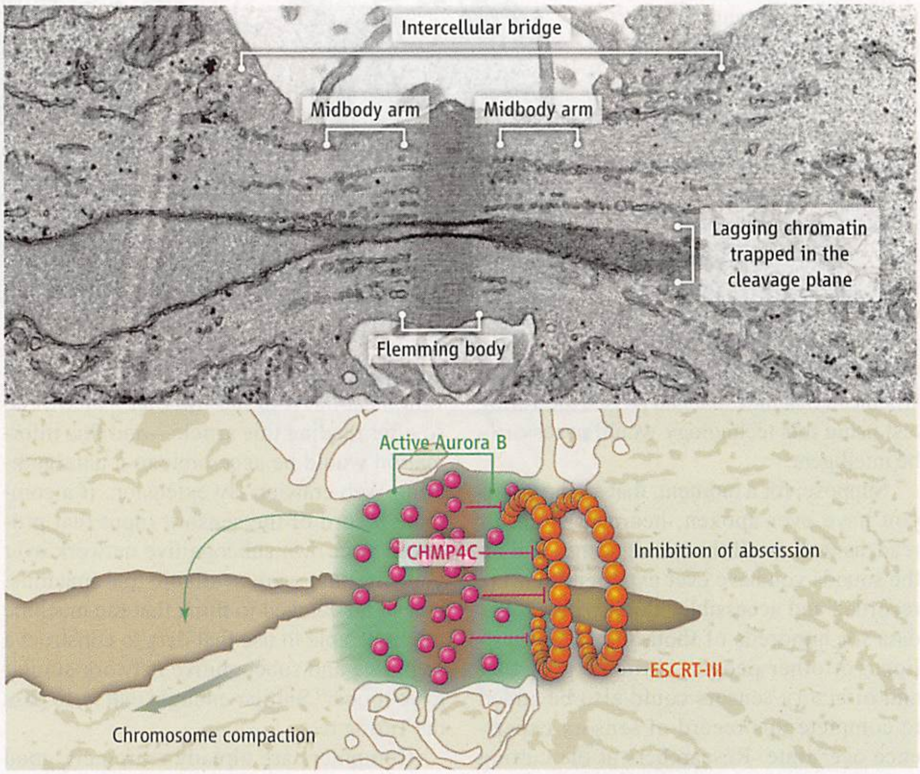
ESCRTing DNA at the Cleavage Site During Cytokinesis

During cell division, Aurora B prevents collisions between chromatin and the cytokinetic apparatus by targeting the ESCRT-III subunit CHMP4C.

Mark Petronczki[1] **and Frank Uhlmann**[2]

Collisions are only good business for insurance companies. During cell division, collisions between separating chromosomes and the cytokinetic apparatus, which physically divides the two daughter cells, must be avoided to prevent catastrophic consequences for genome stability (*1*). Cytokinesis follows the separation of sister genomes, which are pulled to opposite cell poles, and involves splitting the cytoplasm by the ingression of a cleavage furrow followed by a terminal membrane fission event called abscission (*2*). Recent work has identified a monitoring system that prevents cell separation while chromatin lingers in the division plane (*3*, *4*). At the heart of it lies a conserved protein kinase, Aurora B. On page 220 in this issue, Carlton *et al.* identify CHMP4C, a subunit of the ESCRT-III (endosomal sorting complex required for transport) complex, as a key target of Aurora B that delays abscission and prevents DNA damage if chromatin bridges persist in human cells (*5*).

Cytokinesis is initiated by a contractile ring of actin and myosin filaments that drive the ingression of the cleavage furrow at the cell equator. Constriction proceeds until the membrane forms an intercellular bridge covering the midbody, a dense proteinaceous structure that emerges from the anaphase spindle (see the figure). The midbody now serves as a recruitment platform for abscission factors including the ESCRT-III complex. ESCRT-III forms filaments around the abscission site that might eventually contract and break the connection between nascent daughter cells (*6*, *7*). The midbody region is also where Aurora B resides during cytokinesis. As part of the NoCut pathway in budding yeast, Aurora B promotes association of two anillin-like proteins with the contractile ring to delay abscission in response to chromatin at the cleavage site (*3*, *8*). How Aurora B controls the timing of abscission in human cells was not known.



Caught in the middle. Thin-section electron micrograph of a HeLa cell cytokinetic furrow shows chromatin trapped in the cleavage plane (provided by Sergey Lekomtsev). Schematic model depicts how Aurora B kinase at the midbody arms, activated by lagging chromatin, phosphorylates CHMP4C to cause its localization to the Flemming body where it delays abscission. Aurora B also activates condensin to compact chromosomes in order to clear the cleavage plane.

Carlton *et al.* have now made big strides toward explaining the mechanism by which Aurora B achieves this (*5*). They investigated the role of an ESCRT-III subunit called CHMP4, which exists in three isoforms. One of these isoforms, CHMP4C, was found to act as a negative regulator of cytokinesis by delaying abscission if chromosome bridges persist. Aurora B targets a unique short C-terminal insertion in CHMP4C, and, upon phosphorylation, CHMP4C localizes to the central region of the midbody known as the Flemming body (see the figure), where it delays abscission in response to chromatin bridges and thus prevents DNA damage (*5*). These findings suggest that Aurora B puts a brake on abscission in human cells by promoting recruitment of CHMP4C to the Flemming body. The mechanism by which CHMP4C delays abscission merits future investigation. Does CHMP4C prevent ESCRT-III filament assembly or contraction? Another important question is whether additional mechanisms exist that promote longevity of the intercellular bridge to prevent furrow regression and cytokinesis failure, an error with devastating consequences for genome stability (*9*, *10*).

In addition to controlling abscission, Aurora B also prevents collisions between chromosomes and the cytokinetic apparatus by helping to move chromosomes out of the cleavage plane. Normally, the chromosomal condensin complex shortens chromosome arms to prevent them from becoming trapped in the cleavage furrow during anaphase. The condensin complex accumulates on chromatin bridges if they persist, and phosphorylation of condensin by Aurora B enhances chromosome compaction (*11*–*13*). This should

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