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SCIENCE LITERACY OF UNDERGRADUATES IN THE UNITED STATES

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Abstract. Science literacy is a matter of broad concern among scientists, educators, and many policy-makers. National Science Foundation surveys of the general public for biannual Science Indicators series show that respondents on average score less than 2/3 correct on a series of science knowledge questions, and less than half display an understanding of the process of scientific inquiry. Both measures are essentially unchanged over two decades. At the University of Arizona, we have gathered over 11,000 undergraduate student responses to a survey of knowledge and beliefs that is tethered in the NSF survey. This non-science major population demographically represents ten million students nationwide. There is a less than 10% gain in performance in the science knowledge score between the incoming freshmen and seniors who graduate having completed their requirement of three science classes. Belief levels in pseudoscience and supernatural phenomena are disconcertingly high, mostly resistant to college science instruction, and weakly correlated with performance on the science knowledge questions. The Internet is rapidly becoming the primary information source for anyone interested in science so students may not get most of their information from the classroom. Educators and policy makers need to decide what aspects of science knowledge and process are important for adults to know. College science educators have major challenges in better in preparing graduates for participation in a civic society largely driven by science and technology.

1. Rationale and Definitions

Science and technology act like an "amniotic fluid" around everyone living in the industrialized world. Americans encounter science in their various roles as citizens, workers, and consumers. They vote for political candidates with diverse views on climate change, stem cell research, nuclear power, or the space program. They vie for jobs in technology-driven sectors of the economy that didn't exist a generation ago. They are consumers of ubiquitous high-technology devices, and are mostly content to use these emblems of scientific ingenuity without substantial knowledge of how they work. Science is profoundly shaping human culture, yet any ability to assimilate new insights into the natural world depends on an understanding of how scientific knowledge is gained and on how to distinguish scientific facts from other kinds of information. This collection of skills and basic knowledge is often referred to as "science literacy".

Scientists and educators in different fields may not agree on a core set of concepts, principles and facts that every citizen should know, but they are mostly in accord that the health of civic society depends on science literacy. Various policy groups have weighed in. The Organization for Economic Co-operation (OECD) defines it as understanding key scientific concepts and frameworks, the methods by which science builds explanations based on evidence, and being able to critically assess scientific claims and make decisions based on this knowledge (OECD 2002). The American Association for the Advancement of Science (AAAS) says scientifically literate citizens should be aware that science, mathematics and technology all have strengths and limitations and are interdependent human enterprises, they should recognize the unity and diversity of the natural world, and they should be able to use scientific ways of thinking and knowledge for individual and social purposes (AAAS 1993). The National Research Council (NRC) sets even more lofty goals: education should promote science as one of the pinnacles of human thinking capacity, provide a laboratory of common experience for developing language, logic, and problem-solving skills, and prepare students for a democracy which demands that its citizens make personal and community decisions on scientific issues (NRC 2007).

The National Science Foundation has carried out a survey of science knowledge and attitudes for over twenty years, published every two years in the *Science and Engineering Indicators* series, a report to the National Science Board and the US Congress that is used to shape national research and education policy and guide workforce development in technical fields. From their inception, these reports defined literacy criteria based on: (1) a vocabulary of basic scientific constructs, (2) an understanding of the process or nature of science inquiry, and (3) a level of understanding the impact

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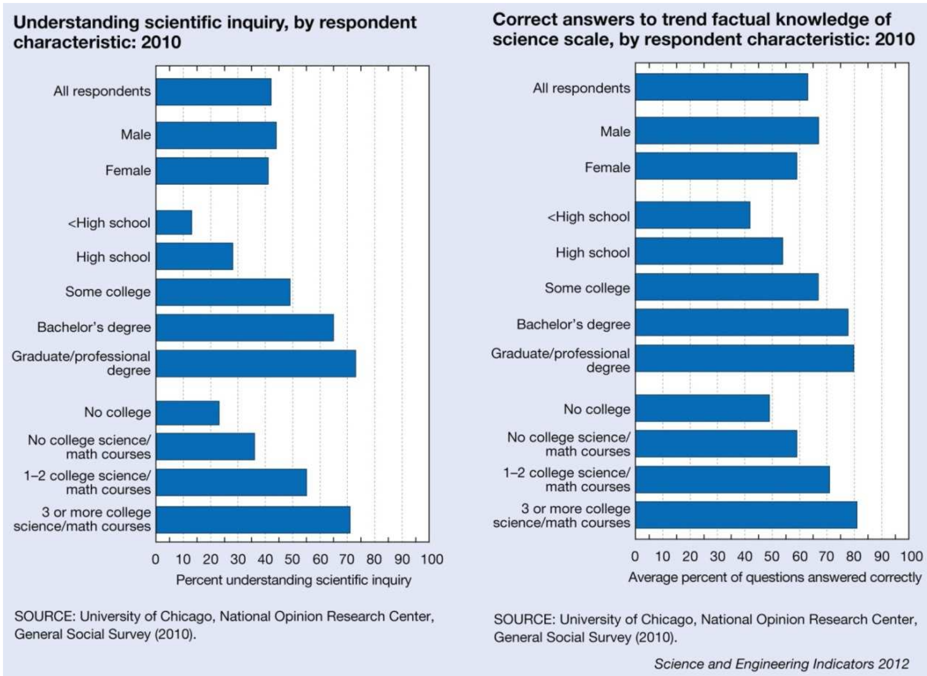

Figure 1. Percentage of the US adult population able to recognize key attributes of scientific inquiry (left) and percentage of correct answers on a 9-question test of basic science knowledge (right). Details of the instruments and coding are given in the *Science and Engineering Indicators 2012* report (NSB 2012). There is a strong dependence of both metrics on formal level of education level and the number of college science classes taken.

of science and technology on individuals and on society. Using thresholds based on (1) the coding of open-ended responses to the question "What does it mean to study something scientifically?" (2) the recognition that astrology is not at all scientific, and (3) correct answers to six or more out of nine knowledge questions, only one in ten American adults was declared scientifically literate (Miller 1987).

In more detail, the level of public science knowledge and familiarity with science as a method of inquiry depends strongly on level of education, and, for those who attended college, on the number of science courses taken (Fig. 1). Traditional models of science literacy imply that the public has a "deficit" of knowledge or understanding relative to a benchmark that may be unrealistic, unattainable, or even irrelevant. Recent discussion of science literacy has become more nuanced, deemphasizing treatment of the public as proxy scientists and recognizing instead that citizens may need to have an active role in the science policy process, but only for topics of particular

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interest (Miller 2002). Workshops sponsored by the NSF have fostered this debate, saying for example that "The starting point for public knowledge of science is the need of the citizen or the information consumer, as opposed to a microcosm of what a scientist knows" (Tuomey 2011).

2. College Science Classes

Advanced math and science are voluntary in most high schools. The majority of students take biology, but less than half takes chemistry, a quarter takes physics, and only 1 in 20 takes calculus (Blank *et al.* 2007). University provides the last formal exposure to science for most Americans. There, students face a smorgasbord of choices, and despite the emergence of General Education science requirements, science is being taken less frequently overall. The National Academy of Scholars surveyed science curricula used in BA degrees from the top fifty institutions in the *US News and World Reports* rankings – the percentage having science requirements dropped from 90% in 1964 to 34% in 1993, and the percentage with both math and science requirements dropped over the same period from 36% to 12% (Balch & Zircher 1996). A Department of Education analysis of the "empirical curriculum" found that science accounted for just 7 of the 100 course categories with the most undergraduates, while a third of all future school teachers do not take any college-level math (Adelman 2004).

The people who teach undergraduate science play an important role in our society. If they teach science majors, they help to fulfill the need for a technically trained workforce by preparing students who are numerate and who have inquiring and analytic habits of mind. If they teach non-science majors, they provide a formal exposure to evidence-based reasoning and the ideas that have transformed our understanding of the natural world, and they are crucial in the efforts to improve public science literacy. For example, introductory astronomy college classes for non-science majors enroll over 250,000 students per year and often represent a student's last formal exposure to science. Nationwide, about 10% of all students take such a class (Fraknoi 2002). Therefore, the astronomy class that serves as a requirement for non-science majors is a useful vehicle for testing new approaches to improving science literacy.

Most educators have goals that go beyond conveying astronomy knowledge and instilling an appreciation for the subject; they also want students to learn about the rational way of thinking and experimenting that has been so successful in revealing the underlying rules of the natural world. Constructivism, a theory of how people learn, posits that students do not enter the college classroom as "empty vessels", ready to be filled with science knowledge (Bransford *et al.* 2000). Rather, students have a complex

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web of prior belief systems and understandings about nature based on their experience, upbringing, popular culture, and social interactions (Donovan & Bransford 2005). Some of the beliefs may align with scientific understanding, while others can be classified as superstitions. Another category is called pseudo-science: a belief system that presents itself as scientific or that has some of the trappings of science, but is not based on logic or evidence (Shermer 1997). Many science educators argue that non-science beliefs interfere with the learning of science and hence with increasing science literacy (Losh *et al.* 2003; Martin 1994). However, it is an open question whether or not non-scientific views or belief systems actually interfere with or compromise learning science or having a scientific worldview.

3. A Survey of Undergraduates

We have been surveying non-science majors regarding their scientific knowledge, attitudes toward science, and pseudoscience beliefs for over twenty years. Initial results from the survey have recently been published (Impey *et al.* 2011, 2012; Antonellis *et al.* 2012; Buxner *et al.* 2010). The University of Arizona sample is representative of the roughly 15 million students at public universities in the US who will graduate with degrees in non-technical subjects. The survey instrument used in this study has been stable since 1988 and has two parts. The first is based on, and has a large degree of overlap with, the instrument used by the NSF in the *Science Indicators* series. It is designed to measure general scientific knowledge using a set of 21 knowledge-based questions, four of which are open-ended with short written answers and the rest of which require true/false or multiple choice responses. The second part measures attitudes to science and technology, perceptions of and susceptibility to certain forms of pseudoscience, and aspects of faith and religious belief. It uses 24 statements where the responses are on a five-point Likert scale. Details of the instrument, its reliability and completion rate, plus a description of the data entry and coding process, are given by Impey *et al.* (2011).

The knowledge-based questions cover a broad range of scientific subjects, from physics ("Which travels faster, light or sound?") and astronomy ("Does the Earth go around the Sun or does the Sun go around the Earth?") to biology ("The oxygen we breathe comes from plants, true or false?"). In the survey instrument, 15 of the 17 questions overlap the NSF Science Indicators survey; a core set of 9 questions have consistently been part of the NSF survey, giving us a twenty year baseline of comparison (Fig. 2). Open-ended questions asked for definitions of the scientific method, DNA, radiation, and computer software. Students also responded to a set of 24 statements on a five-point Likert scale of "strongly agree, agree, no opin-

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ion, disagree, and strongly disagree". Items sample a spectrum of attitudes and beliefs. For example, statements like "Pure science should be funded regardless of its lack of immediate benefit to society" probe general attitudes to science and technology. Others, like "There are circumstances when medical science should not be used to prolong life", address ethical issues. Another set of items probes superstitions and beliefs in pseudoscience, such as "Some numbers are especially lucky for some people" and "The positions of the planets have an effect on everyday life". There are also statements relating to religious belief, like "The Biblical story of creation should be taught alongside evolution in our schools" and "Faith healing is a valid alternative to conventional medicine".

4. Results of the Survey

The University of Arizona survey continues, providing a unique longitudinal view representative of the US undergraduate basic science knowledge, attitudes, and beliefs, with direct tether to an ongoing NSF survey. With half a million individual responses in the database, there is great statistical power for measuring subtle and small effects. The results quoted below include only students taking non-science majors. The most important results so far are:

- *Entering freshmen* perform somewhat higher on knowledge questions than the general public. The UA students at all levels got an average of 7.2 items correct out 9 (80%), compared with 5.6 out of 9 (62%) for the general public in the NSF survey. Neither undergraduates nor the general public show any change in knowledge score over two decades. There are no good predictors of knowledge score, but among the different fields of study, the Education majors (and so future teachers) perform the worst.
- *Gains in knowledge* on any particular item through the time that students graduate are 10 to 15%. That corresponds to a gain of only one additional correct item out of nine between the time a student graduates high school and the time they graduate college, despite taking three science courses. Women score slightly lower than men on knowledge questions.
- *Gaps in knowledge* of graduating seniors are disconcerting. One in three think that antibiotics kill viruses as well as bacteria, one in four think that lasers work by focusing sounds waves, one in five think atoms are smaller than electrons. One in five either does not believe or is unaware that of the fact that humans evolved from earlier species of animals and that the Earth orbits the Sun in a year, two of the central tenets of modern science.

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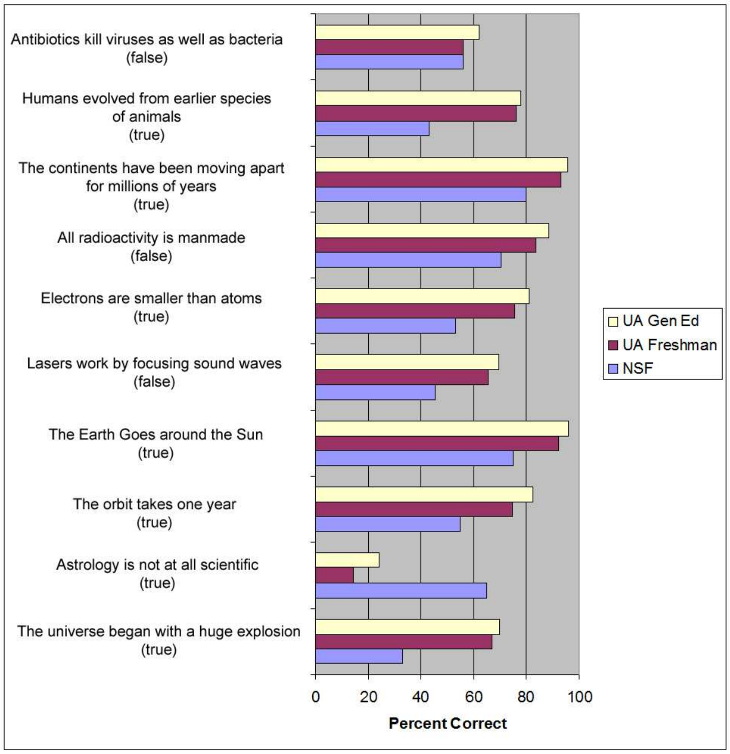

Figure 2. Responses to subset of items on the University of Arizona (UA) science literacy instrument. These items form the basis for a NSF knowledge-based metric of public science literacy. Freshmen have not taken any science classes, whereas Gen Ed students have taken 2 to 3 science classes. Sample sizes are 1864 for NSF, 1275 for UA Freshmen, 828 for UA Gen Ed; the data is 2006 for NSF and 2004 to 2008 for UA.

- *Support of science* and positive attitudes towards research are widespread. Over 90% strongly agreed or agreed with the statement that "Overall, the progress of science and technology has been beneficial to our civilization", and by a ratio of 4:1 students agreed that "Pure science should be funded regardless of its lack of immediate benefit to society". There was also solid support for the space program and the search for life in the universe.
- *Belief in pseudoscience* runs high. About 40% believe that the positions of the planets affect everyday life (Sugarman *et al.* 2011); a similar percentage thinks some people have psychic powers. About 1 in 6 think aliens visited ancient civilizations, 1 in 4 think that faith healing is a legitimate alternative to normal medicine, and a quarter believe in lucky numbers. Surprisingly, none of these beliefs is strongly correlated with level of science literacy.

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- *Beliefs and knowledge* are weakly related. There is a significant negative correlation between the knowledge score and either the level of faith-based beliefs or the level of susceptibility to pseudoscience, but it amount to less than 10% across the full span of beliefs. Taking college science courses has only a small effect on belief in pseudoscience (Goode 2002).

5. Implications for Science Literacy

The most striking results of this research are the weak effects and the null results. There are no major changes in understanding over two decades, and apart from a small gender effect, no demographic variable is a good predictor of level of science knowledge. Undergraduates do not show a marked improvement after taking three university science courses. Miller (2007) analyzed the NSF data to conclude that the number of college science courses taken is the best predictor of civic science literacy (Hobson 2008), closely followed by formal educational attainment, which indicates that overall college experience has as much impact as science instruction. Over the full baseline from 1988-2008, there's no improvement in undergraduate scientific literacy over twenty years. Perhaps the most striking result is the weak relationship between science knowledge and level of belief in pseudoscience and the very modest change in that level of belief after satisfying the standard science requirement for non-science majors (Impey *et al.* 2012; Buxner *et al.* 2010).

There is good and bad news in the Science Indicators surveys and the data from UA surveys. Even though the general public's scores on the knowledge questions have not improved over twenty years, overall public understanding of science has improved over time when cohorts are tracked, even after controlling for the formal level of education (Bauer 2009). Unfortunately, this improvement coexists with strong, and in some cases growing, beliefs in pseudoscience and in non-scientific phenomena (Losh 2011). In NSF surveys, the biggest gains in factual knowledge and in understanding the nature of scientific inquiry accrue to education level and the number of science or math courses taken at college. Undergraduates score 60% before they have taken any science or math courses, which rises to 80% when they have taken three or more. However the gain from high school graduation to college graduation is even larger, from 54% up to 78%, so much of the improvement may be attributed to maturation and the overall educational experience. The percentage understanding the nature of scientific inquiry rises from 36% to 70% when three of more science courses have been taken, but the rise from high school graduation to college graduation

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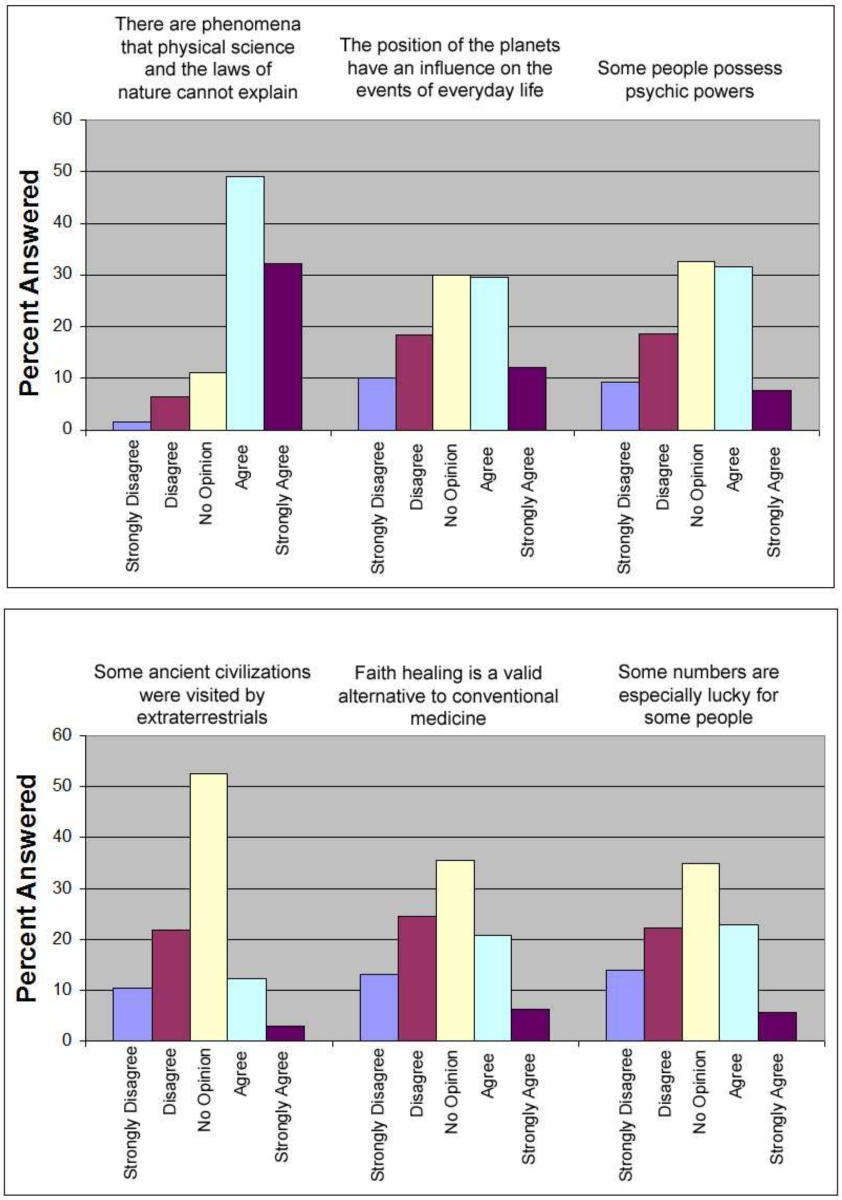

Figure 3. Overall responses, by nearly 10,000 undergraduates over a period of 20 years, to 6 out of 24 statements about science and technology, all items relating to pseudo-science or non-scientific belief systems. These beliefs often coexist with an above-average performance on science knowledge questions.

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is even larger, from 29% to 73%. The NSF data don't support attributing these gains primarily to science classes taken by non-science majors.

This story is mirrored in the UA data. The average knowledge score on the items used by the NSF rises from 76% for students who have taken no science classes to 85% when they have taken three or more, with the same modest gain going from freshmen to seniors. This data cannot be used to follow cohorts, nor are we able to correlate performance on specific biology or physics or astronomy items with the students having taken those particular courses, so as with the national data there's no indication that required science courses are having the desired effect on student knowledge. However, it is clear that students graduate with sizeable holes in their knowledge and with a diverse set of non-scientific beliefs intact.

A typical non-science major at a large university will take three science classes as part of their General Education or distribution requirement. Those several hundred hours of formal science training have varying efficacy, depending on the modes of instruction and the quality of the pedagogy. A recent national report on the science education pipeline stated that "A significant barrier to the broad implementation of evidence-based teaching approaches is that most faculty lack any experience using these methods and they are unfamiliar with the vast body of research indicating their impact on learning" (PCAST 2012). But the classroom does not completely determine the literacy landscape. Surveys by the Pew Research Center, quoted in Science Indicators (NSB 2012), show that the Internet is the primary source of general science information and it eclipses television and print media by a large factor for specific scientific issues (Fig. 4). Wikipedia is notably influential, since it is the most visited information site on the Internet, used by a majority of adult Internet users (Zickuhr & Rainey 2011). The ability of students (and also the public) to distinguish reliable and unreliable sources of science information is currently un-documented.

The pervasiveness of belief in pseudoscience and supernatural phenomena among undergraduates suggests at the very least that their capacity for critical thinking is unevenly applied (Lindeman & Aarnio 2007). It might even mean that relatively high scores on knowledge items give an illusory sense of mastery, because they are unable to apply rational criteria to subjects such as astrology, psychic powers, and lucky numbers. Belief in pseudoscience is such a poor predictor of performance on knowledge questions it begs the question: do irrational beliefs actually matter? The path to improving the science comprehension of students and the public is unclear and represents an interesting challenge for science educators.

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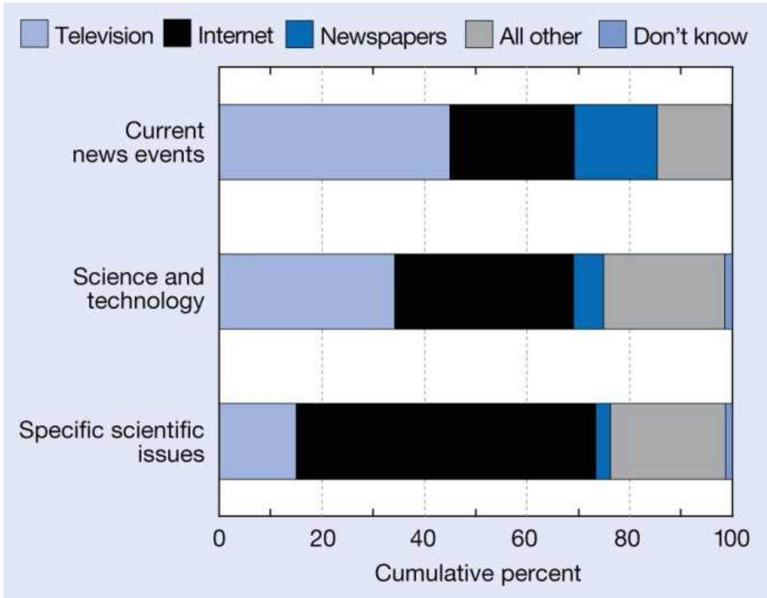

Figure 4. Where the American public gets its science information. This survey from the National Opinion Research Center at the University of Chicago shows that the Internet has grown to rival television as a source of information about science and technology, and is now the primary information source on specific issues in science (NSB 2012).

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