EDUQUAKES

Should Fermi Have Secured His Water Heater?

by Edward M. Brooks, Molly Diggory, Enrique Gomez, Amir Salaree, Mark Schmid, Nooshin Saloor, and Seth Stein

ABSTRACT

A common student response to quantitative questions without obvious answers is "I have no idea." Often these questions can be addressed by Fermi estimation, in which a difficult-to-estimate quantity is estimated by combining order of magnitude estimates of easier-to-estimate quantities. Although this approach is commonly used for numerical estimates, it can be applied to issues combining science and policy. Either application involves dividing an issue into tractable components and addressing them separately. To learn this method, our natural hazards seminar considered a statement by the Illinois Emergency Management Agency that homeowners should secure water heaters to prevent them from being damaged by earthquakes. We divided this question into subtopics, researched each, and discussed them to reach a synthesis. We estimated the net benefit: the difference between the expected value of damage and the cost of securing. This benefit is positive, indicating that securing is worthwhile, only if the probability of damage during the heater's life is relatively large, approximately 1%–10%. To assess whether the actual probability is likely to be this high, we assume that major heater damage is likely only for shaking with modified Mercalli intensity VIII ("heavy furniture overturned") or greater. Intensity data for 200 years of Illinois earthquakes show that this level was reached only in the southernmost part of the state for the 1811–1812 New Madrid earthquakes. As expected, the highest known shaking generally decreases northward toward Chicago, consistent with the fact that we find no cases of earthquake-toppled water heaters in Illinois. We compared the rate of return on securing a water heater in Chicago to buying a lottery ticket when the jackpot is large and found the latter a better investment. This project let us explore ideas that might otherwise have seemed abstract and difficult to grasp, and suggests that other courses might consider similar projects.

INTRODUCTION

On 16 July 1945, when the first atomic bomb was tested in New Mexico, its expected yield was completely unknown. As the blast wave arrived 10 miles away 40 s later, physicist Enrico Fermi (1901–1954) rose and dropped small pieces of paper. From the fact that the wave moved the papers about 2.5 m, Fermi (1945) estimated the bomb's yield at about 10 kt (equivalent to 10,000 tons of TNT), within a factor of 2 of the 20 kt determined later by detailed analysis.

Fermi's ability to simply estimate complex quantities was a hallmark of his successful career that he taught to students. A famous example (Hubbard, 2014) was asking students "how many piano tuners are there in Chicago?" When students responded that they had no idea and no way of sensibly estimating it, Fermi showed how to address the question by breaking it into estimating a series of quantities that, though also uncertain, were easier to estimate.

A common approach is to work with orders of magnitude and, at most, one significant digit. For example, assume that Chicago has about 3 million people, a typical household had three people, and that 1/20 of the households had pianos that were tuned once per year, requiring 50,000 tunings per year. Next, assume that each tuner worked 50 weeks per year, five days a week, and did four tunings per day, yielding 1000 tunings per year. Under these approximations, about 50 tuners would be needed. Other plausible values yield a range of about 30–150 tuners. These estimates were similar to the number of tuners listed in the telephone directory. Although there are uncertainties involved in each quantity, the overestimates and underestimates largely cancel out.

This Fermi estimation approach both gives a reasonable estimate of a quantity and shows how the uncertainty in the estimate arises. Some of the quantities involved (the city's population) will be better known than others (the fraction with pianos). Hence we can identify those quantities that we should try to estimate better.

This approach is widely used in science, notably in the famous Drake equation that seeks to estimate the number of intelligent civilizations in the galaxy (Ward and Brownlee, 2000). Seismological examples include estimating the temper-

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ature within a subducting plate as a function of time since subduction (Stein and Wysession, 2003) or the rate of earthquakes consistent with a geodetic observation (Calais and Stein, 2009). Analogous approaches have been used to explore policy issues, such as the optimal size of U.S. nuclear forces (Enthoven and Smith, 1971), and business decisions, such as whether the potential market for a firm's product would justify expanding into an area (Hubbard, 2014).

Given the power of Fermi estimation, many sources, including books (e.g., Weinstein and Adam, 2008) and websites (see Data and Resources), give introductions to teaching it to students in purely scientific contexts. Fermi questions "are posed with limited information, require that students ask many more questions, demand communication, utilize estimation, and emphasize processes rather than 'the' answer" (mathforum.org website, see Data and Resources).

WATER HEATER PROJECT

To learn to apply Fermi estimation, our seminar for upper-level undergraduates and graduate students interested in decision-making processes in the face of natural hazards looked into applying the approach to issues combining science and policy (Stein and Stein, 2014). An interesting example arose just before class began, when an Illinois Emergency Management Agency spokesperson was quoted in the *Chicago Tribune* (Manchir, 2015) as urging homeowners to strap water heaters and other large appliances to wall studs to prevent them from being damaged by earthquakes. The natural question that arose was whether this would make sense, given that we knew of no cases in Illinois of water heaters damaged by earthquakes or of homeowners in the Chicago area who had secured them.

This question is ideal for our purposes. Most natural hazard policy issues (such as whether it makes more sense to build levees to protect against floods or to prevent new development in the areas at risk, or would more lives be saved by making hospitals earthquake resistant or by using the funds for patient care) are far from students' experiences because they involve rare events and large sums of money. As a result, the crucial question of how to allocate resources between hazard mitigation and other community needs is hard to conceptualize.

Hence a useful educational approach is to apply the key concepts—risk assessment, cost–benefit analysis, and alternative expenditures—on a smaller scale close to students' own experiences such that the costs and benefits are easier to estimate (Stein *et al.*, 2015). Students have a sense of the concepts of costs, benefits, and finite resources: is something worth spending money on, or would the money be better spent otherwise? They appreciate that, although spending decisions are only partly based on economics, people have strong noneconomic preferences, and considering the economics involved is important and can help make better decisions.

We began by considering the costs and benefits of strategies for dealing with home fires (Stein and Stein, 2014). Because fires are more common than natural disasters, students have some sense of the odds and costs involved. We considered options that included relying on the fire department and insurance, a monitored alarm, and a fire-suppressing sprinkler system. More expensive strategies offer additional benefits, so we discussed how to assess the risks of the different approaches and how to use cost–benefit analysis to decide which makes the most sense. Such problems are natural applications for Fermi estimation, in that both costs and benefits can only be estimated imprecisely by making simplifying assumptions, but even crude estimates give insight into which strategies make the most sense.

Our class then explored the water heater issue, which has many of the same features. We divided it into subtopics:

- How vulnerable are water heaters?
- Would damage be covered by insurance?
- What earthquake shaking might be expected?
- How do the costs and benefits of strapping compare?
- Would the state lottery be a better investment?

Students chose a topic to research, based on their interests, and discussed the results we obtained weekly to reach a synthesis. Relevant articles we found and intermediate results were shared via Dropbox. We focused on the Chicago area but also considered the rest of Illinois. We then jointly wrote this article summarizing our results and discussing their educational value.

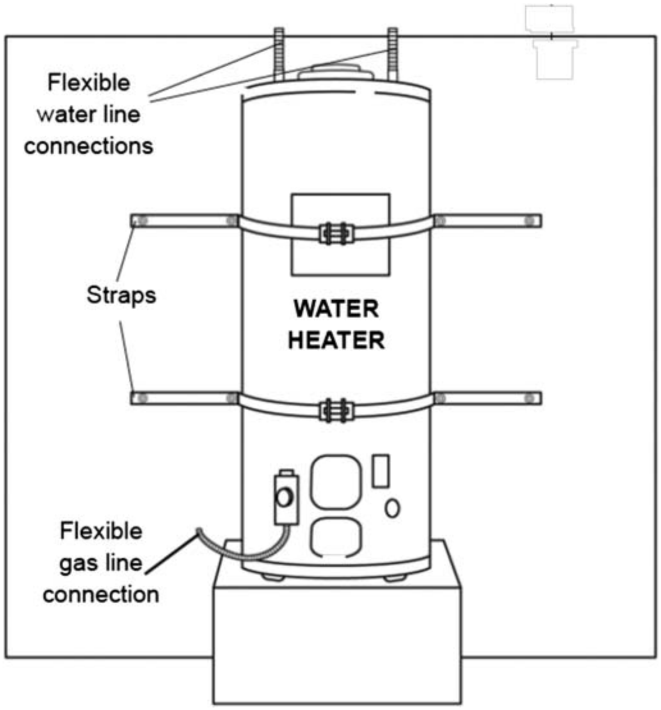
WATER HEATER SECURING

Earthquake safety guides urge residents of seismically active areas to secure home water heaters to reduce the risk of damage to the heater itself and the resulting risk of fire due to disrupted gas lines (Federal Emergency Management Agency, 2005; U.S. Geological Survey, 2011). In California, securing has been legally required since 1991 (Fong, 2004).

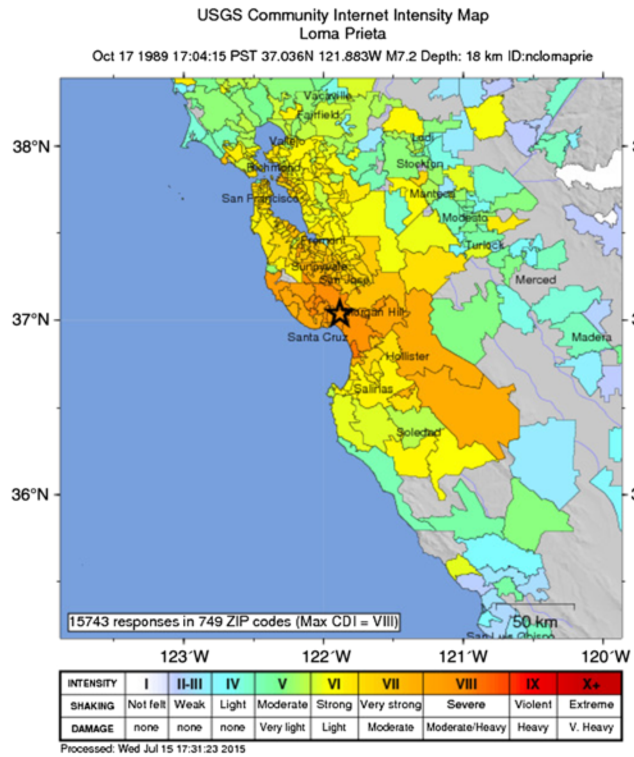
We learned that water heaters cost about \$1000–\$2000, including installation by a qualified plumber. The cost of securing straps is about \$50, and installation by a professional would raise the cost to about \$100.

To our surprise, the results we found about securing water heaters were unimpressive. Levenson (1992) surveyed residents of Santa Cruz, California, following the 1989 M_s 7.1 Loma Prieta earthquake and found that 13% of respondents' water heaters suffered damage, most commonly water leaks costing under \$50 to repair. Two percent of the heaters suffered gas leaks, with none causing fires. No quantifiable reduction in damage occurred for heaters secured with straps of plumbers' tape, a common method (Fig. 1). A study by the Southern California Gas Company after the 1994 M_s 6.7 Northridge earthquake (May and Garcia, 1994) similarly found that secured and unsecured water heaters suffered approximately the same rates of damage. Mohammadi *et al.* (1992) reported that 2 of the 41 fires in San Francisco following the Loma Prieta earthquake were caused by water heater damage but do not say whether the heaters were secured.

A subsequent study commissioned by the National Institute of Standards and Technology (Mroz and Soong, 1997) used shake table experiments and computer modeling to analyze various securing options and their limitations. The study



▲ **Figure 1.** Diagram of typical plumbers' tape water heater strapping (Federal Emergency Management Agency, 2005).



▲ **Figure 2.** Reported shaking for the Loma Prieta earthquake (U.S. Geological Survey [USGS]; see Data and Resources). The color version of this figure is available only in the electronic edition.

found that the common method using galvanized plumbers' tape often allowed the heater to violently collide with a wall. A method using electrical conduit worked well when installed properly, but installation is difficult. The study recommended an improved method using industrial securing brackets. We found no recent data on the fraction of homes with secured heaters or on which securing methods are used.

EARTHQUAKE INSURANCE

Individuals and communities have various ways of managing risk, which involves identifying, assessing, and minimizing the effects of undesirable events. Strapping water heaters is a way of mitigating risk, taking measures to reduce damage. Another approach is to transfer risk using insurance to pass the risk to someone else.

Discussion with an insurance company found that an average two-story house in Evanston is insured for $300,000, and earthquake insurance could be added for $100 per year. The modest premium reflects the fact that there are no known cases of earthquake damage in Evanston. A typical earthquake policy has a 10% deductible, so the homeowner would be responsible for the first $30,000 in damage.

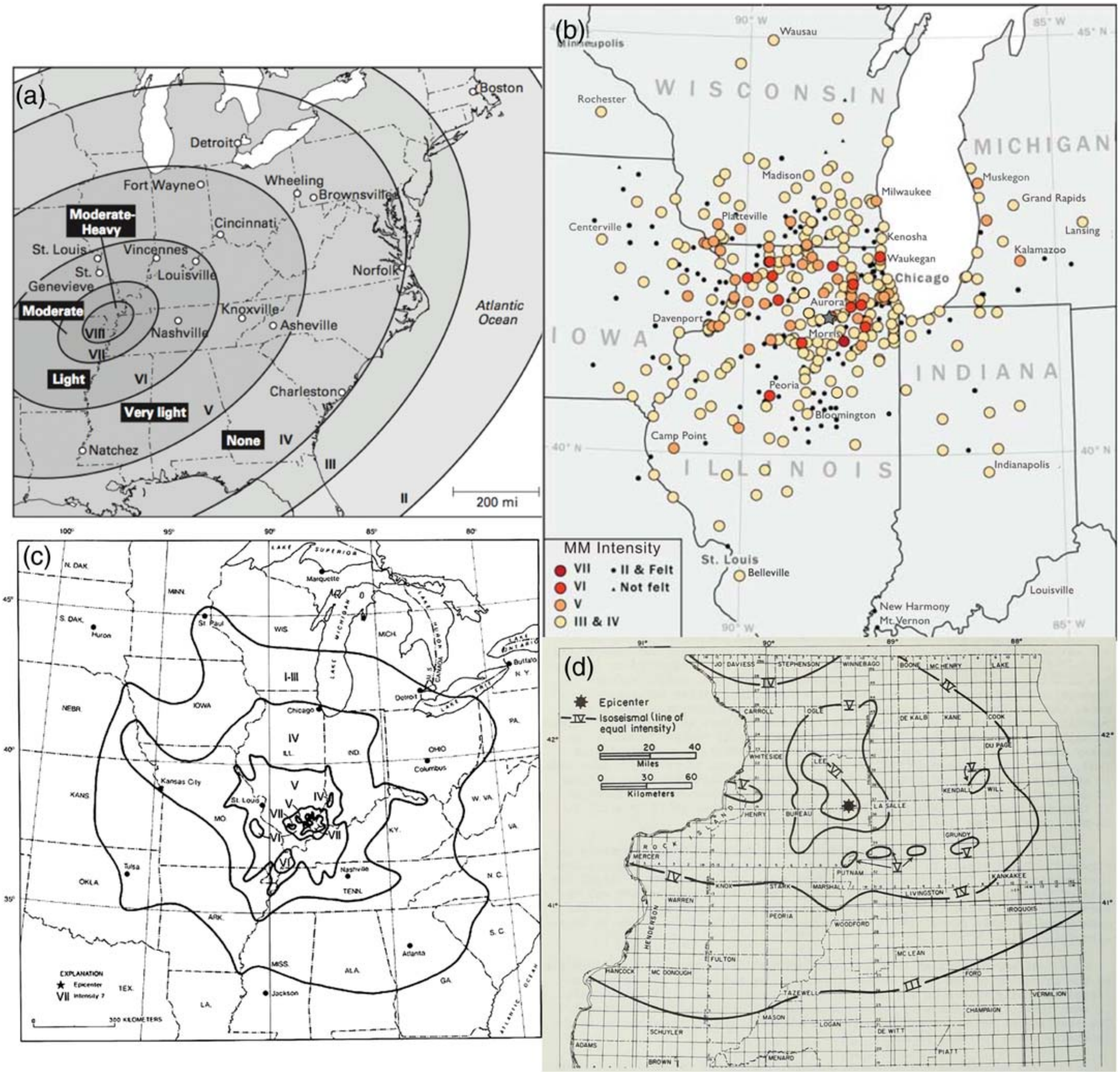
From the Loma Prieta example discussed earlier (Levenson, 1992), we considered several possible levels of damage. The more plausible would be light damage, costing less than $100, which is comparable to the cost of securing the heater. Less likely would be major damage, requiring replacement of the water heater at a cost less than $2000. Because both are under the policy's deductible amount of $30,000, the homeowner would pay out of pocket. Insurance likely would only pay in the rare scenario of a toppled water heater causing a fire.

WATER HEATER VULNERABILITY

The Loma Prieta results discussed earlier (Levenson, 1992) gave us information to develop a simple Fermi-style model of water heater vulnerability. Shaking levels in Santa Cruz were modified Mercalli intensity VII–VIII (Fig. 2). As noted, 13% of respondents' water heaters suffered damage, most commonly water leaks costing under $50 to repair. Some water heater damage makes sense, because the description of intensity VIII (severe shaking) includes "heavy furniture overturned." We thus expect that minor damage can occur for intensity VII and becomes increasingly likely for intensity VIII or above, at which major damage might occur.

HOW LIKELY IS STRONG ENOUGH SHAKING?

Assuming that shaking with intensity of VII—VIII or above can damage water heaters, how likely is this to occur in the Chicago area? We first explored this question by considering Illinois' earthquake history. Although no earthquakes have caused major damage in the state, several have caused minor damage. We examined isoseismal maps (Fig. 3) for four earthquakes: the 16 December 1811 $M_s \sim 7$ New Madrid earthquake, the 1909 $m_b \sim 5.2$ Aurora earthquake, the 1968

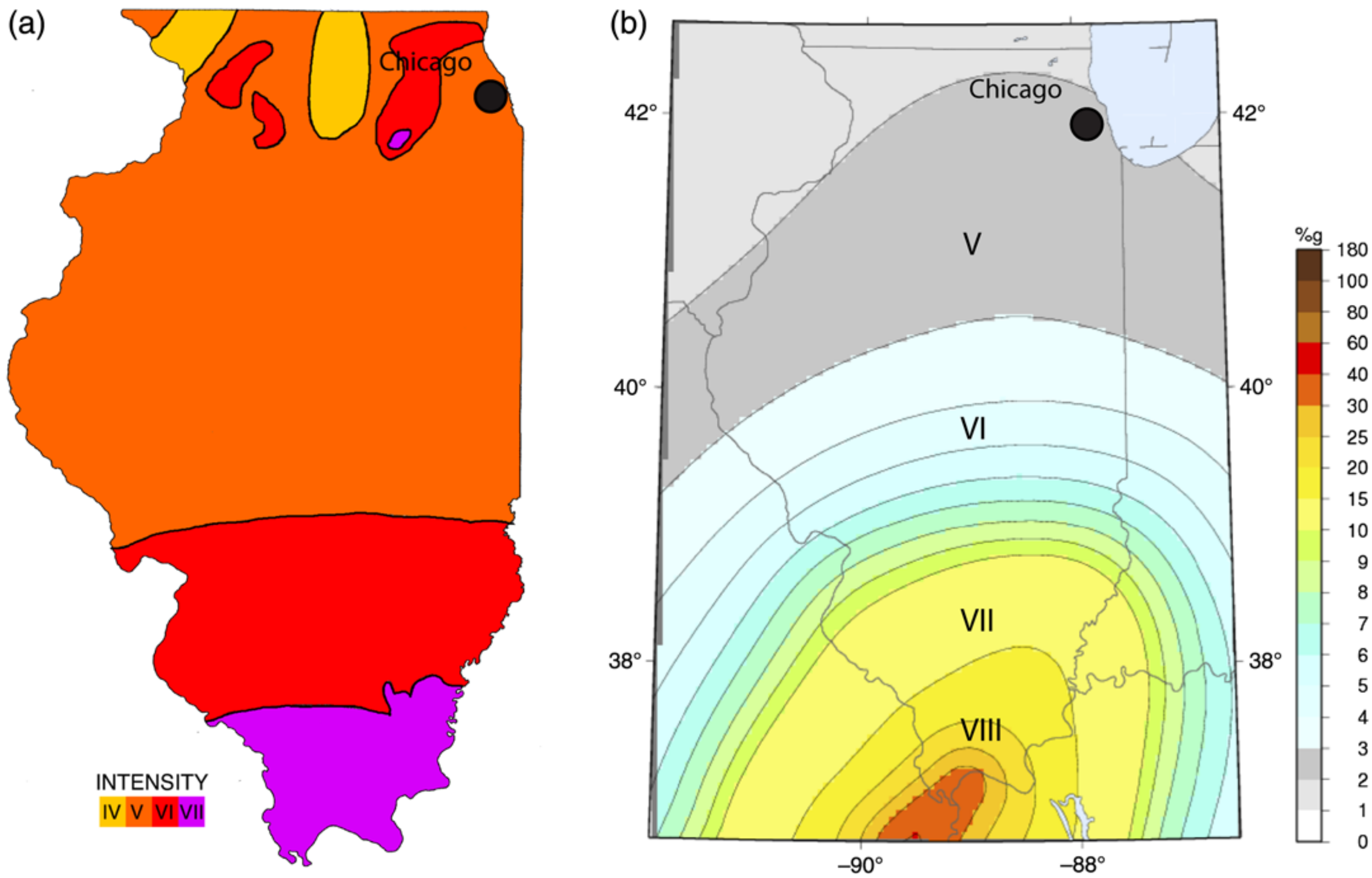


▲ **Figure 3.** Recorded intensities for past Illinois earthquakes: (a) 1811 New Madrid (Hough *et al.*, 2000; Stein and Stein, 2014), (b) 1909 Aurora (Huysken and Fujita, 2013), (c) 1968 Illinois (Gordon *et al.*, 1970), and (d) 1972 M_s 4.0 northern Illinois (Heigold, 1972). The color version of this figure is available only in the electronic edition.

M_s 5.5 Illinois earthquake, and the 1972 M_s 4.0 northern Illinois earthquake. Contours for the 1909 event were approximated based on apparent clusters of a given intensity.

We combined these maps into a smoothed composite map showing the largest known shaking (Fig. 4a). As illustrated by the 1811 event, the dominant effect is that shaking decreases northward, consistent with increasing distance from the New Madrid seismic zone. The smaller events to the north, which are the largest known there, incorporate the effects of smaller faults. No location within Illinois has a history of intensity VIII shaking. The largest known shaking in the Chicago area is intensity V–VI. We found no record of water heater damage in accounts of these or other Illinois earthquakes since 1900, when water heaters became available.

For comparison, we extracted a probabilistic seismic-hazard map for Illinois using the U.S. Geological Survey software (see Data and Resources; Fig. 4b). This map is for peak ground acceleration predicted with a 10% chance of exceedance in 50 years. This corresponds to a 475-year return period, similar to our ∼200-year period of observations. The hazard map is sim-



▲ **Figure 4.** (a) Composite map showing the largest known shaking in Illinois in the past 200 years. (b) Probabilistic seismic-hazard map showing peak ground acceleration and approximate corresponding intensity predicted with a 10% chance of exceedance in 50 years (USGS; see Data and Resources). The color version of this figure is available only in the electronic edition.

ilar to the historic shaking map, with the predicted shaking in the Chicago area expected to be mostly intensity IV–V.

Assuming the strength of future shaking can be inferred from the past, and given that these maps span hundreds of years but show no shaking in the Chicago area with intensity VII or above, it seems unlikely that shaking sufficient to seriously damage water heaters would occur in Chicago during a heater's ~10-year lifetime.

COST–BENEFIT ANALYSIS

The information gathered led us to use a simple model to explore the costs and benefits of strapping a water heater. We posed the model in general terms, following Stein and Stein (2014), and then explored various values of the parameters involved.

The expected benefit of securing a heater is the value of the damage D avoided if a high level of shaking occurs times the probability p that such shaking will occur during the ~10-year life of the water heater. On purely economic grounds, the net benefit NB is

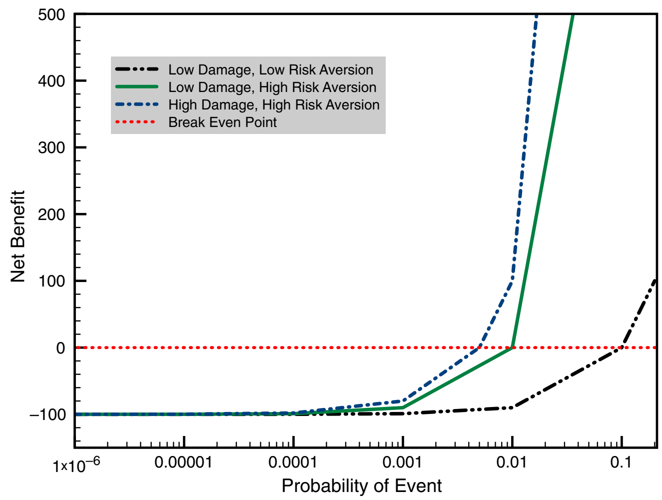
$$\mathrm{NB} = pD - C,$$

in which C is the cost of securing the heater. Because the cost is paid initially, whereas the benefit can occur at any time during the heater's life, we should consider the present value of the benefit by dividing by $(1+i)^T$ in which i is the annual interest rate and T is the heater's life time in years. We neglect this term because interest rates are presently low ($1/1.03^{10} = 0.74$), so this correction is small compared with the uncertainties involved in the various terms.

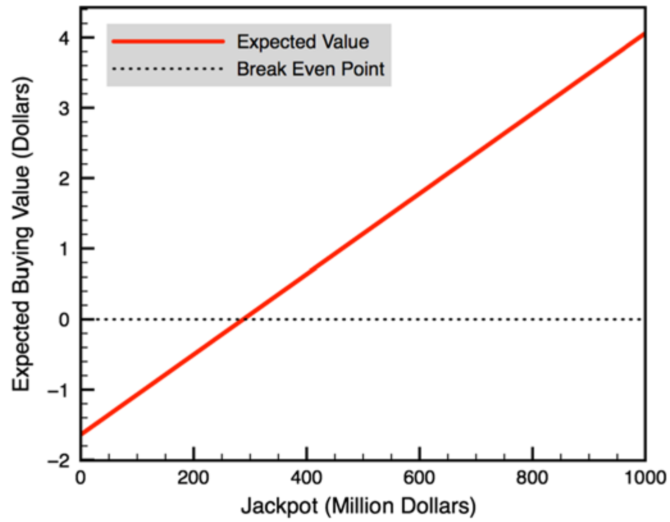
An important factor is people's varying tolerance for risk. In general, people are more concerned with not losing a given sum than in making the same sum, a phenomenon called risk aversion (Stein and Stein, 2014). Risk aversion can be described mathematically as a case in which one will not accept a fair bet, in which the chances of winning and losing are equal, and will only bet when the odds are in one's favor. We include this effect by a factor r, with larger r showing greater risk aversion, so:

$$\mathrm{NB} = prD - C.$$

We estimated the cost of securing the heater as \$100. Our simple damage model considered two damage costs, \$1000 and \$2000. Both are much higher than typically reported in the Santa Cruz survey, so this estimate is between the more likely minor damage and rarer major damage involving fire. For simplicity, above a threshold shaking level, all unstrapped heaters are assumed to be damaged, and all strapped heaters are as-



▲ **Figure 5.** Net benefit of securing a water heater versus the probability of strong earthquake shaking, for several different cases. The color version of this figure is available only in the electronic edition.



▲ **Figure 6.** Expected value of a Powerball ticket (in USD) as a function of jackpot size. The color version of this figure is available only in the electronic edition.

sumed to be undamaged. We considered two risk aversion cases, a person who is risk neutral ($r = 1$) and one who is highly risk averse ($r = 10$).

The probability of damage, corresponding to the probability of severe ground shaking, is the most uncertain factor involved. We thus computed the net benefit as a function of p for different combinations of the other factors, some of which are plotted in Figure 5. The simple model was easily computed with an Excel spreadsheet.

If the net benefit is positive, it makes sense to invest in securing the water heater. If it is negative, securing the water heater costs more than the expected damage that would be avoided if severe shaking occurs. Hence the net benefit is negative for small values of p and becomes positive only if p is large enough.

As shown, the low-damage low-risk aversion case has positive net benefit only if the probability of severe shaking exceeds 1/10 (0.1) during the heater's life. The other two cases have positive net benefit when the probability of severe shaking exceeds 1/100 (0.01) and 0.005 (1/200). As discussed previously, the probability of severe shaking in the Chicago area seems much lower, so securing a water heater would likely cost more than the resulting benefit. However in southernmost Illinois, securing might make sense (see Fig. 4).

LOTTERY ALTERNATIVE

Based on our analysis, we conclude that, had he considered it, Fermi—who made major advances in statistical physics and excelled at numerical estimates—would not have invested in securing his water heater. He might, however, have considered an alternative investment, the state lottery, had it been operating during his life.

State lotteries are useful illustrations for natural hazards education in that they provide one of the few applications in which people consider analogously rare events. We thus explored the alternative of investing the same amount of funds as required to secure a water heater into the lottery instead.

In the Powerball game, a player choose six numbers in hopes of matching those on five white balls with numbers from 1 to 59, and one red Powerball with a possible number from 1 to 35. The payoff depends on the number of balls matched. Table 1 shows the odds and payoffs involved.

The jackpot is variable, depending on the number of tickets sold and whether it has rolled over from earlier drawings when no one won. The remaining prizes are fixed. The net expected value (NEV) of a ticket purchase depends on the jackpot size J, the expected winning $E(J)$, and the cost of a ticket C, in this case \$2.

$$\mathrm{NEV} = E(J) - C.$$

This equation is analogous to that for the net benefit of securing the water heater.

As Figure 6 shows, the net expected value is proportional to the jackpot size. For jackpots less than \$288 million, NEV is negative, so one should expect on average to lose money. However, when the jackpot is more than \$288 million, the NEV becomes positive.

As a result, Powerball is a good investment when the jackpot is large. For example, the 11 February 2015 Powerball jackpot was \$564 million, so the NEV of a ticket was \$1.58. Investing the \$100 required to secure a water heater into the lottery would have a positive net expected value of \$79, rather than the negative value expected for securing the heater. This situation is not that rare, because about 5% of the biweekly drawings have jackpots above \$288 million. The situations for which the investment is rational can be understood by imagining the limiting case: buying all the tickets in the lottery. If the jackpot is small, you would lose money. But if the jackpot is large enough, you would make money.

Table 1
Payoff and Probability of Winning for Combinations of Correctly Matched Balls (see Data and Resources)

Number of Correct White Balls	Number of Correct Red Balls	Payoff (USD)	Approximate Probability
5	1	Jackpot	1/175,223,510
5	0	1,000,000	1/5,153,633
4	1	10,000	1/648,976
4	0	100	1/19,087
3	1	100	1/12,245
3	0	7	1/360
2	1	7	1/706
1	1	4	1/111
0	1	4	1/55

EDUCATIONAL THOUGHTS

Our result, that securing water heaters in Chicago to protect them against earthquakes makes little sense, is hardly surprising given the area's low seismicity. Nonetheless, the process by which we explored multiple aspects of the issue in a group project was interesting and valuable. Learning different methods of problem solving is valuable for our education. Although Fermi estimation is a powerful method worth teaching, many of the traditional examples used (e.g., how many ping-pong balls can fit in a Boeing 747?) seem silly and divorced from reality. Analyzing a more complicated and societally relevant problem better illustrates how to explore a question by estimating a series of quantities that, though also uncertain, are easier to estimate.

Assigning each subtopic to a student with relevant interests, and holding regular discussions, nicely combined the benefits of individual inquiry (work cannot be dumped on teammates) with the feedback and interchange of group discussion. Each participant wrote a draft section of this article and developed the necessary figures, which were then merged into this article.

This project generalized traditional Fermi estimation to a natural hazard policy question. Rather than estimate a specific quantity, for example, how many piano tuners there are, many hazard issues involve assessing whether a policy makes sense or which policy makes the most sense. As in classic Fermi estimation, this involves decomposing the question into more easily addressed ones. In this case, the subquestions involved application of various disciplines. Students chose subquestions depending on their interest—seismology, engineering, or economics. The process of merging the results helped us understand how our individual contributions interfaced with the unfamiliar topics to answer interdisciplinary questions.

We suggest that similar projects be considered for courses in natural hazards and similar topics. Often such courses describe hazards but devote little time to the policy issues related to mitigating them. The policy issues typically involve assessing a hazard, considering various options to mitigate it, and comparing their benefits to those from alternative uses of the same resources, For example, how should a developing nation allocate its budget between building schools for towns without ones or making existing schools earthquake resistant? Does it make more sense to build walls to protect against rising sea level or to retreat from the areas at risk? Is developing shale gas a good or a bad strategy to address climate change? Class size is thus not a problem, because there are enough such issues that a large lecture class could be divided into working groups.

In some sense, our goal was to become foxes. As Dyson (2010, p. 1) explained: "Scientists come in two varieties, hedgehogs and foxes... Foxes know many tricks, hedgehogs only one. Foxes are broad, hedgehogs are deep. Foxes are interested in everything and move easily from one problem to another. Science needs both hedgehogs and foxes for its healthy growth: hedgehogs to dig into the nature of things, foxes to explore the complicated details of our marvelous universe... Enrico Fermi, who built the first nuclear reactor in Chicago, was a fox."

DATA AND RESOURCES

All data used in this article came from published sources listed in the references. Many sources, including books, are available at http://ed.ted.com/lessons/michael-mitchell-a-clever-way-to-estimate-enormous-numbers (last accessed May 2015); details of Fermi questions are available at http://mathforum.org/workshops/sum96/interdisc/sheila2.html (last accessed April 2015); U.S. Geological Survey software is available from http://geohazards.usgs.gov/hazards/apps/cmaps/ (last accessed June 2015); and the payoffs and probabilities of winning for combinations of correctly matched balls are from http://www.illinoislottery.com/en-us/Powerball.html (last accessed March 2015).

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