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Cyber Modeling: Full of Challenges

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Introduction

What do we do when our computer misbehaves or our information is harmed? Why is it that the network is slow or drops our connections? These could be deep, complicated cyber problems that need solving or just simple repairs to software or hardware. Perhaps the modeling process can help solve such problems. So we ask:

What roles do mathematical and interdisciplinary modeling have in cyberspace?

I will try to explain some of these roles, especially as they affect undergraduate interdisciplinary modeling and the ICM.

Cyber Modeling

In a world that is increasingly connected through expanding digital networks, cyber modeling offers a tool to understand the complex issues and to solve the challenging problems that this expansion is creating.

Just as in any other domain (politics, business, finance, science, sports, psychology, warfare, etc.), modeling is a valuable tool in cyberspace to enable understanding of issues and solving problems. Yet, in every domain there are differences in how modeling is used. That is definitely the case in cyberspace. Cyberspace is complex, dynamic, interdisciplinary, and chaotic, where modeling structures and processes are challenged to represent and conceptualize elements of cyberspace and capture the dynamic

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of the attacker-defender interface. Cyberspace itself is the combination of many digital-related components that store, process, transmit, and use information. Modeling, while based on assumptions that simplify the complexity of real problems, must develop ways to enable cyber modelers to contribute to the fast-paced world of digital computing. Cyber modeling is highly interdisciplinary because its elements involve human interactions as well as many forms of science relevant to cyber goals, perspectives, and principles. Computing and networking are important, as are ethics and social issues. Data science, human psychology, and many other disciplines are all parts of this virtual and digital cyber world.

Understanding the Problem

One element of the complexity of cyber space is just understanding the problem to be solved or the issue to be confronted. Often the issues that need to be addressed are hidden and only the symptoms are visible. The cause of the problem—a bug, an innocent human error, bad hardware, or a malicious attack—is often undetectable. The balances between security and performance, privacy, and information availability are delicate and critical. Cyber modeling is needed for fast, time-sensitive problem solutions and robust network designs that are not as common in other domains. We need to ask continually—since the cyber world is developing at an incredible rate: Can our modeling keep pace with the computing and artificial intelligence that are often component parts of the issues and problems?

Hackers vs. Defenders

Another element of the cyber complexity is the underlying competitive nature of the attacker-defender dynamic. Hackers and malicious systems are pitted against defenders of information and systems' performance. There is much more to cyber security than a formidable firewall and virus protection.

In addition, these attacking elements often try to hide their true identity. This game-theoretic setting takes modeling to new heights of what-if, cause-effect, and who-did-it questions.

Cyber problem solving is an unstructured process that often requires high-dimensional nonlinear models, yet still needing dynamic modification to adapt to constantly changing situations. Game theory plays a role, especially when you abstract away all the computers, networks, cables and bits of information, and only the human users remain.

Another role for cyber modeling is in war-gaming the basic elements of the cyber competition. Models that can test capabilities, probe for vulnerabilities, fix performance degradation, and exercise the cyber systems, are needed to enhance cyber security. Artificial intelligence techniques such as machine learning and reinforcement learning are valuable to many cyber modelers.

Information Security

On a larger scale, cyber modeling is a component of the science of information security, which has a goal of building effective systems for information assurance.

A major challenge is that the same elements of the information network that create its positive attributes (effectiveness and freedom) also produce its negative elements (vulnerability and lack of privacy and security). What makes a network robust, survivable, and hard to kill, paradoxically also makes it inefficient, difficult to manage, and vulnerable to penetration.

The Importance of Diversity

Evolutionary biology shows that inherent diversity provides reliability at a price of some inefficiency, yet with still-acceptable performance. Evolutionary biology also teaches that change (adaptation) is needed in order to survive. Today's cyber systems are vulnerable, dangerous, and unpredictable—a place where actions and events happen fast. So to survive on the network, you have to be able to model quickly and effectively—sometimes proactively, sometimes reactively. Diversity is the model attribute that best provides the potential for resilience to vulnerabilities and yet the agility to change fast.

The Uses of Randomness

One natural way to create diversity in cyber systems is through randomness (explicitly-designed random processes). Nature provides diversity in its DNA and cells; cyber modelers need explicitly to build diversity and randomness into their systems.

There is a well-defined and useful definition of what it means for information (numbers, words, symbols) to be random: an impossibility to compress its information content. To build smart systems, cyber modelers need to include that kind of randomness and its consequential diversity.

Where to Put the Diversity?

Designing diversity into a network can make it robust, secure, inefficient and impossible to control. Where do cyber modelers need to put diversity in their models? The goal is to have it nearly everywhere:

- Authentication Procedures

- Connections
- Operating Systems
- Protocols
- Topology

Inefficiency and Brittleness

The analogy of cyber systems to biological systems is powerful. Monocultures are efficient but vulnerable; uniformity creates a form of weakness. Polycultures are inefficient, but usually robust to a changing environment and therefore survivable. The result is that diversity creates a form of strength. The ultra-efficiency of uniform precision can indicate, and will ultimately produce, fragility.

This idea of adding randomness and diversity is not intuitive to modelers who have worked in other domains. Fortunately, despite our intent to make the internet more uniform and efficient, it is not. The internet works because of its diversity and randomness. Yet we continue to follow our intuition and design our networks and systems primarily for efficiency, and the result is super-efficient networks that are often rigid and brittle. Even today, we revert to old, yet unhelpful habits. When things go wrong in our systems, we react by enforcing rigid discipline and control that destroys diversity and ultimately hurts the cyber network. So when weaknesses are found, cyber modelers may have to build in more intentional randomness into the network as long as it meets its operational demands. Then modelers can use the system's diversity for improved survivability at the cost of efficiency. Randomness means that no one (not even the designer or builder) has precise control, but overall performance will still be higher than over-programmed, inflexible, but broken systems.

The Future of Cyber Modeling

Cyber modelers seek to build models that help to defend or attack systems, predict and defend against attacks, respond to cyber problems, design flexible systems, protect our information, and otherwise carefully watch over and monitor their portion of cyberspace. Cyber modeling attempts to take the often chaotic cyber realm and provide just enough organized framework to prepare courses of actions to identify potential problems and create game plans to resolve forecasted and unforeseen events.

There is an active and evolving future for cyber modeling. Through the biological analogy, cyber modeling does require new, original ways of thinking and building models for the tasks that are part of this rapidly changing cyber world. It is not often that the way ahead in modeling is to embrace randomness, embrace diversity, embrace inefficiency, embrace complexity, and embrace interdisciplinarity. Cyber modeling in this non-intuitive form that I have described will be a challenge for our modeling community to accept, understand, develop, and learn.

I give my best wishes to the leaders and learners of cyber modeling; our highly connected information-age society needs your endeavors to succeed.

About the Author

Chris Arney is a Professor of Mathematics at the U.S. Military Academy. His Ph.D. is in mathematics from Rensselaer Polytechnic Institute. He also served as a Dean and acting Vice President for Academic Affairs at the College of Saint Rose in Albany, NY and had various tenures as division chief and program manager at the Army Research Office in Research Triangle Park, NC, where he performed research in cooperative systems, information networks, and artificial intelligence. He is the founding Director of the ICM.

ICM Modeling Forum

Results of the 2016 Interdisciplinary Contest in Modeling

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Introduction

A total of 5,023 teams spent a weekend working on an applied modeling problem in the 18th Interdisciplinary Contest in Modeling (ICM). This year's contest began on Thursday 28 January and ended on Monday 1 February 2016. During that time, teams of up to three undergraduate or high school students researched, modeled, analyzed, solved, wrote, and submitted their solutions to an open-ended interdisciplinary modeling problem. After the weekend of challenging and productive work, the solution papers were sent to COMAP for judging. Fourteen of the papers were judged to be Outstanding by the expert panel of judges; three appear in this issue of *The UMAP Journal*.

COMAP's Interdisciplinary Contest in Modeling (ICM)® involves students working in teams to model and analyze an open interdisciplinary problem. COMAP, whose educational philosophy is centered on mathematical modeling, supports the use of mathematical concepts, methods, and tools to explore real-world problems. COMAP serves society by developing students as problem solvers so as to become better informed and prepared as citizens, contributors, consumers, workers, and community leaders. The ICM is an example of COMAP's efforts in achieving these goals.

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This year's contest offered a choice of three problems instead of two, giving teams more options and variety in the contest problems:

- The D Problem focused on measuring the evolution of society's *information networks*. By taking a historical perspective of flow of information relative to value of information, the modelers sought to understand the methodology, purpose, and functionality of society's news and information networks.
- The E Problem focused on the theme of *environmental science*. Teams sought to identify and understand the drivers of water scarcity to create intervention strategies for a region to mitigate a current or pending water crisis.
- The F Problem introduced *policy modeling* to the ICM. The problem for this first-time topic of policy modeling focused on the Middle-East-to-Europe refugee migration issues.

All three problems were challenging in their demand for teams to utilize aspects of science, mathematics, and data analysis in their modeling and problem solving. The problems were written by the head judges for each problem:

- Problem D, Measuring the Evolution and Influence in Society's Information Networks: Jessica Libertini (Virginia Military Institute) and Ralucca Gera (Naval Postgraduate School).
- Problem E, Are We Heading Towards a Thirsty Planet?: Amanda Beecher (Ramapo College) and Amy Richmond (United States Military Academy).
- Problem F, Modeling Refugee Immigration Policies: Kathryn Coronges (Northeastern University) and Yulia Tyshchuk (United States Military Academy).

Network Problem

The network problem (Problem D) was set in a historical context where society's information networks of five time periods (1870s, 1920s, 1970s, 1990s, and 2010s) were compared. By using the networks of each period, measures for the flow of information relative to value of information were established and compared. Teams used historical data and developed measures and models to determine what qualifies as news and to track the evolution of news throughout the ages.

Members of the 741 successful teams are to be congratulated for their interdisciplinary network modeling and their dedication to challenging problem solving. This was a challenging problem; and unfortunately, an alarming number of student teams were categorized as Unsuccessful because of blatant plagiarism and copying. The ICM expects student teams to be honest about their work. Submitted papers must be the team's own effort; and when data, methodology, or ideas are used from others, which unto itself is good scholarship, credit must be carefully and clearly given to the other sources of those data, methods, and ideas. The ICM expects teams to be scrupulously honest in their research and presentation.

Environmental Problem

The environmental problem (Problem E) involved the critical issue of regional water scarcity. Teams were asked to create intervention strategies for a water-vulnerable region to mitigate its water crisis. The teams had to consider both environmental constraints on water supply and how social factors influence availability and distribution of clean water. Teams were tasked to consider questions such as:

- What are the geological, topographical, and ecological reasons for water scarcity, and how can we accurately predict future water availability?
- What is the potential for new or alternative sources of water (for example, desalinization plants, water harvesting techniques, or undiscovered aquifers)?
- What are the demographic and health related problems tied to water scarcity?

Members of the 3,208 competing teams are to be congratulated for their excellent work and dedication to interdisciplinary modeling and problem solving. This problem clearly generated a lot of interest: It garnered the most solutions of all 21 ICM problems over the history of the competition.

Policy-Modeling Problem

The policy-modeling problem (Problem F) challenged teams to help develop a better understanding of the factors involved with facilitating the movement of refugees from their countries of origin into safe-haven countries. This problem was the first time for the ICM to include explicitly an explicit policy-modeling scenario in the contest.

The problem focused on the current Middle East–Europe refugee migration issue. The problem challenged teams to

- determine the specific factors that can enable or inhibit the safe and efficient movement of refugees,
- create a model of refugee movement that would incorporate projected flows of refugees across the six travel routes, and
- propose a set of policies to support the improvement of conditions in future migration patterns.

Members of the 952 teams that worked and submitted on Problem F are to be congratulated for their excellent work and dedication to interdisciplinary policy modeling and problem solving.

A Brief History of ICM

The range of topics over the 21 problems given over the 18 years of the ICM (provided in **Table 1**) shows the interdisciplinarity of the contest, with problems involving themes from chemistry, physics, biology, engineering, information science, medicine, business, environmental science, network science, operations research, and political science. The problems also show a balance of public (government) and private (business) issues.

Table 1.

Participating teams and topics in the first 18 years of the ICM.

Year	Number of teams	Topic
1999	40	Controlling the spread of ground pollution
2000	70	Controlling elephant populations
2001	83	Controlling zebra mussel populations
2002	106	Preserving the habitat of the scrub lizard
2003	146	Designing an airport screening system
2004	143	Designing information technology security for a campus
2005	164	Harvesting and managing exhaustible resources
2006	224	Modeling HIV / AIDS infections and finances
2007	273	Designing a viable kidney exchange network
2008	380	Measuring utility in health care networks
2009	374	Balancing a water-based ecosystem affected by fish farming
2010	356	Controlling ocean debris
2011	735	Measuring the impact of electric vehicles
2012	1,329	Identifying criminals in a conspiracy network
2013	957	Modeling Earth's health
2014	1,028	Using networks to measure influence and impact
2015	641	Measuring churn and human capital in an organization
2015	1,496	Planning sustainability for low-development countries
2016 D	863	Measuring evolution and influence in information networks
2016 E	3,208	Are we heading towards a thirsty planet?
2016 F	952	Modeling refugee immigration policies

2016 ICM Statistics

- 5,023 Teams participated
- 595 different schools
- 863 Problem D submissions

- 3,208 Problem E submissions
- 952 Problem F submissions
- 91 US teams (2%)
- 4,932 foreign teams (98%) from Australia, Canada, China, Hong Kong SAR, Indonesia, Singapore and United Kingdom
- 14 Outstanding Winners (1%)
- 15 Finalist Winners (1%)
- 935 Meritorious Winners (18%)
- 2,285 Honorable Mentions (45%)
- 1,649 Successful Participants (33%)
- 125 Unsuccessful Participants (2%)
- 59% male participants
- 41% female participants
- 27 teams from high schools and two-year colleges

2016 Problem D: Measuring the Evolution And Influence in Society's Information Networks

When information is spread quickly in today's tech-connected communications network, sometimes it is due to the inherent value of the information itself, and other times it is due to the information finding its way to influential or central nodes of the network that accelerate its spread through social media.

While content has varied—in the 1800s, news was more about local events (e.g., weddings, storms, deaths) rather than viral videos of cats or social lives of entertainers—the prevailing premise is that this cultural characteristic to share information (both serious and trivial) has always been there. However, the flow of information has never been as easy or wide-ranging as it is today, allowing news of various levels of importance to spread quickly across the globe in our tech connected world. By taking a historical perspective of flow of information relative to inherent value of information, the Institute of Communication Media (ICM) seeks to understand the evolution of the methodology, purpose, and functionality of society's networks.

Specifically, your team as part of ICM's Information Analytics Division has been assigned to analyze the relationship between speed/flow of information vs inherent value of information based on consideration of 5 periods:

- in the 1870s when newspapers were delivered by trains and stories were passed by telegraph;
- in the 1920s when radios became a more common household item;
- in the 1970s when televisions were in most homes;
- in the 1990s when households began connecting to the early internet; and
- in the 2010s when we can carry a connection to the world on our phones.

Your supervisor reminds you to be sure to report the assumptions that you make and the data that you use to build your models.

Your specific tasks are:

Task 1:

Develop one or more model(s) that allow(s) you to explore the flow of information and filter or find what qualifies as news.

Task 2:

Validate your model's reliability by using data from the past and the prediction capability of your model to predict the information communication situation for today and compare that with today's reality.

Task 3:

Use your model to predict the communication networks' relationships and capacities around the year 2050.

Task 4:

Use the theories and concepts of information influence on networks to model how public interest and opinion can be changed through information networks in today's connected world.

Task 5:

Determine how information value, people's initial opinion and bias, form of the message or its source, and the topology or strength of the information network in a region, country, or worldwide could be used to spread information and influence public opinion.

Possible Data Sources

As you develop your model and prepare to test it, you will need to assemble a collection of data. Below are just some examples of the types of data you may find useful in this project. Depending on your exact model, some types of data may be very important and others may be entirely irrelevant.

In addition to the sample sources provided below, you might want to consider a few important world events throughout history—if some recent big news events, such as the rumors of country-turned-pop singer Taylor Swift's possible engagement had instead happened in 1860, what percentage of the population would know about it and how quickly; likewise, if an important person was assassinated today, how would that news spread and how might that compare to the news of U.S. President Abraham Lincoln's assassination?

Sample Circulation Data and Media Availability

`http://media-cmi.com/downloads/Sixty_Years_Daily_Newspaper_Circulation_Trends_050611.pdf`

`http://news.bbc.co.uk/2/hi/technology/8552410.stm`

`http://www.gov.scot/Publications/2006/01/12104731/6`

`http://www.technologyreview.com/news/427787/are-smart-phones-spreading-faster-than-any-technology-in-human-history/`

`http://newsroom.fb.com/content/default.aspx?NewsAreaId=22`

`http://www.poynter.org/news/mediawire/189819/pew-tv-viewing-habit-grays-as-digital-news-consumption-tops-print-radio/`

`http://www.people-press.org/2012/09/27/section-1-watching-reading-and-listening-to-the-news-3/`

`http://theconversation.com/hard-evidence-how-does-false-information-spread-online-25567`

Historical Perspectives of News and Media:

`https://www.quora.com/How-did-news-get-around-the-world-before-the-invention-of-newspapers-and-other-media`

`http://2012books.lardbucket.org/books/a-primer-on-communication-studies/s15-media-technology-and-communica.html`

`http://firstmonday.org/article/view/885/794`

Campbell, Richard, Christopher R. Martin, and Bettina Fabos. 2007. *Media and Culture: An Introduction to Mass Communication*. 5th ed. Boston, MA: Bedford St. Martin's.

Poe, Marshall T. 2011. *A History of Communications: Media and Society from the Evolution of Speech to the Internet*. New York: Cambridge.

Biagi, Shirley. 2007. *Media/Impact: An Introduction to Mass Media*. Boston, MA: Wadsworth.

2016 Problem E: Are We Heading Towards A Thirsty Planet?

Will the world run out of clean water? According to the United Nations, 1.6 billion people (one quarter of the world's population) experience water scarcity. Water use has been growing at twice the rate of population over the last century. Humans require water resources for industrial, agricultural, and residential purposes. There are two primary causes for water scarcity: physical scarcity and economic scarcity. *Physical scarcity* is where there is inadequate water in a region to meet demand. *Economic scarcity* is where water exists but poor management and lack of infrastructure limits the availability of clean water.

Many scientists see water scarcity becoming exacerbated with climate change and population increase. The fact that water use is increasing at twice the rate of population suggests that there is another cause of scarcity: Is it increasing rates of personal consumption, or increasing rates of industrial consumption, or increasing pollution which takes water off the market, or what?[1]

Is it possible to provide clean fresh water to all? The supply of water must take into account the physical availability of water (e.g., natural water source, technological advances such as desalination plants or rainwater harvesting techniques). Understanding water availability is an inherently interdisciplinary problem. One must not only understand the environmental constraints on water supply but also how social factors influence availability and distribution of clean water. For example, lack of adequate sanitation can cause a decrease in water quality. Human population increase also places increased burden on the water supply within a region. In analyzing issues of water scarcity, the following types of questions must be considered:

- How have humans historically exacerbated or alleviated water scarcity?

[1] The 2013 Mathematical Competition in Modeling (Problem B) and the 2009 High School Modeling Competition in Modeling (Problem A) were related to modeling different aspects of water scarcity.

- What are the geological, topographical, and ecological reasons for water scarcity, and how can we accurately predict future water availability?
- What are the potential for new or alternative sources of water—for example, desalinization plants, water harvesting techniques or undiscovered aquifers?
- What are the demographic and health-related problems tied to water scarcity?

Problem Statement

The International Clean water Movement (ICM) wants your team to help them solve the world's water problems. Can you help improve access to clean, fresh water?

Task 1:

Develop a model that provides a measure of the ability of a region to provide clean water to meet the needs of its population. You may need to consider the dynamic nature of the factors that affect both supply and demand in your modeling process.

Task 2:

Using the UN water scarcity map at

`http://www.unep.org/dewa/vitalwater/jpg/0222-waterstress-overuse-EN.jpg`

pick one country or region where water is either heavily or moderately overloaded. Explain why and how water is scarce in that region. Make sure to explain both the social and environmental drivers by addressing physical and/or economic scarcity.

Task 3:

In your chosen region from Task 2, use your model from Task 1 to show what the water situation will be in 15 years. How does this situation impact the lives of citizens of this region? Be sure to incorporate the environmental drivers' effects on the model components.

Task 4:

For your chosen region, design an intervention plan taking all the drivers of water scarcity into account. Any intervention plan will inevitably impact the surrounding areas, as well as the entire water ecosystem. Discuss this impact and the overall strengths and weaknesses of the plan in this larger context. How does your plan mitigate water scarcity?

Task 5:

Use the intervention you designed in Task 4 and your model to project water availability into the future. Can your chosen region become less susceptible to water scarcity? Will water become a critical issue in the future? If so, when will this scarcity occur?

Task 6:

Write a 20-page report (the one-page summary sheet does not count in the 20 pages) that explains your model, water scarcity in your region with no intervention, your intervention, and the effect of your intervention on your region's and the surrounding area's water availability. Be sure to detail the strengths and weaknesses of your model. The ICM will use your report to help with its mission to produce plans to provide access to clean water for all citizens of the world. Good luck in your modeling work!

Possible Resources

An Overview of the State of the World's Fresh and Marine Waters. 2nd ed. 2008. `http://www.unep.org/dewa/vitalwater/index.html`.

The World's Water: Information on the World's Freshwater Resources. `http://worldwater.org`.

AQUASTAT. Food and Agriculture Organization of the United Nations. FAO Water Resources. `http://www.fao.org/nr/water/aquastat/water_res/index.stm`.

The State of the World's Land and Water Resources for Food and Agriculture. 2011. `http://www.fao.org/docrep/017/i1688e/i1688e00.htm`.

GrowingBlue: Water. Economics. Life. `http://growingblue.com`.

World Resources Institute. `www.wri.org`.

2016 Problem F: Modeling Refugee Immigration Policies

With hundreds of thousands of refugees moving across Europe and more arriving each day, considerable attention has been given to refugee integration policies and practices in many countries and regions. History shows that major political and social unrest and warfare can produce mass fleeing of populations. These crises bring a set of unique challenges that must be managed carefully through effective policies.

Events in the Middle East have caused a massive surge of refugees emigrating from the Middle East into safe-haven countries in Europe and parts of Asia, often moving through the Mediterranean and into countries such as Turkey, Hungary, Germany, France, and the UK. By the end of October 2015, European countries received over 715,000 asylum applications from refugees. Hungary topped the charts with nearly 1,450 applications per 100,000 inhabitants; but only a small percentage of those requests was granted (in 2014, only 32%), leaving close to 1,000 refugees homeless for every 100K residents of the country. Europe has established a quota system in which each country has agreed to take in a particular number of refugees, with the majority of the resettlement burden lying with France and Germany.

The refugees travel multiple routes from the Middle East through

- West Mediterranean,
- Central Mediterranean,
- Eastern Mediterranean,
- West Balkans,
- Eastern Borders, and
- Albania to Greece.

See these routes mapped out in

`http://www.bbc.com/news/world-europe-34131911`.

Each route has different levels of safety and accessibility, with the most popular route being Eastern Mediterranean and the most dangerous being Central Mediterranean. Countries that have been burdened the most are concerned about their capacity to provide resources for the refugees, such as food, water, shelter, and healthcare. There are numerous factors that determine how the refugees decide to move through the region. Transportation availability, safety of routes, and access to basic needs at destination are considered by each individual or family in this enormous migration.

The UN Commission on Refugees has asked your team, ICM-RUN (RefUgee aNalytics), to help develop a better understanding of the factors involved with facilitating the movement of refugees from their countries of origin into safe-haven countries.

Your specific tasks are:

Task 1: Metrics of refugee crises

Determine the specific factors that can either enable or inhibit the safe and efficient movement of refugees. There are attributes of the individuals themselves, the routes they must take, the types of transportation, the countries' capacity, including number of entry points and resources available to refugee population. This first task requires ICM-RUN to develop a set of measures and parameters and justify why they should be included in the analysis of this crisis.

Task 2: Flow of refugees

Create a model of optimal refugee movement that would incorporate projected flows of refugees across the six travel routes mentioned in the problem, with consideration of transportation routes and accessibility, safety of route, and countries' resource capacities. You can include different routes, different entry points, single or multiple entry points, and even different countries. Use the metrics that you established in Task 1 to determine the number of refugees, as well as the rate and point of entry necessary to accommodate their movement. Be sure to justify any new elements you have added to the migration and explain the sensitivities of your model to these dynamics.

Task 3: Dynamics of the crisis

Refugee conditions can change rapidly. Refugees seek basic necessities for themselves and their families in the midst of continuously changing political and cultural landscapes. In addition, the capacity to house, protect, and feed this moving population is dynamic in that the most desired destinations will reach maximum capacity the quickest, creating a cascade effect altering the parameters for the patterns of movement. Identify the environmental factors that change over time; and show how capacity can be incorporated into the model to account for these dynamic elements. What resources can be pre-positioned, and how should they be allocated in light of these dynamics? What resources need priority, and how do you incorporate resource availability and flow in your model? Consider the role and resources of both governments and non-governmental agencies (NGOs). How does the inclusion of NGOs change your model and strategy? Also consider the inclusion of other refugee destinations such as Canada, China, and the United States. Does your model work for these regions as well?

Task 4: Policy to support refugee model

Now that you have a working model, ICM-RUN has been asked to attend a policy strategy meeting, where your team is asked to write a report on your model and propose a set of policies that will support the optimal set of conditions to ensure the optimal migration pattern. The UN commission has asked you to consider and prioritize the health and safety of refugees and of the local populations. You can include as many parameters and considerations as you see fit to help to inform the strategic policy plan, keeping in mind the laws and cultural constraints of the effected countries. Consider also the role and actions of non-governmental organizations (NGOs).

Task 5: Exogenous events

In addition to endogenous systemic dynamics, in these volatile environments exogenous events are also highly likely to occur and alter the situation parameters. For example, a major terrorist attack in Paris has been linked to the Syrian refuge crisis and has resulted in substantial shifts in the attitudes and policies of many European countries with respect to refugees. The event has also raised concerns among local populations. For example, Brussels, Belgium was placed in a lockdown after the Paris raids in attempts to capture possible terrorists.

- What parameters of the model would likely shift or change completely in a major exogenous event?
- What would be the cascading effects on the movement of refugees in neighboring countries?
- How will the immigration policies that you recommend be designed to be resilient to these types of events?

Task 6: Scalability

Using your model, expand the crisis to a larger scale—by a factor of 10. Are there features of your model that are not scalable to larger populations? What parameters in your model change or become irrelevant when the scope of the crisis increases dramatically? Do new parameters need to be added? How does this increase the time required to resolve refugee placement? If resolution of the refugee integration is significantly prolonged, what new issues might arise in maintaining the health and safety of the refugee and local populations? What is the threshold of time where these new considerations are in play? For example, what policies need to be in place to manage issues such as disease control, childbirth, and education?

The Report

The UN Commission on Refugees has asked your ICM-RUN team to provide a 19-page report that considers the factors given in your tasks. Your team should also write a one-page policy recommendation to be read by the UN Secretary General and the Chief of Migration. The Commission has also provided you with some online references that may be helpful:

`http://www.bbc.com/news/world-europe-34131911`

`hhttp://www.iom.int/`

hhttp://iussp2009.princeton.edu/papers/90854

hhttp://www.unhcr.org/pages/49c3646c4d6.html

hhttp://www.nytimes.com/2015/08/28/world/migrants-refugees-europe-syria.html?_r=0

hhttp://www.who.int/features/qa/88/en/

hhttp://www.euro.who.int/en/health-topics/health-determinants/migration-and-health/migrant-health-in-the-european-region/migration-and-health-key-issues

hhttps://www.icrc.org/en/war-and-law/protected-persons/refugees-displaced-persons

The Results

The 2,137 solution papers were coded at COMAP headquarters so that names and affiliations of the authors were unknown to the judges. Each paper was then read preliminarily by triage judges. At the triage stage, the summary, the model description, and overall organization are the primary elements in judging a paper. Final judging by a team of modelers, analysts, and subject-matter experts took place in late March. The judges classified the papers as follows:

Problem	Outstanding	Finalist	Meritorious	Honorable Mention	Successful Participant	Total
D	5	5	183	254	304	864
E	5	4	545	1,644	1,007	3,209
F	4	6	207	390	338	952
Combined	14	15	935	2,288	1,649	5,025

Outstanding Teams

Institution and Advisor **Team Members**

Network Problem: Measuring the Evolution and Influence in Society's Information Networks

Institution and Advisor	Team Members
Northwestern Polytechnical University Xi'an, China Junqiang Han	Wenbin Zhang Xiangtian Li Jing Ou
Communication University of China Beijing, China Shanzhen Lan	Lu Lei Yongguo Ren Xue Bai

Chongqing University Chongqing, China Xiaobing Hu	Dong Liu Kaimin Lei Yipeng Xue
Huazhong University of Science and Technology Wuhan, China Zhengyang Mei	Xiao Liu Dingchang Wang Guodong Jiang
Rensselaer Polytechnic Institute Troy, NY Peter R. Kramer	Alex Norman Madison Wyatt James Flamino

Environmental Problem: Are We Heading Towards a Thirsty Planet?

Brown University Providence, RI Bjorn Sandstede	Julia Gross Clayton Sanford Geoffrey Kocks
Xiamen University Xiamen, China Zhong Tan	Yuchen Liu Yuwei Huang Huijuan Jiang
United States Military Academy West Point, NY Jong Chung	John McCormick Matthew Yuan Zachary Zimmerman
University of Colorado Denver Denver, CO Gary A. Olson	Robert Lewis Lawrence Pelo Samuel Loos
NC School of Science and Mathematics Durham, NC Daniel J. Teague	James Chapman Tejal Patwardhan Vibha Puri

Policy Modeling Problem: Modeling Refugee Immigration Policies

Renmin University of China Beijing, China Wei Xue	Xi Cheng Lingchu Liu Tianze Yue

Sun Yat-Sen University Guangzhou, China Qiru Wang	Qi Zheng Wenbo Feng Ruoyu Lan
Shandong University Jinan, China Baodong Liu	Pingge Hu Xiaoran Wang
NC School of Science and Mathematics Durham, NC Daniel J. Teague	Anna Hattle Katherine Yang Sichen Zeng

Awards

Leonhard Euler Award

The Leonhard Euler Award is presented to a team solving the D Problem that performs especially creative and innovative modeling while showing good understanding of interdisciplinary science. The award honors the 18th-century Swiss applied mathematician, who was known for the breadth of his research applications, his considerable contributions to sciences and mathematics through his written work, his excellent teaching, and his interdisciplinarity. This year's Euler Award goes to the team from Rensselaer Polytechnic Institute, advised by Peter Kramer, with team members Alex Norman, Madison Wyatt, and James Flamino.

Rachel Carson Award

The Rachel Carson Award honors the American conservationist whose book *Silent Spring* initiated the global environmental movement and whose work spanned many disciplines concerned with the local and global environments. This award for excellence in using scientific theory and data in modeling Problem E goes to the team from the United Sates Military Academy, advised by Jong Chung, with team members John McCormick, Matthew Yuan, and Zachary Zimmerman.

Vilfredo Pareto Award

This award for outstanding modeling in the Policy Modeling problem (Problem F) honors the work and legacy of a famous social science problem solver, who at various times was an engineer, sociologist, economist, political scientist, mathematician, and philosopher. For this award, the head judge seeks to highlight a paper that best models the more dynamic and challenging contextual human elements that make simplification or refinement of policy models so difficult. This year is the first time for this award to be presented. The award goes to the North Carolina School of Science and Mathematics, advised by Daniel Teague, with team members Anna Hattle, Katherine Yang, and Sicheng Zeng.

INFORMS Awards

The Institute for Operations Research and the Management Sciences (INFORMS) provides prizes to include plaques, money, and student membership in INFORMS for the members of an outstanding team for each problem. The year's winners are:

- Problem D: Huazhong University of Science and Technology, Zhengyang Mei (advisor), Xiao Liu, Dingchang Wang, and Guodong Jiang (members).
- Problem E: North Carolina School of Science and Mathematics, Daniel Teague (advisor), James Chapman, Tejal Patwarhan, and Vibha Puri (members).
- Problem F: Sun Yat-Sen University, Qiru Wang (advisor), Qi Zheng, Wenbo Feng, and Ruoyu Lan (members).

Two Sigma Scholarship Award

A Two Sigma Scholarship Award went to the Outstanding team from Rensselaer Polytechnic Institute, advised by Peter R. Kramer, with members Alex Norman, Madison Wyatt, and James Flamino. They received a total of $10,000. This was the second year of this award, for which the 480 U.S. teams competing in the ICM or the accompanying Mathematical Contest in Modeling (MCM)® were eligible for one of two such scholarship prizes. We thank Two Sigma Investments LLC of New York (`http://www.twosigma.com/`) for making this award possible.

Judging

Contest Directors
Chris Arney, Dept. of Mathematical Sciences, U.S. Military Academy, West Point, NY

Associate Director
Tina Hartley, Dept. of Mathematical Sciences, U.S. Military Academy, West Point, NY

Problem D: Network Problem: Measuring the Evolution and Influence in Society's Information Networks

Head Judges

Jessica Libertini, Dept. of Applied Mathematics, Virginia Military Institute, Lexington, VA

Ralucca Gera, Dept. of Mathematics, Naval Postgraduate School, Monterey, CA

Final Judges

Fuping Bian, Tianjin University, Tianjing, P.R. China

Robert Ulman, Network Sciences Division, Army Research Office, Research Triangle Park, NC

Jie Wang, Computer Science Dept., University of Massachusetts, Lowell, Lowell, MA

Rui Wang, Office of Performance Measurement and Evaluation, New York State Office of Mental Health, Albany, NY

Problem E: Environmental Problem: Are We Heading Towards a Thirsty Planet?

Head Judges

Amanda Beecher, School of Theoretical and Applied Sciences, Ramapo College, Mahwah, NJ

Amy Richmond, Dept. of Geography and Environmental Sciences, U.S. Military Academy, West Point, NY

Judges

Kristin Arney, (Ph.D. student), Dept. of Industrial and Systems Engineering, University of Washington, Seattle, WA

Rachelle DeCoste, Dept. of Mathematics, Wheaton College, Norton, MA

Carrie Diaz-Eaton, Center for Biodiversity, Unity College, Unity, ME

Kasie Farlow, Dept. of Mathematical Sciences, U.S. Military Academy, West Point, NY

Tina Hartley, Dept. of Mathematical Sciences, U.S. Military Academy, West Point, NY

Veena Mendiratta, Bell Labs, Alcatel-Lucent, Naperville, IL

Kari Murad, Dept. of Physical and Biological Science, The College of St. Rose, Albany, NY

Joseph Myers, Mathematics Division, Army Research Office, Research Triangle Park, NC

Rodney Sturdivant, Dept. of Statistics, The Ohio State University, Columbus, OH

Ashwani Vasishth, Dept. of Environmental Studies, Ramapo College, Mahwah, NJ

Problem F: Policy Modeling Problem: Modeling Refugee Immigration Policies

Head Judges
Kathryn Coronges, Network Science Institute, Northeastern University, Boston, MA
Yulia Tyshchuk, Network Science Center, U.S. Military Academy, West Point, NY

Judges
Eleanor Abernethy, (Ph.D. student), Dept. of Mathematics, University of Tennessee, Knoxville, TN
Chris Arney, Dept of Mathematics, U.S. Military Academy, West Point, NY
Kira Hutchinson, Training and Doctrine Command, U.S. Army, VA
Rachel Sondheimer, Dept of Social Sciences, U.S. Military Academy, West Point, NY

Triage Judges in the USA

Chris Arney and Tina Hartley, Dept. of Mathematical Sciences, U.S. Military Academy, West Point, NY
Amanda Beecher, Dept. of Mathematics, Ramapo College of New Jersey, Mahwah, NJ
Andrew Glen, Dept. of Mathematics and Computer Science, Colorado College, Colorado Springs, CO
Hilary Fletcher, Mathematician, NJ
Ralucca Gera, Dept. of Mathematics, Naval Postgraduate School, Monterey, CA
Alex Heidenberg, US Army, Ft. Bragg, NC
Jessica Libertini, Dept. of Applied Mathematics, Virginia Military Institute, Lexington, VA
Elizabeth Russell, National Security Agency, Fort Meade, MD
Michael Smith, Missile Defense Agency, Huntsville, AL
Robert Wooster, Dept. of Mathematics, College of Wooster, Wooster, OH
Richard Allain, (graduate student), Naval Postgraduate School, Monterey, CA
Gregory Allen, (graduate student), Naval Postgraduate School, Monterey, CA
Ryan Miller, (graduate student), Naval Postgraduate School, Monterey, CA
Karoline Hood, (graduate student), Naval Postgraduate School, Monterey, CA
Nicholas Sharpe, (graduate student), Naval Postgraduate School, Monterey, CA
Scott Warnke, (graduate student), Naval Postgraduate School, Monterey, CA

Triage Judges in China

Fuping Bian, Tianjin University, Tianjing
Minghua Deng, Peking University, Beijing
Mingfeng He, Dalian University of Technology, Dalian
Qiuhui Pan, Dalian University of Technology, Dalian
Xingzeng Wang, Shandong University of Science and Technology, Qingdao
Huayong Xiao, Northwestern Polytechnical University, Xi'an
Yin Xu Tianjin, University of Technology and Education, Tianjin
Mengda Wu, National University of Defense Technology, Changsha
Enshui Chen, Southeast University, Nanjing
Lei Chen, Xi'an Jiaotong University, Xi'an
Rudong Chen, Tianjin Polytechnic University, Tianjin
Xiongda Chen, Tongji University, Shanghai
Hengjian Cui, Capital Normal University, Beijing
Haitao Fang, Chinese Academy of Sciences, Beijing
Qu Gong, Chongqing University, Chongqing
Zuguo He, Beijing University of Posts and Telecommunications, Beijing
Liangjian Hu, Donghua University, Shanghai
Guangfeng Jiang, Beijing University of Chemical Technology, Beijing
Xinhua Jiang, Beijing University of Chemical Technology, Beijing
Yalian Li, Chongqing University, Chongqing
Kangsheng Liu, Zhejiang University, Hangzhou
Yicheng Liu, National University of Defense Technology, Changsha
Yongming Liu, East China Normal University, Shanghai
Guohua Peng, Northwestern Polytechnical University, Xi'an
Chunjie Su, East China University of Science and Technology, Shanghai
Zhiyi Tan, Zhejiang University, Hangzhou
Zhong Tan, Xiamen University, Xiamen
Dan Wang, National University of Defense Technology, Changsha
Yanhui Wang, Shandong University of Science and Technology, Qingdao
Qifan Yang, Zhejiang University, Hangzhou
Jun Ye, Tsinghua University, Beijing
Yuanbiao Zhang, Zhuhai College of Jinan University, Zhuhai
Rong Zhou, Shandong University of Science and Technology, Qingdao
Jinxing Xie, Tsinghua University, Beijing
Fengshan Bai, Tsinghua University, Beijing
Jianping Du, Zhengzhou Information Science and Institute, Zhengzhou
Xiwen Lu, East China University of Science and Technology, Shanghai
Zhaohui Liu, East China University of Science and Technology, Shanghai
Xiaoyin Wang, Huazhong Agricultural University, Wuhan
Zhenbo Wang, Tsinghua University, Beijing
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Acknowledgments

We thank:

- the Institute for Operations Research and the Management Sciences (INFORMS) for its support in judging and providing prizes for a winning team;
- Two Sigma Investments LLC for providing its prize; and
- all the ICM judges and advisors for their valuable and unflagging efforts.

Cautions

To the reader of research journals:

Usually a published paper has been presented to an audience, shown to colleagues, rewritten, checked by referees, revised, and edited by a journal editor. Each of the team papers here is the result of undergraduates working on a problem over a weekend. Editing (and usually substantial cutting) has taken place; minor errors have been corrected, wording has been altered for clarity or economy, and style has been adjusted to that of *The UMAP Journal*. The student authors have proofed the results. Please peruse these students' efforts in that context.

To the potential ICM advisor:

It might be overpowering to encounter such output from a weekend of work by a small team of undergraduates, but these solution papers are highly atypical. A team that prepares and participates will have an enriching learning experience, independent of what any other team does.

Editor's Note

The complete roster of participating teams and results is too long to reproduce in the *Journal*. It can be found at the COMAP Website:

`http://www.comap.com/undergraduate/contests/mcm/contests/2016/results`

About the Authors

Chris Arney is a Professor of Mathematics at the United States Military Academy, where he has taught for 27 years. His Ph.D. is in mathematics from Rensselaer Polytechnic Institute. He also served as a Dean and acting Vice President for Academic Affairs at the College of Saint Rose in Albany and had various tenures as division chief and program manager at the Army Research Office in Research Triangle Park, NC, where he performed and managed research in cooperative systems, information networks, and artificial intelligence. Chris is the founding Director of the ICM and served as a team advisor and associate director of the Mathematical Contest in Modeling in its first years.

Tina Hartley is an Academy Professor at the United States Military Academy. Her Ph.D. is in computational mathematics from George Mason University. Tina began her military career as an Air Defense Artillery Officer and also served as an Operations Research Analyst. She is currently the Director of the Core Mathematics Program at the United States Military Academy. She has been an ICM judge for the past eight years and has coordinated the triage judging for several of those years.

Characterizing Information Importance and Its Spread

James Flamino
Alex Norman
Madison Wyatt

Rensselaer Polytechnic Institute
Troy, NY

Advisor: Peter R. Kramer

Abstract

Our goal is to analyze information spread by understanding the modes by which people communicate and the information that they convey, from the 1860s to now.

First, we designate news as consumption, politics, or entertainment. We then define the importance of an item by its relative novelty, accessibility, attractiveness, and compatibility, and determine an overall relevance factor.

Our model enhances the information diffusion model to account for conflicting information and the topical distribution of news in terms of popularity in a given era. We translate this information to a graphical node model to determine the spread of a news item of a given category and relevance factor.

We build a network simulator based on our model that processes information spread for different eras, categories, and importance. From simulations and a comparison of real data from media archives, we find the characteristics of mass appeal. Our model accurately depicts the spread of news such as Abraham Lincoln's death and the erection of the Berlin Wall.

Finally, we expand our model and simulation to account for competing sources, changing topography (e.g., city vs. rural town), and isolation, to determine a strategy for optimizing information spread.

Introduction

Context and Motivation

Communication has evolved from small networks of groups with limited connections to the massive transmission of the internet. What has

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remained constant is the practice of seeking and sharing news. Communication theory suggests a few fundamental reasons: to persuade, to give or provide information, to seek information, and to express emotions. These basic desires drive the ways in which we build networks and determine the importance of each interaction.

We seek to develop a mathematical model of social networks to analyze communication at its core. To do this, we need to understand the modes by which people communicate, the information people convey and accept, the science of implanting news and the effects these all have on the resulting spread of the news.

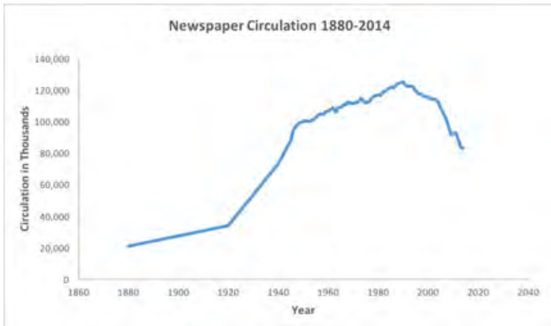
Assumptions

- Topical distribution trends are uniform throughout a given era.
- Noteworthy news overcomes the threshold of noise and disregards static information traffic.
- We assume a discretized time variable, updating the status of an information string in each node at regular intervals.
- The probability of someone registering and paying attention to a string of data, or indeed sharing it, is random.
- When a node shares data, it shares with all of its neighbors.

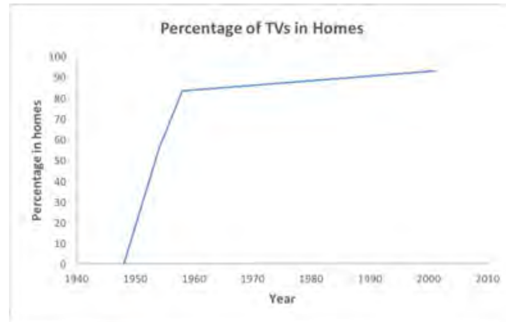
Data Analysis

Trends of News Sources

By compiling data from census reports, statistical assessments, and available databases, we determine the trends of four information transfer media: newspaper, radio, television, and the internet. The Industrial Revolution brought a massive increase in newspaper production so that the number of newspapers and subsequent circulation increased dramatically. In the 20th century, radio and TV began to replace newspapers as major sources of information; and more recently, the internet has massively expanded the spread of information, working to replace outdated media outlets as a primary source. Newspaper circulation skyrocketed from 1880 to 1940, until radio began to gain influence. In 1920, only about 3 million homes had a radio set; but that number reached 30 million by the end of the 1930s. By 1945, 80% of homes had a radio, and today radios are in virtually every car and home. The introduction of TV saw an even greater increase, with only 0.4% of households having a set in 1948 to 56% four years later. Finally, the internet has exceeded the trends of the previous



(a)



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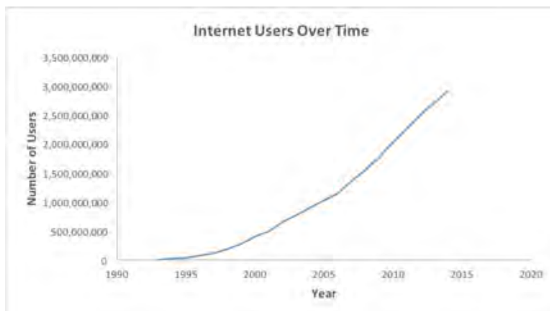


(c)

Figure 1. a) Newspaper circulation trends over time.

b) Percentage of TVs in US households over time.

c) Number of internet users over time (currently, 41% of the world).

media in unparalleled rapid expansion. These trends can be seen in **Figure 1a-1c**.

The introduction of each new medium contributed to an eventual downfall of the others. Although there was not extinction of any one, since they complement one another, increased usage of a novel medium brings a decrease in relevance of the current and past types. However, the internet combines the functions of newspapers, radio, and television with eNews, internet podcasts and instant streaming, respectively. Such comprehensive inclusion could make previous media obsolete.

What is News?

What makes news? How does one piece of information gain relevance over another? For our purposes, we define "news" as a piece of information that overcomes two thresholds: the threshold of *penetration* and the threshold of *retention*. We are concerned with the potential for widespread and/or lasting impression. The threshold of penetration is the minimum number of mentions across various sources for a piece of information to catch wind. The threshold of retention is the minimum amount of time that a piece of information is relevant enough to be shared. Essentially, in everyday news there is a level of noise of information that a story must overcome to be considered.

To determine what qualifies as news, we look at major news stories of the past 150 years. We track the volume change of phrases mentioned over periods of time in a database of over 10 million archived newspapers 1836–1922, in the *Washington Post* 1960–1963, and in data compiled from internet use today. We choose a phrase in terms of its relevance to the time period, and we track the volume of mentions per day over time.

We introduce two similar pieces of news and explore their ability to break above the thresholds. First, we examine the volume over time of mentions of the word "Lincoln" in newspapers 1864–1866. As seen in **Figure 2**, there is a consistent level of noise until April 15, 1865, corresponding to the assassination of President Lincoln.

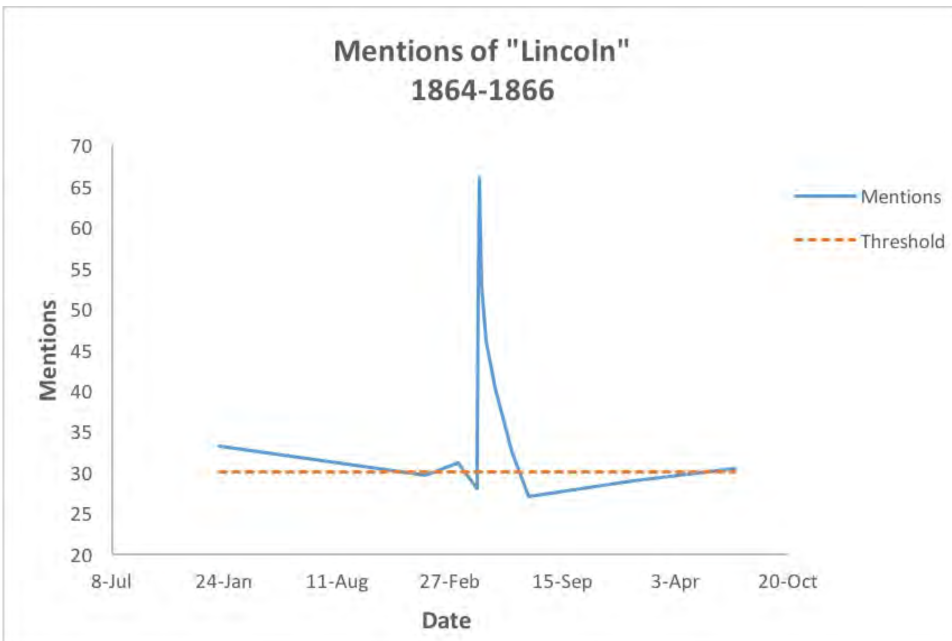


Figure 2. Mentions of "Lincoln" over time in US newspapers 1864–1866.

After a while, the volume of mentions returns to the threshold, even delving below as a phrase becomes less relevant over time. This is also seen in a similar scenario from 2012. There is an equal distribution of mentions of "Osama Bin Laden" and "Moammar Gaddafi" until a mention of Bin Laden's death was released into a communication network, spiking in his mentions (**Figure 4**).

Across the board, this shape and trend is seen for differing types of news in all eras, topics, and importance to the period (**Figure 4**).

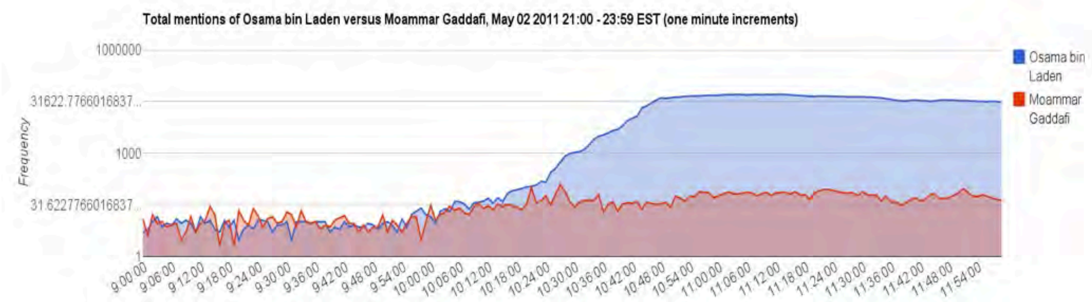


Figure 3. Mentions of the phrase "Osama Bin Laden" rose over time by a factor of 1,000, while mentions of "Moammar Gaddafi" (included for comparison) rose much less.

Trends of Topical Distribution

Finally, we examine the change over time of topical distribution in news sources. We categorize stories as falling into categories of *consumption*, *politics*, or *entertainment*. Compiling data from census reports on the circulation of different types of newspapers over the years, statistical data on radio and TV broadcast breakdown, and finally examining the top-10 news sources with the highest internet traffic for information type, we arrive at a topical distribution for the type of information being spread over time (**Figure 5**). There is a clear trend away from political news towards entertainment that is reinforced by the comparison of phrase volume distributions within eras (**Figure 6**).

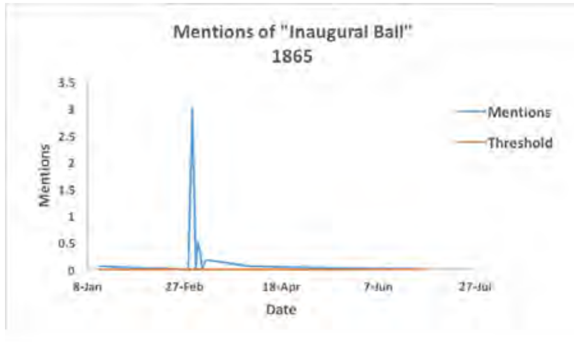
Models

How Information Spreads

We consider that communication is either *active* or *passive*:

- *Active* communication requires focus on the part of both the sharer and receiver of information. A notable example would be newspapers, the journalists and editors of a newspaper must certainly pay attention as they place stories in the next day's run, and those that consume newspapers have to focus on consuming the text presented.
- Conversely, some media are *passive* in nature. Radio and (at times) television require the focus of only one of the participants, the one sharing the information. The person receiving may instead focus on other things, such as driving a car or tasks around the home.

The internet is distinctly upload-oriented, which is one of its major selling points: the freedom of people to express themselves universally. However, the internet is at times both passive and active. There are articles



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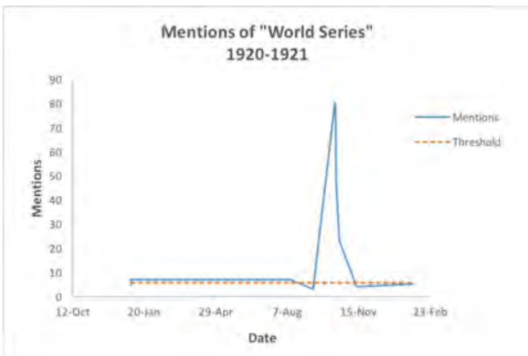

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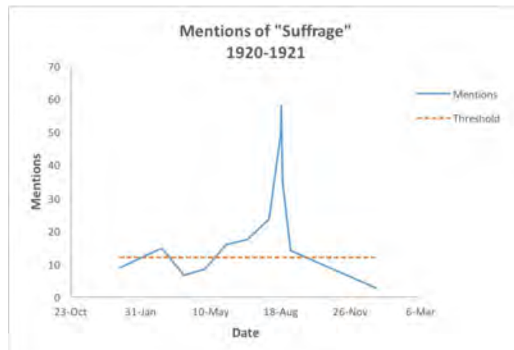

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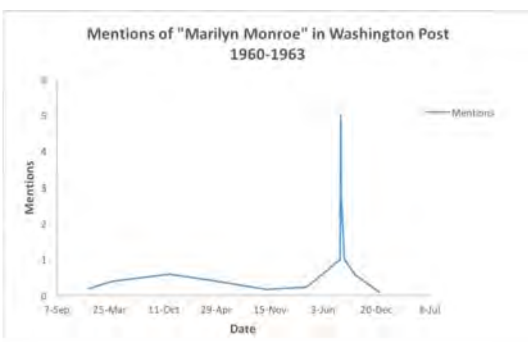

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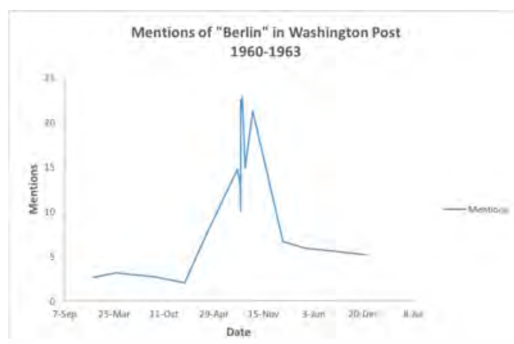


(e)

Figure 4. a) Mentions of "Inaugural Ball" in newspapers 1864–1866. Peak corresponds to Lincoln's 2nd Inaugural Ball.

b) Mentions of "World Series" in the early 1920s. Peak corresponds to a Cleveland victory.

c) Mentions of "Suffrage" in the early 1920s. Peak corresponds to the ratification of the 19th Amendment. Notice the dip below threshold after the release, as the phrase lost relevance .

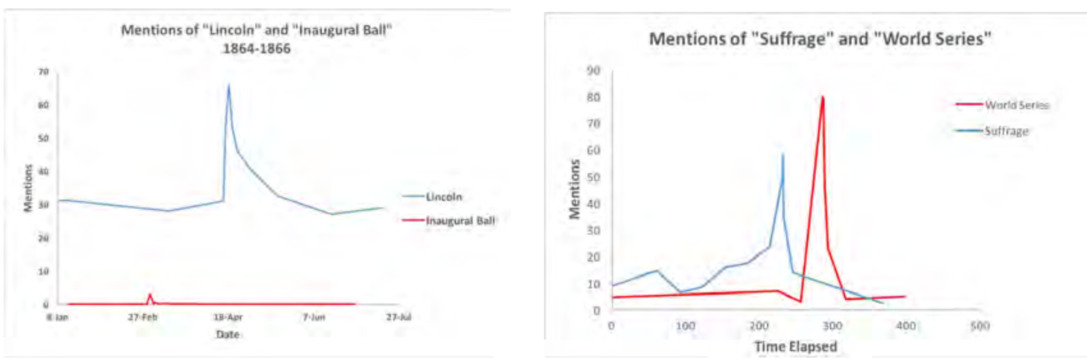
d) Mentions of "Marilyn Monroe" 1960–1962. The peak corresponds to her deadly overdose in 1962.

e) Mentions of "Berlin" 1960–1962. The peak shows the date of erection of the Berlin Wall. Notice the retention of the news.

(a) Circulation proportion of newspaper type in 1880.

(b) News type by user volume of the top ten visited websites in 2015.

Figure 5. Comparison of news sources in 1880 vs. 2015.



(a) **(b)**

Figure 6. Comparison of (a) a political news story and (b) an entertainment piece in 1865.

to read and interactive games, but also streaming services such as Netflix, Spotify, and podcasts. While the internet has not yet branched out to encompass areas traditionally held by passive media, steps are being taken, such as listening in a car to podcasts rather than to the radio.

Previous Models and Limitations

The comparison to physical diffusion is largely seen in modeling information spread. The model has a basic form of

$$\frac{dA(t)}{dt} = i(t)[P - A(t)],$$

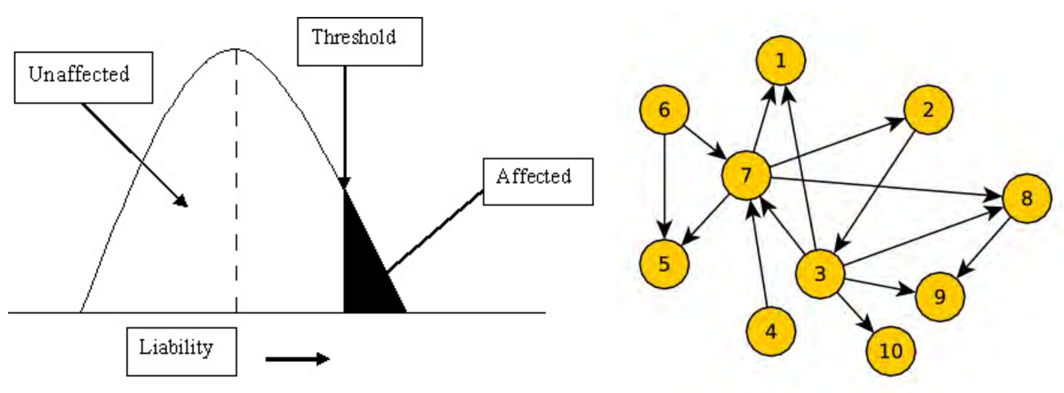
where $A(t)$ are the individuals that have received the information, P is the total population, and $i(t)$ is a diffusion coefficient.

The diffusion coefficient can be expanded to include an addition factor independent of the number of current individuals with the information, a multiplicative factor accounting for internal effect of imitation on the spread of the knowledge, or a combination of the two, as we indicate:

$$i(t) = \begin{cases} \alpha, \\ \beta A(t), \\ \alpha + \beta A(t) \end{cases}$$

Such a model maps the diffusion, given internal and external influence qualities. However, it lacks versatility and does not account for other factors that enhance or inhibit the spread of information.

Previous work in modeling the spread of information in a graph can be categorized into two types (Figure 7). A *threshold model* is defined by a system in which people adopt a position if a certain ratio of their neighbors adopt it. In a *cascade model*, each node with information has a certain probability to spread it to each of its neighbors; so one node can actually begin an information cascade simply by spreading something that is "infectious," in analogy to viral media.



(a) **(b)**

Figure 7. Basic representation for
(a) a threshold model (graphic courtesy of Hawaii Department of Health Genomics Section, `http://health.hawaii.gov/genetics/glossary/`), and
(b) a cascade model
(courtesy of Suman Kundu, `http://sumankundu.info`).

Diffusion Model with Multiple Sources

We introduce an enhanced model of information diffusion that accounts for factors omitted in the previous model. To describe accurately the adoption of a story into mainstream news and track the resulting spread, we take into consideration the following factors:

- The topical distribution of newsworthy items changes over time. In a community oriented toward one subject, an item of that subject will spread more quickly than one on a different subject. The topic of the item will affect the spread among a population and is an internal factor.
- Items have varying levels of importance to a community. Some items with high importance, such as assassination of a President, span the gaps of interest distribution in a population. The importance of a item is an external factor that affects the spatial spread of the information as well as the speed of spread. The importance of an item is determined by:
  - novelty or shock (ability to spark interest without back story),
  - accessibility (ability of any individual to understand),
  - attractiveness (impact of news on individual), and
  - compatibility (alignment with societal values and/or acceptable notions).

These considerations combine to give a total *Relevance Factor* which we scale from 1 to 10. This factor determines the rate of spread of the information to the connected nodes of the network. An item with a high relevance factor will have high probability of penetration, velocity, and retention. We remind the reader that an item run through our model has already been categorized as "news" and therefore exceeds the respective thresholds. Thus, we assume that an item will propagate to some extent, and we model the subsequent spread through its relevance factor.

Let $y(t)$ denote the number of individuals who know a piece of information at time t. To model the topical distribution for a given time, we designate a certain percentage of individuals to be "interested" in each topic, based on compiled data of the time. For example, for a model of 1880, 89% of the individuals will be politically oriented and 7% will be entertainment. We are not insinuating that real individuals have single-minded interests, but simply that the percentages of interest of a community will change given the relative distribution of the time. We model this feature by designating percentages of nodes, which in turn account for the respective effect of item topic on the spread.

If a news piece is topically relevant to a community, it will naturally spread between individuals within that community; but it also has the potential to leak to other communities. Essentially, an entertainment individual will still hear and share news of a high-profile political story, and vice versa. The key to this cross-community sharing lies in the relevance of the information itself. A low-relevance political story will spread slowly in an entertainment network, and a high-relevance political story will still spread quickly in a consumption network despite the conflicting interest.

This concept can be modeled in the following way:

$$\Delta y = R(t)\{[\beta_1 y_1(t) + \eta_{12} y_2(t)]\,(N_1 - y_1(t)) \\ + [\beta_2 y_2(t) + \eta_{21} y_1(t)]\,(N_2 - y_2(t))\}\Delta t,$$

or more generally,

$$\Delta y = R(t)\left\{\sum_{i=1}^{n}\sum_{\substack{j=1\\ j\neq i}}^{n}[\beta_i y_i(t) + \eta_{ij} y_j(t)]\,(N_i - y_i(t))\right\}\Delta t,$$

where

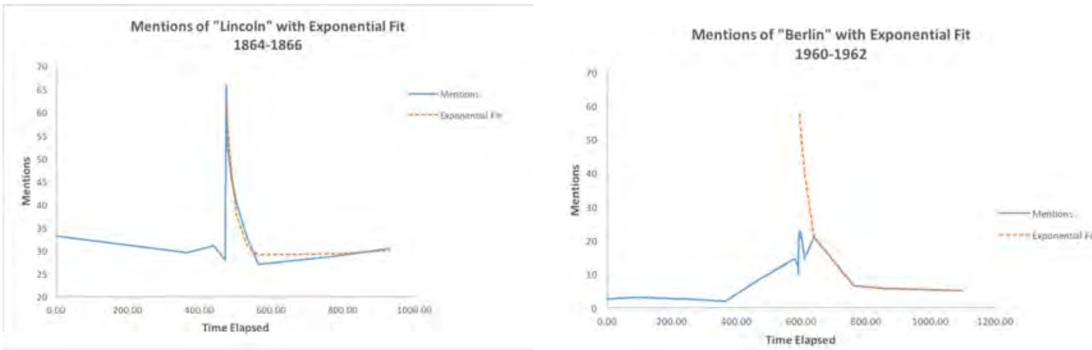
- i represents a topical community. For example, N_1 denotes the community interested in entertainment, N_2 in politics, etc.
- β_i represents the rate at which an individual in community i spreads an information piece relevant to that community.
- η_{ij} represents the rate at which an individual in community i will spread the information to someone in community j who does not know the information.

A piece of information relevant to one community will spread most quickly between nodes of this community, more slowly between those nodes and conflicting nodes, and most slowly through two nodes of conflicting interest to the story. Generally, when information i is released, we have $\beta_j < \eta_{ji} < \eta_{ij} < \beta_i$ where i and j range over the number of categories and $i \neq j$.

In determining the final number of individuals privy to the information at a given time, the function $y(t)$ is multiplied by an external relevance factor, $R(t)$, to account for information that spans the gaps in community interest. Although as a community we value some news pieces more than others, there are certain viral news stories that bridge these differences: We are affected by major political changes, influenced by mass entertainment, and impacted by new innovations. Although we are trending away from political news towards technological and entertainment-oriented news, spikes of important stories make their way to the individuals of all communities.

The function $R(t)$ can be dynamic in time and allow for consideration of the characteristics described above. In general, items rise and decay *exponentially* at a speed proportional to their relevance. For example, an item that is novel but not necessarily impactful will have a quick ascent in volume followed by a quick decay; but an item that is novel, impactful, and accessible will have a quick ascent and slow decay, corresponding to high penetration and retention.

This property of exponential decay is reinforced in volume data that we collected from spread of real events (**Figure 8**). The accuracy of the fit of exponential decay is shown in **Table 1**.



(a) **(b)**

Figure 8. An exponential function fitted to the decay of mentions over time.

Table 1.

High values of R^2 for fits for previously-mentioned news stories indicate that exponential decay in our model is reasonable.

Phrase	R^2
Berlin	1.00
Lincoln	.96
World Series	.94
Suffrage	.90
Marilyn Monroe	.89

Network Model

Thus far, we have shown that the spread of a piece of information depends on internal and external influence factors that contribute to a combined relevance factor that varies with time. We have also shown the ability to model and predict the nature of $R(t)$ given the characteristics of the incident information.

To further our model, we base it in graph theory, with the goal of observing the flow of information in a population connected by different means of communication, which we model by different types of edges.

Some forms of communication are distinctly consumption-oriented in nature, where one merely receives information from these media, such as newspapers, radio, and television. We represent such a relationship with a directed edge. Forms of communication that are upload-oriented in nature include telegraph, the internet, and talking; we represent these by undirected edges.

Take a node i at time t in internal state $\mathcal{I}_{i,t}$ with inward connections to nodes $\{1, 2, \ldots, j\}$ and outward state (the state to which the node is transmitting to its neighbors) represented by $n_{i,t}$. We represent the absorption of information by:

$$\mathcal{I}_{i,t,k} = n_{k,t-1} \cdot P_{N_i},$$
$$\mathcal{T}_{i,t} = \prod_{k=1}^{j} (1 - \mathcal{I}_{i,t,k}),$$
$$\mathcal{I}_{i,t} = 1 - \mathcal{T}_{i,t},$$

where

- $n_{k,t}$ is either 0 or 1;
- P_{N_i}, also either 0 or 1, is a function that semi-randomly decides whether i shares something or not; and
- $\mathcal{T}_{i,t} = 0$ if i notices the information shared by any of the other nodes; if not, it stays at 1;
- $\mathcal{I}_{i,t} = 0$ denotes the node not "believing" the piece of information, whereas 1 denotes holding said piece of information.

Now, while this is a method to update the internal "belief" of a node, it does not necessarily signal this information to other nodes . We update their "external beliefs," what they share to the public, after a gestation period G from time t_0, in the following manner, where P_{S_0} is 0 or 1 in the same sense as P_{N_0}, but for sharing rather than noticing:

$$n_{i,t} = \delta_{t,t_0+G} \cdot P_{S_i} \cdot \mathcal{I}_{i,t}.$$

This expression is only ever 1 at a single time slice, since it uses the Kronecker delta δ to denote when the "belief" is put out into the open—that is, we have it a pulse of information, not a sustained signal. This formulation resembles a modified independent cascade model for social networks, or an SIR epidemic model but with increased intricacy.

Network Versatility

While our model is already quite versatile and can represent a number of scenarios, a few important problems stand out. While there is a "gestation" period for vertices, the model lacks any means of transmitting data from two connected points over a timescale longer than a single step. To that end, we bifurcate our vertices into two subcategories, "real nodes" and "ghost nodes":

- A *real node* represents a person, with whom information may or may not reside.
- A *ghost node* i is mathematically equivalent to a real node, except that $P_{S_i} = P_{N_i} = 1$, meaning that it is both noticing and transmitting data. A ghost node between also only has two directed connections, one inward and one outward.

  If the time that it takes to transfer between two nodes is as N steps (equivalent to things such as newspapers moving on trains), a ghost node would have a gestation period of $N - 1$.

Finally, to account for the real-world scenario of an individual forgetting a piece of news, the internal state of node i, who "believed" something at time t_0, at times after t_0 is represented by:

$$\mathcal{I}_{i,t} = \mathcal{I}_{i,t_0} \cdot P_{V_{i,t}},$$

where $P_{V_{0,t}}$ is 0 or 1, based on a weighted number generator that changes over time. As $t - t_0$ increases, $P_{V_{0,t}}$ will tend towards 1, since people become more forgetful of information over time.

Now, instead of the model simply reflecting people retaining information, it has people receiving information, forgetting it, then receiving it again from another source. This is much like how people hear news from an initial source, such as the newspaper or Facebook, go about their day and forget it, then hear about it again from someone in the home.

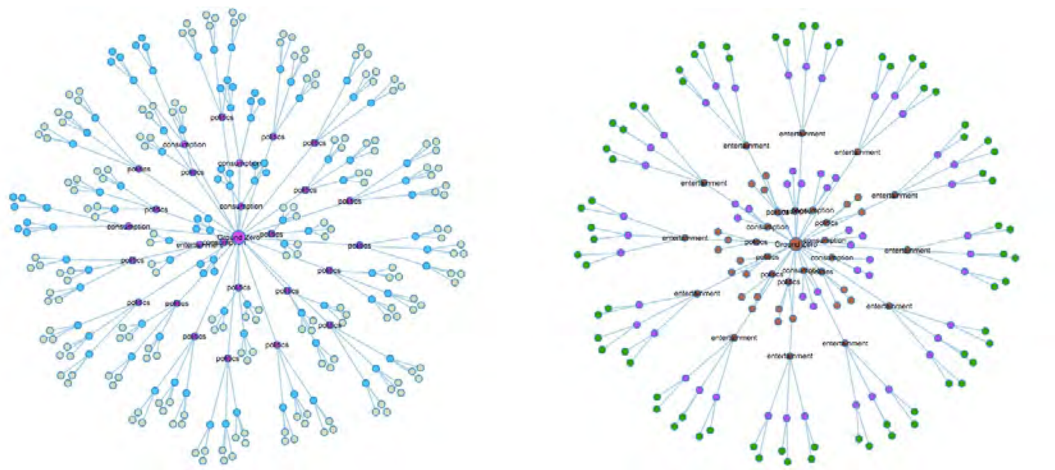
Simulations

We placed the parameters mentioned above into a simulation with a few additional modifications. As mentioned earlier, we categorize news as falling into one of three functions: politics, entertainment, and consumption. The nodes follow the proportional topical distribution of each time era. We allow data to originate from only one source, and the nodes themselves can only hold one string at a time until another piece of data overrides it.

We ran the simulations on two networks representing the cultures of the 1880 and 2015. The differences include the topical proportions and spread layouts, corresponding to the media categories and sources of the times. Finally, the simulation allows for a random generation of information input (order, type, relevance) or a controlled news input. A few simulations are represented in **Figure 9**.

Validity of Simulation

To validate our model, we simulate news of varying topic and relevance and compare it with real world data collected.



(a) **(b)**

Figure 9. Randomly generated news simulated in (a) the 1880 model and (b) the 2015 model. Notice the differences in community proportions and graph connections.

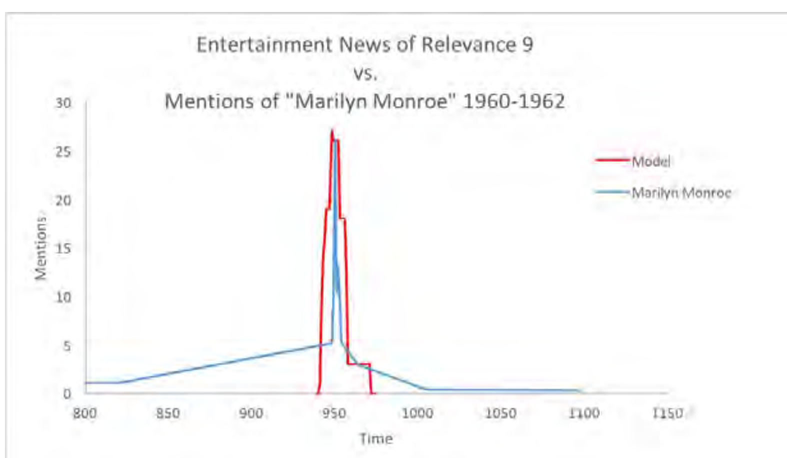
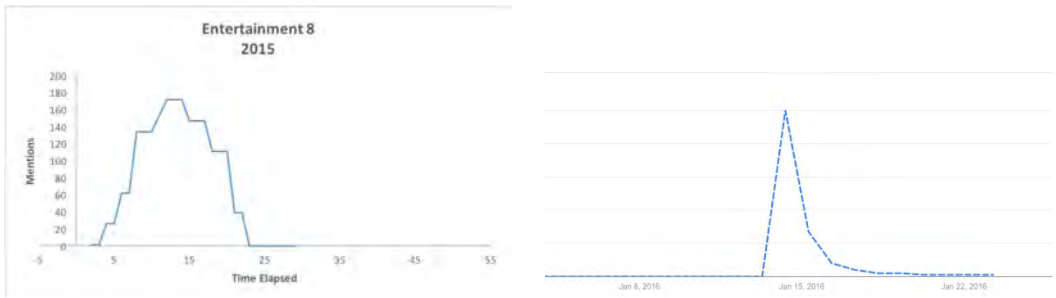


Figure 10. The volume of mentions in time of an entertainment item of relevance 9 and the data compiled around Marilyn Monroe's death.

As seen, the components of the real data are accurately reflected in the model. This news was highly relevant with high novelty, attractiveness, and accessibility. The death of Marilyn Monroe clearly had a high relevance factor, and that is reflected in the model (**Figure 10**). In a similar sense, our model for current spread and distribution reflects the news of Alan Rickman's death in January 2016 when compared with volume data from Google Trends (**Figure 11**).



(a) Model simulation of entertainment news in the 2015 model.

(b) Real-world trend of mentions of "Alan Rickman" over a given time.

Figure 11. Comparison of simulation with a real-world event.

Robust Nature of Simulation

To test the robustness of our model, we evaluate the predicted propagation of current news in past networks and vice versa. Take, for example, the announcement of Osama Bin Laden's capture and death. This would be considered political news of relevance 10. Also, consider the announcement of Kim Kardashian's pregnancy, an entertainment relevance of 6. We then test information of relevance 10 and of relevance 6 in our 1880 network to model their spread, with the results shown in **Figure 12**.

To get a sense of the accuracy of the data found, notice the similarities between real-volume data of Abraham Lincoln's assassination and news of the Inaugural Ball (**Figure 13**). The maximum height is lower for the entertainment news, and so is the retention period. We confidently state that the model reflects real scenarios across time periods.

The Future of Communication

There are active and passive news sources, as well as upload- and consumption-based sources. Upload-oriented networks, in and of themselves, can do everything that a consumption-oriented network can and more, and will dominate when the resources needed to sustain both are present.

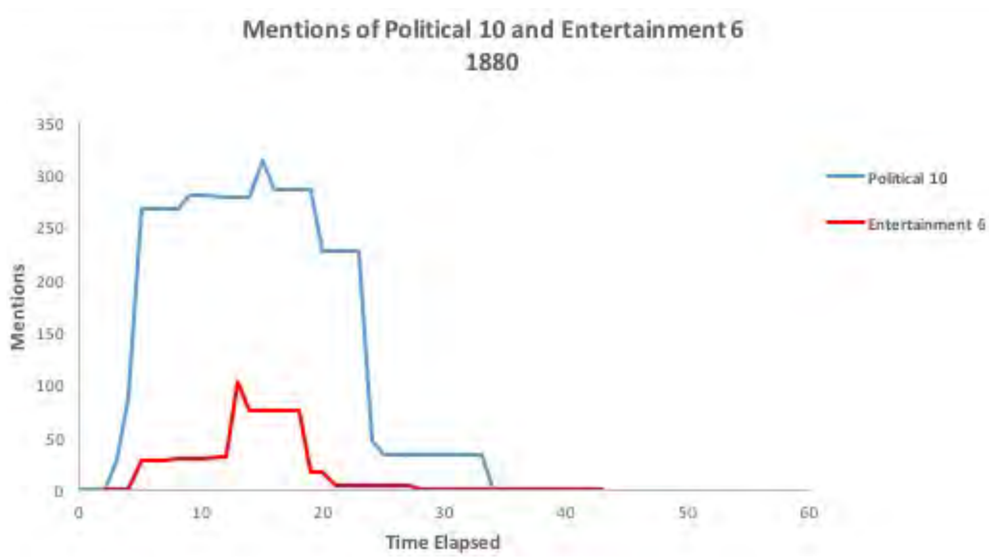


Figure 12. Simulation run on 1880 network with news of political relevance 10 and news of entertainment relevance 6.

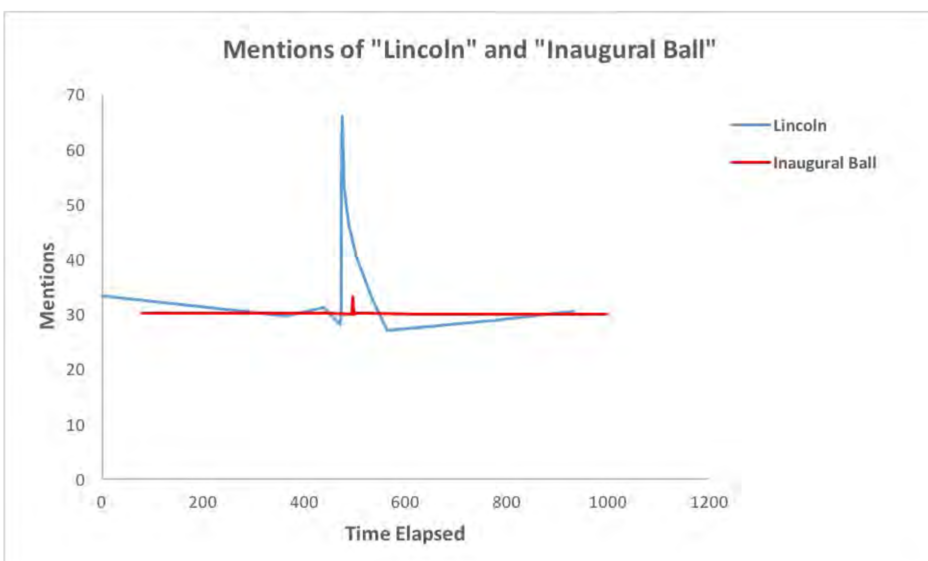


Figure 13. The volume spread of Lincoln's assassination and his earlier inaugural ball. The inaugural ball data has been shifted linearly in time to see direct comparison.

However, while those modes of communication fight each other for relevance, active and passive media act differently, complementing each other. Active media have a higher volume of communication in a given period of time, while passive media have occupancy space advantages. For example, passive media can be consumed while driving or completing other tasks, while active cannot. In this sense, the two complement each other and neither can dominate entirely.

As it stands, the internet is immune to competition, since it encompasses all of the above qualities. A new source of media must either improve an existing feature or remove flaws that inhibit information spread of the future.

A common occurrence in science fiction is a "neural uplink," instant direct transmission of information between minds. It is inherently faster than the internet, drastically shortening the gestation period. Additionally, it combines all types of communication. With such a new technology, it is impossible to predict if individuals would lose community sense and begin to function on a personal premise, given the immediate availability and personal nature of media.

Sensitivity Analysis

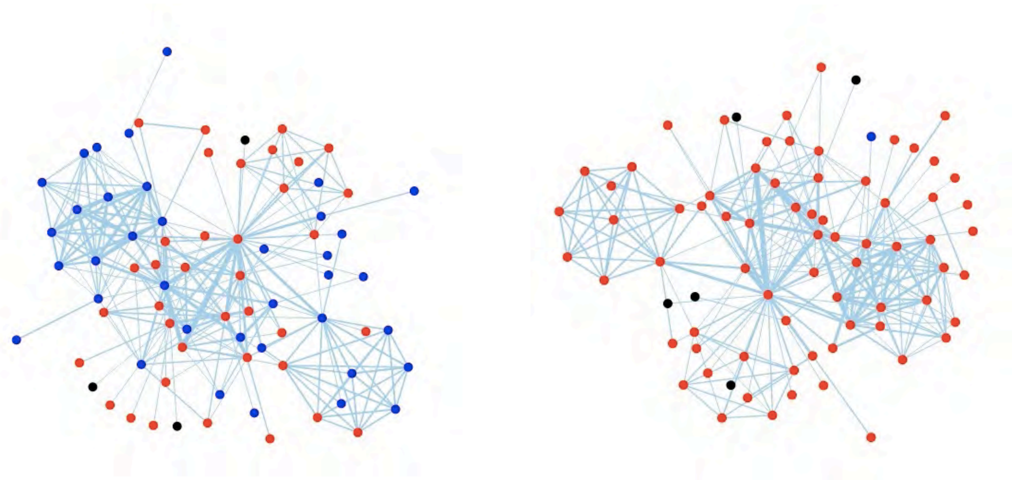
We address the impact of the parameters in our base model for simulating spread of information by varying them in the following ways.

Competing Sources

To study the propagation of news, we had limited the number of source nodes to one. We altered our simulation to include two competing news sources of the same type released simultaneously and follow the subsequent spread.

Varying Levels of Importance

We had assumed that there is a 50/50 chance for dominance when two pieces of data meet at a node. We ran two simulations: one in which the two pieces are equally believable; and one in which one is much more believable than the other, or equivalently, has higher relevance. The results are just as one would expect, with the first splitting the graph equally and the second being overrun by the more popular belief (**Figure 14**). Thus, we can see how misinformation that suits our preconceived notions spreads, since it is more believable to us and thus blots out real information in the network.



(a) Equal value. **(b)** Unequal value.

Figure 14. Information of higher value spreads quicker and further than that of a lower value. This is amplified if the competition is increasingly uneven.

Varying Initial Connectivity

For two sources of equal believability, the location of the initial nodes is important (cf. news beginning in a rural village vs. a large city). We find that an item beginning at a more-connected node reaches a larger number of subsequent nodes in a shorter time. This notion is reasonable in that fewer people will be privy to, and thus willing to accept, town gossip over city news.

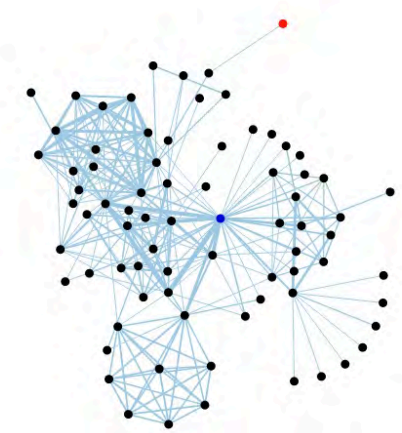
Recall the internet volume data surrounding the news of Osama Bin Laden's capture and death (**Figure 2**). The distribution closely resembles the spread of competing information (**Figure 15**). As "Osama Bin Laden" became a more relevant phrase, its volume and spread overtook "Moammar Gaddafi".

Varying Connection Distances

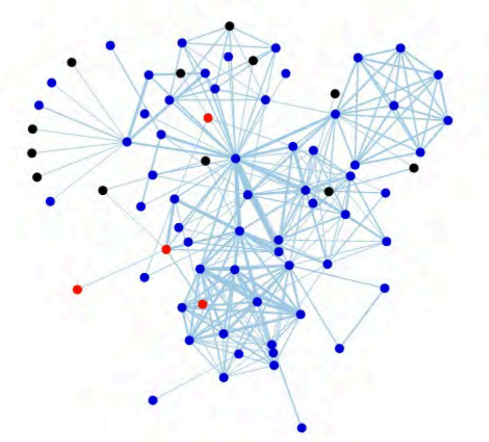
Finally, we alter the model to vary the distance between connections, making it take longer to move across certain edges than across others. There are now groupings of connectivity that vary in size and spread, which allows simulations of differing topologies. Consider, for example, an island in a network with the mainland. It takes a fair amount of time to move information between them by boat, but information propagates much faster on either the island or the mainland alone. This scenario differs from the previous simulation in that the connective speeds, as well as the connectivity volume, are varied.

As before, we consider two items that are equally relevant or believable.

We find that the information originating on the island remains isolated to the island, while the mainland information dominates the mainland (**Figure 16**).



(a) Initial sources.



(b) Spread after time.

Figure 15. Influence of the initial position or connections on spread.

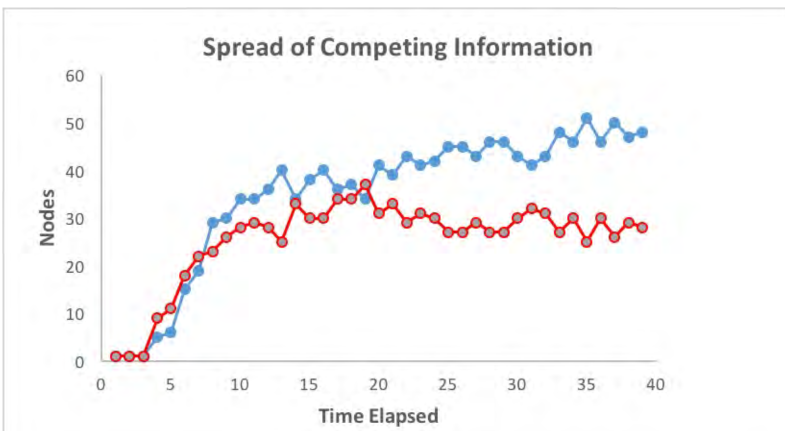
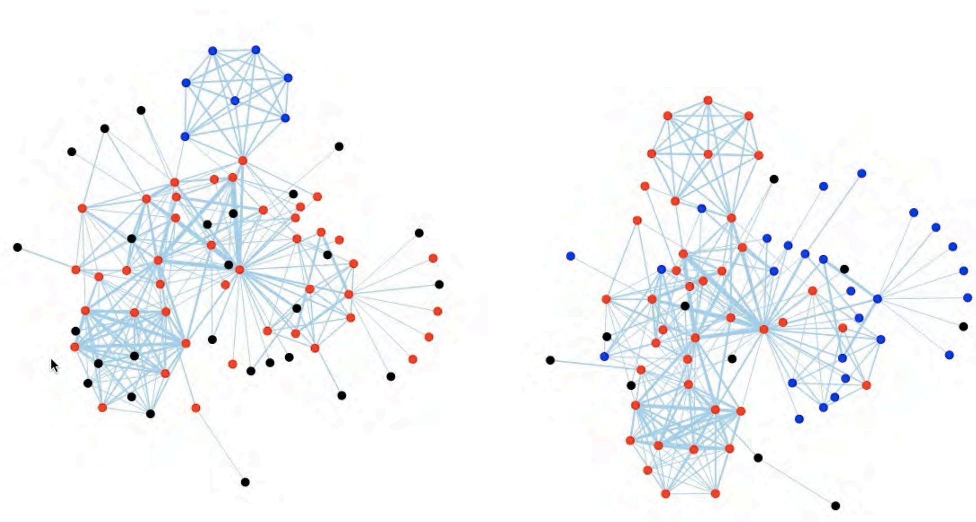


Figure 16. Red and blue information pieces with equal relevance factors of 10 were released simultaneously; blue was released in a more-connected hub.

Next, we also consider news beginning with a higher relevance or believability, this time on the less-connected island, and news with a lower value, now beginning on the mainland. The two views establish an equilibrium with roughly the same adopting nodes (**Figure 17**).

Finally, if the data from the mainland are more relevant, the data on the island die out quite quickly (**Figure 18**). If news starts out isolated by topology, it must make up for it in other ways simply to remain relevant.



(a) **(b)**

Figure 17. The resulting spread of two pieces of information beginning in an isolated (blue) and connected (red) community, respectively. (a) Equal relevance information simultaneously spread. (b) More highly relevant information (blue) released in the isolated community.

Figure 18. Higher relevance information (red) is initiated in a connected community simultaneously with information (blue) initiated in an isolated community.

Optimization of Spread

From these simulations, we can also make statements about optimizing spread strategy. Our analysis furthers the expected belief that to maximize spread, the information needs high relevance, topical importance, and a carefully-selected initial source. Ideally, a piece of information needs to be novel, accessible, attractive, and compatible. It needs in some way to be able to be characterized with the dominant topic of the time. Finally, it needs to be initiated in a carefully selected initial place with the highest connectivity—both in personal node connections and global community connections. A node with many edges is not necessarily more connected if the surrounding nodes are weak.

Conclusion

The relationship between the importance of a piece of information and its resulting spread is a combination of many factors separately intrinsic to the item and to the community. We have extensively shown that our model can account for changes in these factors and accurately reflect the penetration, spread, and retention of the information. Although news items spike and decay at varying levels, they follow a consistent model. Thus, by examining the spread of an item, we can extrapolate the underlying factors that contribute to its relevance. Conversely, by knowing the characteristics of an information piece, we can predict the resulting spread. Finally, we can use this knowledge to spread an information item strategically.

Strengths in the Models

Our models are multifaceted and inclusive:

- The diffusion model allows for varying levels of importance affecting volume of mentions. It is easily modified for an increased number of interest categories or types of news, and it models the interactions of a news piece between the categories.
- The graph model excels in versatility: Spatial distance can be represented by assigning velocities to edges, and different media can be assigned for the propagation of information based on velocities and direction of edges.
- The versatility allows us to see relationships between information with different levels of importance based on a number of inherent characteristics and the spread of an item.

Weaknesses in the Models

We are unable to model true preferences of individuals, only the preferences of the network as a whole. The connections are generated randomly, so the more-realistic scenario of having more connections with like-minded people within certain communities is lost, even if the overarching preference of the community is preserved. The models rely on discrete time values and weighted randomness in deciding how information is noticed and shared. In addition, our graph model involves a static graph, in that no nodes appear or disappear and no edges change.

Appendix

Our simulation at `http://www.silverwebsim.com` implements the models developed in this report.

The user can either activate an indefinitely-long simulation with a number of randomly-generated news events, or else release a singular controlled and customized news event in order to study its spread through a system.

The simulation can be altered to release two similar news events at two user-chosen hubs in order to model the spread of competing information.

After running an event (or a number of events) for a chosen time, the user can select the compile option and the simulator will then process the information and present the data in a tabular format.

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Judges' Commentary: Spread of News Through the Ages

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Introduction

In 2016, the Interdisciplinary Contest in Modeling (ICM) offered a choice of three problems to student teams. Problem D, the 2016 Network Science / Operations Research problem, asked teams to explore the historical evolution of media and its role in spreading information, defining news, and ultimately shaping public opinion. The problem statement is given in the contest report earlier in this issue.

Judges' Criteria

This year's judging panel included representatives from both industry and academia with areas of expertise that included applied mathematics, mathematical modeling, network science, operations research, and engineering. Given the broad scope of the question, only a handful of papers were able to answer all of the elements of the question thoroughly; so even in the final rounds of judging, there were a few papers that did not address all elements. Ideally, we sought papers that addressed the following elements and communicated these elements clearly:

The UMAP Journal 37 (2) (2016) 145–154.

- a predictive model to capture the evolution of the flow of information throughout the ages,
- a way of defining or filtering what qualifies as news,
- validation of the predictive model using past data to compare with today's reality,
- projection of the state of societal media communication in the year 2050 using the predictive model, and
- a means of modeling and measuring the influence of media and society's networks on public and/or individual opinions.

Each paper was evaluated using a common assessment guide. We offer commentary on the components of the problem and discuss strong examples from this year's submissions.

Executive Summary

As always, the clarity of the executive summary is an important factor. The purpose of the executive summary is to prepare the reader by providing an overview of the report; therefore, it *should include a brief description of the problem, the methods used, and the overall findings or results*. Weaker executive summaries often take the form of an abstract, failing to include a description of the problem and/or a summary of the findings. The complete omission of an executive summary generally results in the elimination of an otherwise strong paper from consideration.

Developing the Model(s)

As judges read the papers, they were looking to make sure that teams presented a reasonable set of well-justified assumptions, and that those assumptions were actually used in the model. Some teams unfortunately listed reasonable considerations as assumptions, but then these assumptions were not reflected in the model. Conversely, some teams presented rather simplistic models with simplifying assumptions that were not well-explained or were not justified. The judges note that for some models, assumptions could be best explained in a dedicated section of the paper, but for other models—particularly those in which the assumptions change—the assumptions and their justifications could be clearly folded into the discussion of the development of each model.

The judges also looked for clear exposition in the development of the models. The diversity of the solutions presented this year is a testament to the fact that there is no one right way to answer these questions. Therefore, the judges were not looking for the use of any one specific modeling approach; rather, they were looking for teams that proposed a reasonable model and explained how their model could capture the dynamics of the real world.

The problem asked that teams present a way to define news and identify or filter information that qualifies as news; unfortunately, some teams failed to address this consideration, causing their papers to be eliminated from further consideration. However, for those teams who answered it, this part of the problem offered an opportunity to be very creative in developing their own metric to identify news. Some teams defined news using a temporal threshold, by tracking how long a story stayed "alive" in their time-dependent models. Other teams defined news based on the number or percentage of the population that heard the news, using a news propagation model. Some teams used a combination of time and population to set a threshold. Another approach was not only to look at the number of people who were exposed to the story, but also to use an influence model, based on repeated exposure and source credibility, to determine what percentage of the exposed population believed the story and/or were willing to spread it further.

The problem implicitly asked teams to explore the evolution of information spread as a function of time. However, some teams focused on separate explorations of how information spread within set periods of history, and the judges did not penalize this interpretation of the question. The judges looked holistically at each model presented and how that model was able to answer the question as restated by the team.

Testing and Using the Model

The judges looked for papers in which the teams validated their models before using them to address the questions. Since there was such large diversity in the models used, it is not surprising that the submissions offered a wide variety of approaches to validation. The judges were particularly impressed by papers that found reliable historical data and used it to validate their models; strong examples are offered by some of the Outstanding papers, outlined at the end of this article.

Following validation, teams then implemented their models. It was only through interpretation of their results that teams were able to present meaningful and actionable conclusions that could be used to better understand news spread throughout the ages, including the prediction of the state of the communications system in the year 2050.

In addition to validating the model before use, it was important for teams to assess the quality of their model by identifying its strengths and weaknesses. The judges often use this aspect of the paper, as well as any sensitivity analyses, as a discriminating factor, since it illustrates how well the team really understands the connections between their model and the real world that it represents.

Presenting the Results

Last but certainly not least, the judges were, as always, looking for papers that provided a very clear explanation of the work and the findings. The judges were particularly impressed with papers that were well organized and included smooth transitions between sections of the paper. Additionally, they were impressed with papers that offered a balance between verbal descriptions, mathematical equations / symbolic representation, and graphics to communicate methodologies and results.

Discussion of Outstanding Papers

This year five papers received the distinction of Outstanding. Although several of these teams started with the idea of an epidemiology model (e.g., SIR), the implementations were all different. Additionally, despite the diverse approaches and implementations, each team offered clear expositions of their process as well as very keen insights relating their model and its answers back to the real issue of the spread of news throughout the ages. Summaries of the five Outstanding papers follow.

Chongqing University, China: "Abridge the Distance between Human Minds—Research on Social Information Circulation"

As with many teams, this team started with an epidemiology model to study the spread of information. Specifically, they divide the population into four types of nodes:

- those ignorant of the news;
- those who know the news and spread it;
- those who know the news but do not spread it; and
- super-spreaders, nodes with an ability to deliver the information to a large number of people

Early in the paper, the team offers a table illustrating their interpretation of each form of mass communication through the ages, the topology of that communication network, and an itemized list explaining how properties of the model network reflect characteristics of that form of media in the real world. This team also develops a fuzzy evaluation model to filter what is news; as part of this model, they introduce the idea of an audience awareness index designed to uncover the inherent value of information.

The team also builds two different prediction models and compares their results, ultimately combining their epidemiology model with a neural network model, and using real data to validate their efforts and form the baseline for their prediction of the state of society's communication network in the year 2050.

Ultimately, the team explores public opinion and influence by starting with their existing models and adding another layer of complexity that accounts for attenuation (the idea that interest in a story wanes over time) and social strengthening (the idea that our opinions are shaped by those of our neighbors).

Rensselaer Polytechnic Institute, United States: "Characterizing Information Importance and the Effect on the Spread in Various Graph Topologies"

This team's paper uses a diffusion model over a network to model the propagation of news and a simulation is built from this model. News is divided into categories, and news events in different eras and categories are utilized to investigate the model and the underlying phenomena.

The paper defines newsworthiness as overcoming thresholds of both penetration and retention. There are several examples of newsworthy events from the 1860s to the present (e.g., President Lincoln's assassination and Osama Bin Laden's death). Media are categorized as active (such as newspapers, which a user must actively read) or passive (such as television and radio, which streams to the user little to no effort on the user's part). The paper also delineates types of stories, with categories including politics, trade, religion, consumption, and entertainment. One interesting observation is the change in emphasis of the types of news stories from politics, which was a large majority 1880s, to entertainment being the most populous in 2015.

The authors develop a regression model that takes into account the different diffusion rates within different communities of interest and apply it to the various topics. Communities of interest are created, that are interested in one topic, but some major events are of interest to all communities. A total relevance factor is given to topics to measure the interest to all communities that includes penetration and retention, mentioned before, as well as velocity. Differing effects of a news item as it crosses communities are added to the diffusion model. The use of artificial or "ghost" nodes between two real nodes is an innovative way create delays of more than one step.

To validate further and experiment with the model, the authors developed a simulation. The simulations are run for 1880 and 2015, and the distribution of nodes and stories follows the distribution found earlier, but with only politics, entertainment, and consumption represented. The model has one centralized source for all news. The model is compared to Marilyn Monroe during the period that included her death, which matched very well, but another actor's death recently (Alan Rickman) does not appear to match as well. One thing that is unclear is how relevancy is determined.

There are several sensitivity analyses. Varying the importance level gives the intuitive result that the higher importance dominates. Another varies the location of the source and shows that releasing the information from a more-connected node spreads it faster. The simulation is also used to investigate how information spreads in a more-or-less-connected portion of the network. The authors discovered for themselves the network science principle that the node with the highest connectivity is not necessarily the one that propagates news the faster, but the node's neighborhood must also be considered.

Northwestern Polytechnical University, China: "Analysis of Society's Information Networks"

The team presents a comprehensive review of information network value and influence, and then they develop a double-layer network of information flow to demonstrate the relationship between speed/flow of information vs. inherent value of information. This hierarchical framework closes the gap of the heterogeneous nature of the information network, leveraging five different time periods, with inner layers modeling the information within a region and outer layers modeling information flow from region to region.

On the graph of the inner layer, nodes and edges are attributed by the type of media, value of information, the media effect and personal subjective emotions, the flow of information is simulated with an optimization model. The outer layer combines single layer networks with the same nodes. The Reaction-Diffusion Model is applied to establish a global network to adjust the propagation probability and delay by the factor of distance.

As part of validation process, this paper applies their model to large-scale case simulations, with the support of sensitivity analysis, graphs of results, and minimized prediction error. It also validates with today's predictions, then provides the forecast in 2050 under reasonable assumptions. It's notable that the parameters for the suggested models are calculated; along with the corresponding thresholds also provided, those can be useful in terms of managing public interest and opinion, controlling the value of thresholds, and guaranteeing the quality of news.

For predicting influence in public interest and opinion, the team assumes that individual opinion is not static over time but is influenced by the spread information. A "bounded confidence model" is used to model the public interest and opinion change. With regard to the task of demonstrating factors that influence the spread of information and public opinion, the team uses interesting examples to show the geographical difference in the modeling of propagation probability by information value.

The judges appreciated the model updates and insight into the regional difference with constructing the double-layer network framework. At the end, the team recommends a course of action for the ICM and other relevant entities to adopt, supported by strong analysis and discussion.

Communication University of China, China: "How to Understand the Information"

This team uses a wide variety of methods to address the question, including an SIR model for news spread, an SN–SIR model for the spread of public opinion, a classification method for identifying news, and a hybrid learning approach for networks. The report includes plenty of good ideas that excited the judges, but at times the paper seems a bit segmented. However, the clarity of the exposition for the development of each model helped propel this paper to its final standing as Outstanding. In addition to strong exposition, the team's models are soundly based in real-world assumptions that are well-justified, and a thorough sensitivity analysis offers further insight into how their findings could be related back to the real world. This team also uses a variety of graphics to help readers visualize both their methodology and their findings.

In addition to answering the questions, the team further applies their work to social media, introducing the idea of both "regular nodes" and "hot nodes," the latter representing particularly influential members of an online community. This idea parallels the team's idea of a "hot transmit node" in a more traditional news network.

Overall, the judges felt this team used a diverse yet appropriate set of mathematical modeling tools to address this year's problem.

Huazhong University of Science and Technology, China: "Who Moved My Opinion?"

This team's paper opens with a very clear executive summary that provides an overview of their work while orienting the reader to the structure of the paper. The team starts by defining two types of communication, person-to-person vs. mass media, and then they describe how these two types of communication result in different network topologies. Further, for each type of media communication, the team develops a different network and offers a balance of mathematical rationale and real-world observations to justify each network. To examine the overall network in any one time period, the team creates a multilayered network by layering the single-layered networks for the types of media that would have been prevalent at that time.

The team also uses three states for each individual, similar to an SIR model from epidemiology. However, rather than just throw the SIR model at the problem, the team thought through the meaning of the analogous states and presents the following conditions: known, unknown, and tired, where the tired nodes have exhausted their interest in sharing the news further. The communication model is tested against real data tracking the exposure of a particular story released by the BBC. The team also attempts to predict the introduction of new forms of communication and the decline of existing modes of media by identifying and analyzing the usage trends of current and past modes, such as the telegraph and newspapers.

With a few well-justified modifications, the team then uses their information flow model to explore the networks influence on opinion, introducing and defining a range of clever elements such as powerful media nodes and stubborn minority nodes.

Although some of the writing is a bit unclear, the team does an excellent job of using graphics such as **Figure 1** to help communicate their ideas with clarity and efficacy.

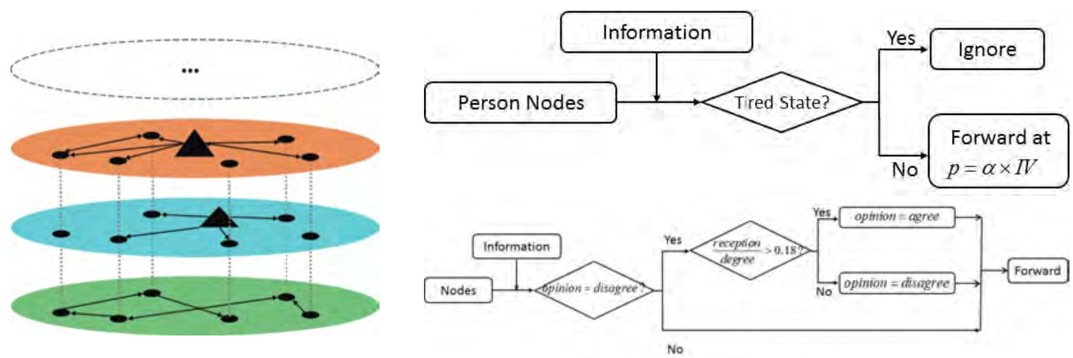

Figure 1. Three figures from the Huazhong University of Science and Technology report illustrating the layered network, the personal communication model, and the opinion-changing model.

Conclusion

Overall, the judges were excited to see the diverse approaches that teams took to address this problem, leveraging tools in a variety of fields, including network science, machine learning, and dynamical systems. There were many teams that did an excellent job of modeling at least one aspect of the problem, even if other aspects were not addressed as thoroughly or as thoughtfully. Also many teams presented a variety of models that each addressed part of the question, but only the strongest teams were able to shape all of these into a single story that flowed throughout the paper. Ultimately, the teams that advanced to the top were those that offered compelling and seamless presentations of well-reasoned solutions to most, if not all, of the questions posed.

Recommendations for Future Participants

- **Do your own work, use strong references, and cite them!** This recommendation is critical. Sadly, a record number of plagiarized papers were submitted this year. In some cases, the violation was blatant and intentional; copying whole papers or sections of papers is directly contrary to the spirit of the competition, which is about providing the opportunity to showcase creative ideas. Other cases were less egregious and perhaps less intentional, such as failing to include a citation for a downloaded image. It is important to give credit where it is due, so as you work, keep track of the resources you use, and be sure that you include both citations (inline, footnotes, endnotes) and a full bibliography.
- **Manage your time**. It can help to develop a timeline for the 96 hours, including interim deadlines and contingency plans. If something goes awry, you can always list it as a weakness of your model and discuss how you might fix the issue in the future work section.
- **Build a strong and diversified team**. Due to the interdisciplinary nature of the ICM questions and the contest format, it is beneficial to have a team whose members have knowledge and skills that complement one another.
- **Answer the problem** (or at least as many parts as you are able), and connect the ideas into a single story that flows seamlessly throughout the paper. Often the strongest papers include a unified model that can be used to address each part of the problem. Even if separate models are developed to answer various elements of the question, your team should discuss how these models are related or connected to one another.
- **Understand the context**. Depending on the question and your team's areas of expertise, you may need to spend time reading and learning about the relevant topic(s).
- **Set aside time for writing**. Your final report should be a clear paper that includes good writing, and when beneficial, thoughtfully designed figures that make the process and/or the results more easily absorbed by your audience. The most clever solution cannot be effective (in the competition or in real life) if it is not understood by others.

About the Authors

Robert Ulman received his B.S. in electrical engineering from Virginia Tech in 1984, his M.S. from Ohio State University in 1986, and his Ph.D. from the University of Maryland in 1998. He worked as a communications system engineer and research engineer at the National Security Agency 1987–2000. Since then, he has worked as the program manager for the Wireless Communications and Human Networks at the Army Research Office (ARO). At ARO, he has built a research program in wireless multihop communications networking. More recently, he has included social networking in his program, emphasizing the application of information theory and other mathematical and engineering techniques to analysis of the vast amount of social data created by the internet revolution. He is also investigating the interaction and interdependence of social and communications networks.

Jessica Libertini holds advanced degrees in both Applied Mathematics and Mechanical Engineering. Jessica is on the faculty at Virginia Military Institute, where she actively engages students in a variety of applied mathematical and educationalresearch topics, both in the classroom and beyond. In order to contextualize mathematical concepts for her students, Jessica draws heavily on her industry experiences working with General Dynamics, the Missile Defense Agency, the National Research Council, and the Army Research Laboratories. She is involved in the development of classroom materials to support the teaching and learning of mathematical modeling, and her two most active research interests are K-16 STEM education and multi-scale mathematical and network-based modeling of food and health systems.

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Projected Water Needs and Intervention Strategies in India

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Abstract

We formulate an "excess water ratio" (EWR) metric for water scarcity that improves upon currently used metrics such as the Water Stress Index (WSI), by computing the per capita excess water available in a region, thus measuring the impact of water shortage on individuals.

We start with the amount of naturally available water, then subtract personal use, industrial use, and agricultural use. Dividing the result by the total population determines the annual amount of water available but unused per individual, a goal that is unique to our model.

We apply our model to India, which suffers from lack of safe drinking water and a high rate of waterborne diseases. We model growth rates for the environmental and social factors that influence water use so as to determine the growth of water needs. We develop a secondary model that utilizes government predictions of water use and population growth to extrapolate our EWR measure.

Taking these two models together, we conclude that excess water per capita in India will be around half of its current level by 2031.

We explore intervention measures, addressing both supply and demand sides, including watershed development, waste treatment, and broader cultural changes in food production.

We find the cumulative impact of proposed infrastructure improvements to be minimal, delaying the point at which India's EWR diminishes to zero by just one year (from 2083 to 2084).

Changes in agriculture could have more impact. Specifically, switching all rice and wheat production to millet over a 30-year period pushes the year India hits zero EWR back to 2097.

All of this means that large cultural shifts in demand for water will ultimately be necessary for India to achieve long-term water sustainability.

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Introduction

Water has been absolutely critical for all humans, everywhere, since the beginning of time. Every human needs at a bare minimum 20 liters of water to survive [1]. The need for that water is rooted deeply in our biology: at 1% water deficiency humans get thirsty, a 5% shortfall causes fever, at 10% short we are rendered immobile, and death strikes after just a week of 12-15% water loss [2]. Given these biological realities, it is not a surprise that the first and most basic category of water use in human society is personal consumption.

However, it is not enough simply to have sufficient water to drink. In terms of total water consumption, personal use is actually a fairly small—if absolutely essential—piece of the pie, just 5% on average of a given country's consumption [3]. By far, the majority of water that all societies consume, 75% on average, is used not to keep from dying of thirst but rather to keep from dying of hunger; that is, it is used on agriculture. The remaining 20% of water consumption is by industry.

On the face of it, it is hard to imagine why water scarcity could ever be an issue on a planet that is 70% covered with water [4]. The problem arises when we consider the conditions that make water usable: It must be fresh (not too salty), liquid, and physically accessible. The first condition eliminates all but 2.5% of all water from consideration, the second eliminates two-thirds of what remains, and the final condition brings the total of fresh liquid water near or at the surface (i.e., usable water) down to just 0.003% of Earth's fresh water [3].

Due to natural replenishment through the water cycle, even that tiny fraction of available water has managed to sustain all human life that has existed since antiquity. The main reason to expect that condition to be different going forward is the exponential growth of the human population. It took almost 12,000 years for the human population to go from zero (circa 10,000 BCE) to one billion (circa 1800 CE). It took 125 years to go from one billion to two circa 1930, 30 years to get from two to three billion in 1959, and 15 years or less to acquire each remaining billion, all the way up to today's 7.3 billion people [5], [6]. The UN projects 11 billion people by the year 2100 [7].

This ongoing massive increase drives up water usage in all three categories. More people means more direct individual consumers of their 20 daily liters and more water-intensive industry, but—most importantly—it means that everyone must grow more crops. Industrial and agricultural uses also contribute to pollution [8].

In short, humanity faces conditions of water scarcity that are unprecedented in human history. Accurately modeling future water needs—plus developing strategies that we are all able and willing to implement to bring necessary water consumption down to (or preferably somewhere far below) the upper limit of physical water availability—will be one of the defining challenges of our time.

Model for Water Needs

Outline of Our Approach

In formulating a quantitative measure of water scarcity, we start with a reflection of the Water Stress Indicator (WSI), created in 2005 by Smakhthin, et al. [9]. This model has credibility due to its use in informing international policy making, since the UN Environmental Programme uses the WSI as its measure of water scarcity on public maps [10]. The WSI is calculated using the following formula:

$$\text{Water Stress Indicator (WSI)} = \frac{\text{Water Withdrawals}}{\text{Mean Annual Runoff (MAR)}}$$

Water withdrawals are thus interpreted as a reflection of water use, and the MAR is interpreted as a reflection of water availability. MAR is the difference between water available from precipitation and water lost due to evaporation [11]. Water withdrawals are taken as a sum of water withdrawals for the primary uses of water within a region: industrial, agricultural, and personal. Beyond its use in the WSI, these concepts have precedents in Vorosmarty's index of local relative water use and reuse (2005) and Shiklomanov and Markova's water resources vulnerability index (1993) [10].

A significant weakness of the WSI is that it does not allow for any conclusions to be drawn about the average impact of water scarcity on an individual level. Two regions with the same levels of water availability and water use will have different strains on the daily living of individuals within the regions depending on their populations. Thus, a more thorough reflection of a region's water scarcity should factor in the population of the region. Our approach is to use data representative of water use and availability and formulate a ratio that determines how much water this leaves *per capita* for recreational, commercial, or hygienic uses.

Assumptions

A myriad of cultural and environmental factors impact the availability of water and how much water is needed to sustain the living standards of a region. Because it is impossible to account for the impact of each of these factors on the overall water demands and availability, we adopt a number of simplifying assumptions for our model:

- The only source of water for a region is its MAR. There is precedent for this assumption in the prevailing models of the Water Stress Indicator

(WSI) and of the U.S. Geological Survey. The assumption is reasonable, because while other technologies exist to acquire water, these are not yet widespread enough to present long-term solutions to water shortages.

- Utility from water use for individuals is a strictly increasing monotonic function. This assumption allows us to conclude that individuals, regardless of current water levels, would enjoy having more water available to them. Therefore, although cultural practices in various regions create a perceived need of different water levels, we assume that an increase in water availability would be appreciated by any individual.
- The current aggregate level of water use is in a temporary equilibrium, as the region seeks to efficiently use all water available based on existing demands and technologies. This assumption is reasonable, because to assume the opposite would imply that the region is currently using more water than is physically present.
- Government policy and individuals are informed about the safety of the water available to them and accordingly use the available water for appropriate purposes. Historically, this assumption has not always held because unclean water has led to diseases. A more complex model would take into account the ubiquity of this knowledge throughout the population.
- Geographic distribution of water sources and consumption is not a factor in a country's water scarcity. In reality, available water in one region does not necessarily provide adequate water to another region, due to the economic and logistical challenges of transporting large quantities of water. However, because people commonly settle and farm in land with abundant water, we do not consider the effects of transportation of water.

An Approach to Projecting Water Availability

We formulate an Excess Water Ratio (EWR), which represents the amount of unused water in a region that is available per person. A higher ratio implies that more water is available per person, and thus a higher EWR for a region suggests that water scarcity is less of a concern for the region:

$$\begin{aligned}\text{Water Use} = \text{Water Use from Industry} + \text{Water Use for Agriculture}\\ + \text{Water Use for Personal Use}\end{aligned}$$

$$\text{Water Availability} = \text{Mean Annual Runoff}$$

$$\text{EWR} = \frac{\text{Water Availability} - \text{Water Use}}{\text{Population}} = \frac{\text{MAR} - \text{WU}_i - \text{WU}_a - \text{WU}_p}{\text{Population}}$$

For the model to be used for projections into how water scarcity of a region will change in the future, it is important to break down the variables of the EWR into components that factor into the long-term growth rate. By understanding the trends of these components and the relationship between the components and the long-term growth rate of water use, rates for future water needs can be extrapolated.

Water use in agriculture has several factors that are similar to the factors of water use in industry, such as the level of agricultural production and the water-intensity of agricultural products. For instance, in low-income countries, irrigation can make up to 90% of water withdrawals. The most water-intensive crops include rice and cotton, which require up to 29,000 and 5,000 liters of water per kilogram of crop respectively [12]. Other factors important to take into consideration are the availability of irrigation technology and the increase in needed water due to climate change. In particular, climate change increases the amount of water needed for agriculture, through rising temperatures, and requires modifications in agricultural practices due to shifts in global climate systems [13].

Water use in industry is primarily influenced by the level of production in a country and the water efficiency of the production [14]. The most water-intensive industries include paper, chemicals, and coal products [15]. The water-intensity of the industry is typically measured by its "water footprint," the amount of water needed throughout production. We assume that water use in industry in a country is proportional to the product of the amount of the economy based in industry and the average water footprint of industry in that country. This would be scaled differently depending on the total economic output of a country.

Water use in personal use is directly related to the population of the region; and we assume that in a region, an individual's water use remains constant over time. We acknowledge that there may be variations in water use depending on the economic development of a region, but because significant changes in economic development are difficult to predict and often occur sporadically, economic development should only be taken into consideration when there is a large potential for a region to experience significant growth.

Finally, mean annual runoff is most directly related to the climate of the region and the amount of precipitation that it receives [16]. When extrapolating the potential mean annual runoff for a region in the future, the historic MAR of the region should be plotted against factors such as precipitation and average temperature.

Evaluation of the Model

Correlation with Water Stress Indicator (WSI)

The scatterplot of **Figure 1** compares the WSI (on the horizontal axis) and the EWR (on the vertical axis); we observe a strong relationship. One significant strength of our model is that the differences between the EWR in water-scarce and water-abundant countries is more extreme than the WSI, thus allowing for a more precise measure of water scarcity.

Additionally, the impact of water scarcity on individual citizens is made clearer by factoring in population. For instance, China and the United States have a very similar WSI (0.48 and 0.50); but the difference in populations means that this water shortage has a larger impact on a citizen of China than on a citizen of United States, so China's EWR is one-third as great (**Table 1** and **Figure 1**).

Table 1.
WSI and EWR for several countries.

	WSI (dimensionless)	EWR ($times 10^3$ gal / person / year)
Saudi Arabia	0.995	1
India	0.967	5
South Africa	0.687	273
USA	0.499	393
China	0.478	116
Spain	0.181	837
Russia	0.111	956
Argentina	0.352	422
Sweden	0.040	1675
Colombia	0.037	1673

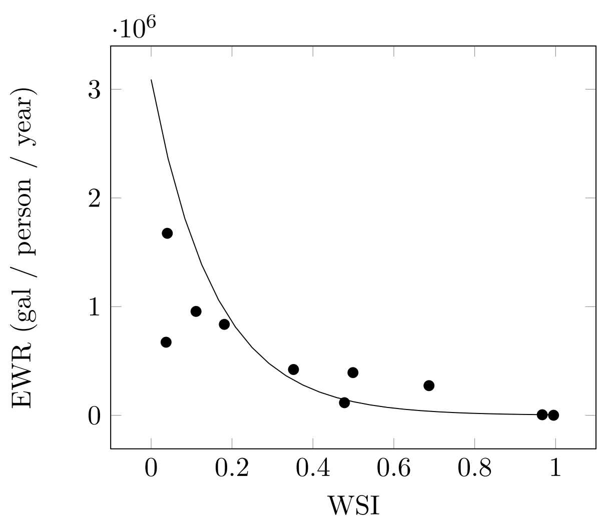

Figure 1. EWR vs. WSI.

Strengths

- **Impact of population.** The most pertinent statistic in water scarcity is how much spare water there is per person, which is taken into account by our model. This accurately reflects that countries with large populations face more significant challenges in harnessing their water supply.
- **Lack of an upper limit on available water.** Other measures, such as the WSI, include a lower limit of 0 on water stress, which makes it difficult to determine the extent to which countries have a surplus of water. Because our equation goes in the opposite direction, such that a high value correlates to little water scarcity, regions can potentially continue to increase their EWR.
- **Predictive power.** By breaking the data into the components that impact their long-term trajectories, our model has more predictive power than pre-existing models. It accounts for the underlying causes of changes in water usage and can take the growth rates of those factors into consideration when predicting the growth rate of water usage.

Weaknesses

- **Availability of data.** Ideally, the model should be applied to a region of any size to determine the overall water scarcity in the area. However, typically information is available only on a national level, which makes it particularly hard to determine levels of water scarcity in small regions within countries.
- **Broadness of categories.** Our model treats agriculture, industry, and personal use as monolithic categories, when in reality each of these factors has various components that can move independently. However, other models such as the WSI have this same drawback, so our model is no weaker than established models in that regard.

A More Complex Model for Water Availability

More recent formulations of the Water Stress Indicator (WSI) acknowledge the importance of environmental needs in calculations of a region's water use [9]. Such calculations are an improvement because they recognize that the maintenance of the environment of a region requires a constant flow of water for the well-being of nearby plants and animals (WU_e). While this water previously was included in the water available to humans for industrial, personal, and agricultural use, the previous model ignores the fact that dipping into the supply of water required for the environment harms the overall ecosystem.

Additionally, a more complex model recognizes that while a region used to get all of its water primarily from its surroundings, technology now enables regions to import water from areas that naturally have more abundant water sources. For instance, Singapore recently has been importing water from the Johore River catchment in Malaysia to make up for its large water needs, and India has established water treaties with Pakistan and China [16].

A more complex model for water is therefore reflected below:

$$\mathrm{EWR} = \frac{\mathrm{MAR} + \mathrm{Import} - \mathrm{WU}_i - \mathrm{WU}_a - \mathrm{WU}_p - \mathrm{WU}_e}{\mathrm{Population}}$$

Case Study: India

Rationale

We select India for our case study, with its 1.3 billion people [17], just over 18% of the total population of Earth.

Simply put, this massive country is in a major water crisis. The following excerpt from a paper published by the National Bureau for Asian Research sets the scene:

> The World Health Organization estimates that 97 million Indians lack access to safe water today, second only to China. As a result, the World Bank estimates that 21% of communicable diseases in India are related to unsafe water. Without change, the problem may get worse as India is projected to grow significantly in the coming decades. [18]

Main Drivers of Water Scarcity

One important cause of the water scarcity in India is "large spatial and temporal variability in the rainfall" [19]. This means that water is distributed unevenly throughout the country in terms of both geography and of time. Each of these conditions produces water scarcity in specific contexts: the former in relatively dry regions during otherwise wet months, and the latter during relatively dry months in regions both wet and dry.

Another factor exacerbating water stress is poor irrigation systems [19]. This unfortunately is a self-perpetuating problem, because the rates charged for users of the system are very low. The low rates mean that insufficient revenue is generated to support the operation and maintenance of high-quality infrastructure. This results in low-quality infrastructure, which renders stakeholders reticent to pay more for it, which means the quality won't get better, etc.

Some farmers have responded to the previous two challenges by drawing water directly from the ground to irrigate their crops. This has led over the years to widespread overuse of the groundwater, far past the point of environmental sustainability. The resulting depletion of naturally occurring groundwater for agricultural/irrigation purposes has become a driver of water scarcity in its own right [20].

All three leading causes of water stress pointed out above are for agriculture. This is because agriculture is responsible for a staggering 92% of water usage in India. However, in the relatively short-term future, the population is expected to grow rapidly and industrialize. Both of these trends will require more water, both in absolute terms, and as a percentage of water used. What this means is that over the long term, the country will be required to "produce more [food, to support the expanded population and industrialization] with less water" [19]—or else India will face massive food shortages and/or be unable to develop industrial resources.

Finally, one additional challenge related to rapid population growth that is very much in evidence in India is contamination. "More than 100 million people in India are living in places where water is severely polluted. Out of the 632 districts examined to determine the quality of groundwater, only 59 districts had water safe enough to drink" [21]. Even assuming that the same amount of water is being collected—which may or not be a valid assumption— keeping all of it clean enough to use will be imperative as the country grows.

Prediction of Water in India in 15 Years

Determining the Current State of Water Scarcity

Applying our model for water needs to India means calculating an EWR for India. A variable in our model that is not readily available for the country as a whole is the MAR, which varies significantly throughout the country. For example, in 1997 the MAR of the Ganges River at Farakka was approximately 415×10^9 m^3, while the MAR of the Brahmaputra at Pandu was approximately 511×10^9 m^3 [22]. However, the published WSI statistic requires an estimate of a total MAR for the country, so we can manipulate the formula for WSI to write the EWR in terms of WSI rather than MAR:

$$\mathrm{WSI} = \frac{\text{withdrawals}}{\text{MAR}}$$

$$\mathrm{EWR} = \frac{\text{MAR} - \text{withdrawals}}{\text{population}} = \left(\frac{1}{\text{WSI}} - 1\right)\frac{\text{withdrawals}}{\text{population}}$$

As of 2009, India had a WSI of 0.967, total water withdrawals of 761×10^9 m^3, and a population of 1.25×10^9 [14], [23]. This gives an EWR of $20.75 m^3 \approx 5482$ gallons/person/year. This means that the average individual in India has 15 gallons per day of extra water that could theoretically be used, a number extremely low relative to the amount of water currently being used. Moreover, a lack of technology in much of rural India prevents this water from being used. Thus, there is a large strain on India's water, especially when compared to the EWR of other countries. For example, China, with a much lower WSI of 0.478, has an EWR of $374m^3$, which puts it in a much better position.

Preliminary Estimation of Growth Rates of Water Use

We assume that in the relatively short span of 15 years, the MAR for India will remain constant. This assumption is not fully accurate, since climate change will likely alter India's climate in a way that decreases water availability. However, the proposed model will still be helpful because it places a lower bound on the state of India's water scarcity, such that water shortages in the next 15 years will be at least as bad as proposed by the model.

We start by formalizing our assumptions about the factors that impact the water use from industry, agriculture, and personal. Water use from industry and agriculture are each assumed to be a product of their respective production levels and water footprints. We also assume that there are two distinct population groups, urban and rural, with differing personal water use (assumed constant for each group). These equations are formalized below:

$$\begin{aligned}&\text{Industrial Water Use } (I)\\ &\qquad = \text{Industrial Output}(O_i) \times \text{Industrial Water Footprint}(F_i)\end{aligned}$$

$$\begin{aligned}&\text{Agricultural Water Use } (A)\\ &\qquad = \text{Agricultural Output}(O_a) \times \text{Agricultural Water Footprint}(F_a)\end{aligned}$$

$$\begin{aligned}\text{Domestic Water Use } (D) &= \text{Urban Pop.}(U) \times \text{Avg. Urban Water Use}(W_u)\\ &\quad + \text{Rural Pop.}(R) \times \text{Avg. Rural Water Use}(W_r)\end{aligned}$$

$$\text{Total Water Use}(W) = I + A + D$$

$$\text{Growth Rate of Water Use from } I(g(I)) = g(O_i) + g(F_i)$$

$$g(A) = g(O_a) + g(F_a)$$

$$g(D) = \frac{U \times W_u}{D}\, g(U) + \frac{R \times W_r}{D}\, g(R)$$

$$\begin{aligned}\text{Water Use(target year)} &= I\big(1 + g(I)\big)^{\text{target}-\text{current}}\\ &\quad + A\big(1 + g(A)\big)^{\text{target}-\text{current}}\\ &\quad + P\big(1 + g(D)\big)^{\text{target}-\text{current}}\end{aligned}$$

In the equations, we use the common approximation that the growth rate of a product is approximately equal to the sum of the growth rates of each factor. According to the World Bank, India's urban population growth is 2.38% and rural population growth is 0.68%, with a total population growth of 1.2% [24]. Additionally, the average urban citizen of India uses 126 liters of water per day for personal use [25]. Factoring in information on India's population, total personal water use in India, and the current percentage of the population that is urban, we calculate the growth rate of water for personal use:

$$g(D) = (0.319)(0.0238) + (0.681)(0.0068) = 0.0122 \approx 1.22\%/\text{yr}$$

Because of the large variations in water footprints for different industries and crops in India, we assume that $g(F_a) = g(F_i) = 0$ within the 15 years of our projections. However, we ultimately conclude that this assumption is reasonable, since India's government has been slow to adopt policies that promote drastic economic change. [26] Therefore, within the relatively short timespan of 15 years it is unlikely that the economy will change in a way that drastically alters the average water footprint of industries. The growth rate of India's agriculture sector varies significantly each year but has centered around 3.8% between 2006 and 2014 [27]. Additionally, the growth rate of India's industrial sector has been about 5.0% during the same timespan [28]. We therefore estimate that water use in 2031 will be given by:

$$\begin{aligned}\text{Water Use}(2031) &= (688 \times 10^9\text{m}^3)(1.038)^{15} + (56 \times 10^9\text{m}^3)(1.0122)^{15} \\ &\quad + (17 \times 10^9\text{m}^3)(1.050)^{15} = 1306 \times 10^9\text{m}^3\end{aligned}$$

This means that unless water use decreases or water availability increases beyond this projection over the next 15 years, the EWR will become negative, since water use will surpass availability. Effectively, this simplistic first model shows that with no change in current behavior India will be out of water before 2031.

Our model presents a more extreme outcome than other models, such as those of the Indian government [29]. One factor that accounts for this is that we assume that each realm of water use is growing exponentially, which represents a worst-case scenario. Additionally, we assume that average water footprints remain constant, while it is entirely possible that the average water footprint decreases with the scale of industry.

A More Robust Computer Model

Because the Indian government predicts the amount of water available and water used in different sectors of the economy [29], we can estimate the excess water ratio in a given year by matching the amount of water in each category to a polynomial function using Matlab's `polyfit` function. We use the Indian government's predictions rather than data from past years. We reason that interpolation of the EWR for a year between the years predicted by the government will be more accurate than an estimation extrapolated from data from many years before. To find the EWR, we compute the excess water ratio with each component's value corresponding to its output of the polynomial function for that year:

$$\text{Excess Water Ratio} = \frac{\text{WU}_a + \text{WU}_d + \text{WU}_i + \text{WU}_p + \text{WU}_{in} + \text{WU}_{ec} + WU_{ev}}{\text{Population}} - \text{WAPC},$$

where WU_a represents water use for agriculture and irrigation, WU_d represents domestic water use, WU_i represents industrial water use, WU_p represents water use for power, WU_{in} represents water use for inland navigation, WU_{ec} represents water use for ecology, and WU_{ev} represents water lost to evaporation. These are the categories detailed in [29] as significant Indian water uses. WAPC is water available per capita.

Furthermore, we can use the model to assess the effects of intervention policies. We graph India's EWR from 2000 to 2050, rooted in the Indian government's predictions of water availability and usages in 1997, 2010, 2025, and 2050. For the purpose of demonstrating the model, we assume that intervention projects will increase the amount of water by 30 billion m^3 in 2020 and 50 billion m^3 in 2030. **Figure 2** shows the EWR without interventions, and **Figure 3** the estimated results with interventions. In each graph, the lower curve is a high projection for increases of water usage while the upper curve above gives a low projection. Because the government predictions assume the development of the nation as a whole, the added components for intervention policies are for policies not already envisioned and accounted for by the government.

Assumptions for the Computer Model

- Changes to population and amounts of water available/used are predictable. A variety of political, economic, and social factors influence how much water India consumes and has available, some of which are not quantifiable. To avoid arbitrarily quantifying possible events, our model assumes that the Indian government's predictions in [29] will be accurate.
- Changes to quantities over the time interval can be interpolated accurately with polynomials.

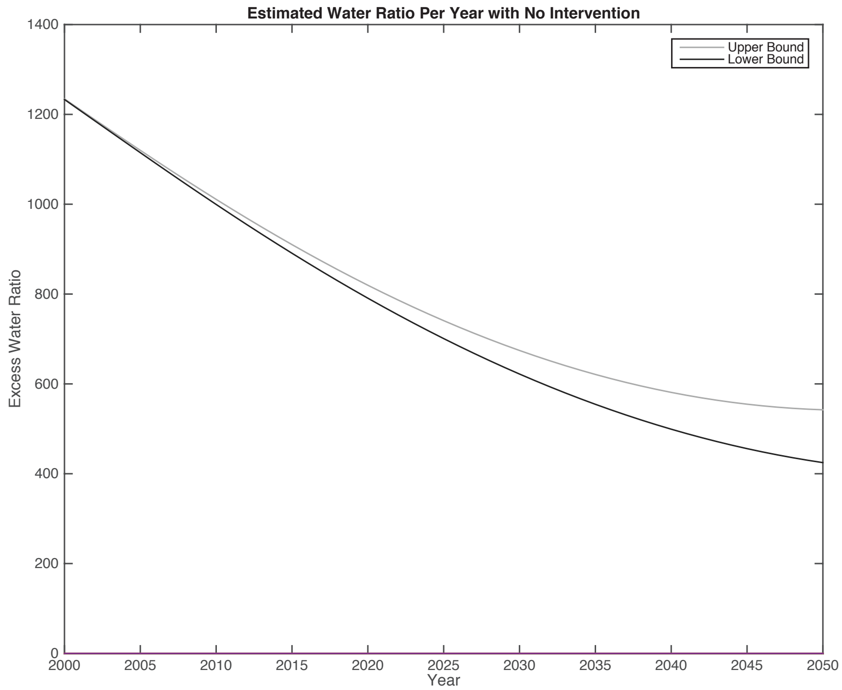

Figure 2. India's projected excess water ratio (EWR) without interventions, 2000 to 2050.

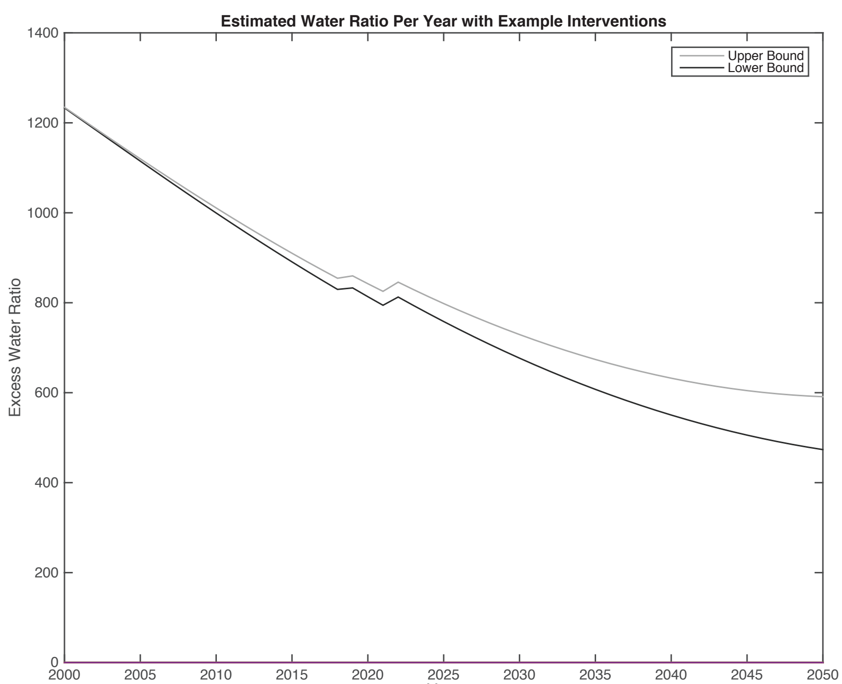

Figure 3. India's projected excess water ratio (EWR) with interventions, 2000 to 2050.

Conclusions for Impacts on Citizens

From the first model, we note that a demographic shift impacting water scarcity in India is the increasing proportion of the population living in urban areas. Because urban populations typically use more water than rural populations, this puts a larger strain on India's water supply and is one of the largest sources of predicted water increases in the next 15 years. Therefore, an impact of water scarcity will be a decrease in standard of living for cities, as resources strain.

The first model also assumes that water use will increase along with the current growth rates of industry and agriculture. However, one of our assumptions is that society cannot use water beyond the water physically available. Thus, the prediction of water use from the first model should be interpreted as the ideal amount of water availability given current growth rates. Realistically, a water shortage will limit India's economic growth potential, as agriculture and industry will have to slow down their current rate of expansion with water as a limiting resource. However, the most powerful impacts are the impacts of water shortages on the lives of ordinary citizens in India. With its current water shortages, over 21% of India's diseases are water-related and only 33% of the country has access to traditional sanitation [31]. Unless the pace of technology improvement is somehow able to keep up with the pace of water needs, these issues will only worsen.

Intervention Plans for India

Intervention Plans for India's Water Scarcity

In [32], the UN Food and Agricultural Organization (FAO) notes that the most comprehensive water scarcity interventions address both the demand and supply sides of water scarcity to help align the goals of parties on each side. This report in fact deals with interventions for agricultural water use in India, which is particularly relevant since this category makes up the largest share of India's water use. We discuss two intervention strategies that would increase supply: watershed development and water recycling from waste. We also discuss intervention strategies that focus on decreasing demand, such as societal changes in food consumption and changes in agricultural production. Some additional projects may be helpful but are limited. For instance, many scientists believe that dams would help to improve India's water supply; but dams also have many adverse side effects, as illustrated by the Narmada Dam project in India, which displaced 200,000 people and had disastrous environmental consequences such as the flooding and salination of land near the dam that ruined crops [30].

Watershed Development

Water supply can first be improved by constructing watersheds throughout India. A 2005 study performed a meta-analysis of 311 watershed development case studies and determined that the construction of watersheds increases water storage capacity, increases cropping intensity, reduces water lost to runoff, and reduces soil loss [33]. The same report concludes that approximately 380 watershed projects have been constructed in India, allowing for an increase of 260,000 hectares of agricultural production. On average, then, each project has provided irrigation needed for 684 hectares. Different crops require different amounts of water, so the water requirement is not uniform for each hectare of land. However, due to the absence of more specific data, we make the simplifying assumption that water consumption per hectare is constant throughout India's farmland. India cultivates 170×10^6 hectares and uses 688×10^9 m^3 of water for irrigation [19], which averages out to 405 m^3 per hectare. We conclude that each completed watershed allows for an increase of $276,800$ m^3 of water for agriculture.

Of course, watersheds cannot be constructed infinitely, because there is a limit on how much water can be recovered; but so far, no limiting capacity of watershed development has been seen in India. We therefore recommend that the Indian government selects 50 areas that could potentially benefit from a watershed and begin construction immediately, which would give a yearly increase of 1.38×10^7 m^3 of water. Studies suggest that the areas that would benefit most are semi-arid regions with erratic monsoons that prevent water from quickly recharging [34]. We assume in our model that these watersheds will begin construction in the next year, and will follow the timeline of the Neeranchal National Watershed, which was built over six years. The changes will then go into effect in 2022 [35].

Water Recycling and Waste Treatment

India's population produces a large amount of waste that can be treated to be used for agricultural purposes. There is precedent for treating waste that can be expanded over the next several years to provide a consistent source of water. Water from waste can only be used for agricultural purposes, because it does not meet the quality standards for personal or industrial use [30]. Currently, this water is being used to irrigate trees in public parks in Hyderabad, to cultivate wheat paddies over 2100 hectares along the Musi River, and to support fisheries in East Calcutta. As of 2011, India had 270 municipal wastewater treatment facilities, which have the total capacity of treating 4.573×10^9 m^3 per year [19]. Even treating the wastewater at full capacity leaves 11.03×10^9 m^3 per year is left untreated.

Based on the current capacity of the treatment facilities, each facility can treat 1.69×10^7m^3 per year, so constructing new facilities for the treatment of wastewater would require the construction of 651 new treatment plants. While pricing information for waste treatment plants is not readily available, the construction would be very expensive. However, we believe that the plants would be worth the cost in the long run because they would provide a future sustainable source of water for agriculture.

When we account for this intervention policy in our model, we assume that all untreated wastewater will eventually be treated and used for agriculture, adding 11.03×10^9 m^3 per year. Based on building times for large-scale waste treatment facilities in the United States, we estimate that these could be built in three years and begin working by 2019.

Societal Changes in Food Consumption

One of the largest impacts on demand for water is currently due to food consumption, as "90% of personal water footprints are devoted to food in the form of crop and animal production" [36]. To predict future water availability, we do not assume that this change will be enacted or successful. However, to approach the supply and demand sides of the water consumption issue, governments will soon need to address the unsustainable eating habits of populations. Meat and dairy products are much more water intensive than crops, and the consumption of these foods increases as populations move to urban areas. A cultural shift in eating habits, while requiring a change in attitudes toward foods that would take several years, may eventually become necessary as lower water levels decrease the potential for water-intensive farming.

Changes in Food Production

One of the most significant intervention techniques that India can undertake is to decrease the demand for water from agriculture by subsidizing the production of more water-efficient crops. For example, millet is a much more water-efficient crop than rice or wheat, which currently make up the largest shares of India's agriculture [19]. Specifically, the growth of rice requires 1250 mm on average of rain or irrigated water, wheat requires 550 mm, and millet requires just 350 mm [40], [41]. Millet can also be grown in soil that is far poorer quality than traditional crops. Critically, millet is nutritionally equivalent to rice or wheat, containing comparable levels of protein, fiber, minerals, iron, and calcium.

In our model, we have considered the water impact of switching all of India's wheat and rice production to millet over the course of 30 years. For each land unit of water converted from rice to millet we save 900 mm of water annually, with 200 mm more in savings added for each land unit converted from wheat to millet. Over the timespan modeled, we expect this intervention to produce considerable water savings.

Impact of Water Available of Surrounding Area

One of the most significant strengths of watershed development is that there is no evidence of negative impacts on the surrounding areas. Typically, watershed development serves the purpose of making degraded lands suitable for agriculture, which is independent of the agricultural output of surrounding regions. While the treatment of wastewater has the potential to provide large amounts of additional water for agriculture, studies suggest that the use of treated water may alter soil quality over time [30]. According to the International Water Management Institute, "Ample evidences are available which show that the groundwater in all wastewater irrigated areas has high salt levels and is unfit for drinking. Further, high groundwater tables and water-logging are also common features of these areas" [30]. This poses a health risk to communities that are located downstream of the area, since it may be difficult to separate this agricultural water from personal use in communities that do not have the technology for advanced water purification.

Evaluation of Strengths and Weaknesses

A World Resource Institute report identifies many social and economic benefits of watershed development and concludes that there is a net present value between $5.08 million and $7.43 million. It also points out other benefits that could not be included in the cost-benefit analysis, such as "improvements in nutrition, dietary diversity, and human health" as well as "improved resilience to drought and temperature fluctuations" [30]. A weakness of this proposal is that the development of watersheds can be expensive, and modifications of the natural environment can have unpredictable consequences on the ecosystems. Additionally, a social problem brought up by watershed construction is that historically the construction of watersheds has negatively impacted women in India [37]. The development of watersheds required the closing of common areas where poorer women grazed goats, which deprived them of a large source of income. However, in carrying out future projects,"Some of the negative effects on women could be overcome if a great effort was made to include them in decision making" [37]. Finally, watersheds require a significant upkeep cost, and historically a lack of attention to constructed watersheds has caused them to be leaky or damaged [38].

One strength of waste treatment is that it creates a reliable source of water supply for agriculture, removing much of the uncertainty that characterizes water scarcity in developing countries. The Weighted Anomaly Standardized Precipitation (WASP) index computes deviations in monthly precipitation, and shows that parts of Central India frequently are drier than their average precipitation, making it difficult to group crops given uncertain weather conditions [39]. By diverting treated wastewater to these areas, water can be more efficiently used. Additionally, the treatment of wastewater has a positive externality of long term economic growth for workers in the region. The construction of the facilities requires the hiring of several construction workers, and the constant treatment of waste requires a large permanent staff. As noted above, however, wastewater has the potential to make water less usable downstream, and the construction of the facilities will require a large initial cost from the government. Thus, it is unlikely that the government would be able to fund the construction of all of the plants at one time.

The main benefit of shifting crop production away from rice / wheat and towards millet (and more generally towards more water-efficient varieties) is water savings. Other strengths of this approach include consumers taking advantage of the enhanced nutritional value of millets vs. wheat and rice, and the existence in the status quo of prototype models of effective programs that already provide "training via internet and mobile phone, adapted to smallholder farmers and practitioners, on the best farming practices for drought and heat tolerant crops such as millet and sorghum" [42]. There are at least two key challenges standing in the way of adopting this approach:

- Local tastes have to be taken into account. If no one wanted to eat millet, and thus there was no demand for it, no sensible farmer would grow it. Accordingly, gathering and heeding input from the local population of both farmers and consumers to create demand for millet as a food crop would be critical to the success of this intervention.
- Even assuming that it would be possible to convince everyone to love millet overnight, far more investment would be needed to ensure that sufficient training in proper millet growing techniques, and financial support to purchase millet seed was available to every small farmer that could and would use it to convert their wheat or rice farm into a millet farm [42].

Projection of Future Water Availability

Interventions in infrastructure (**Figure 4**) are insignificant: India would run out of water between 2084 and 2094, rather than between 2083 and 2093 without improvements.

By replacing wheat and rice crops with millet (**Figure 5**), water use significantly decreases, leading to a much higher EWR. Instead, India will run out of water between 2097 and 2107.

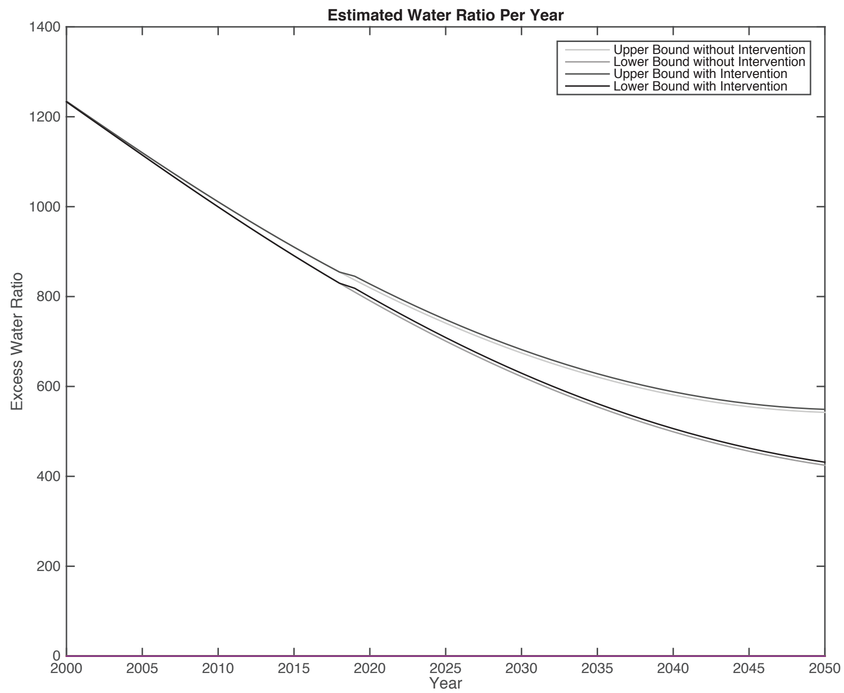

Figure 4. India's projected excess water ratio with and without infrastructure interventions, 2000 to 2050.

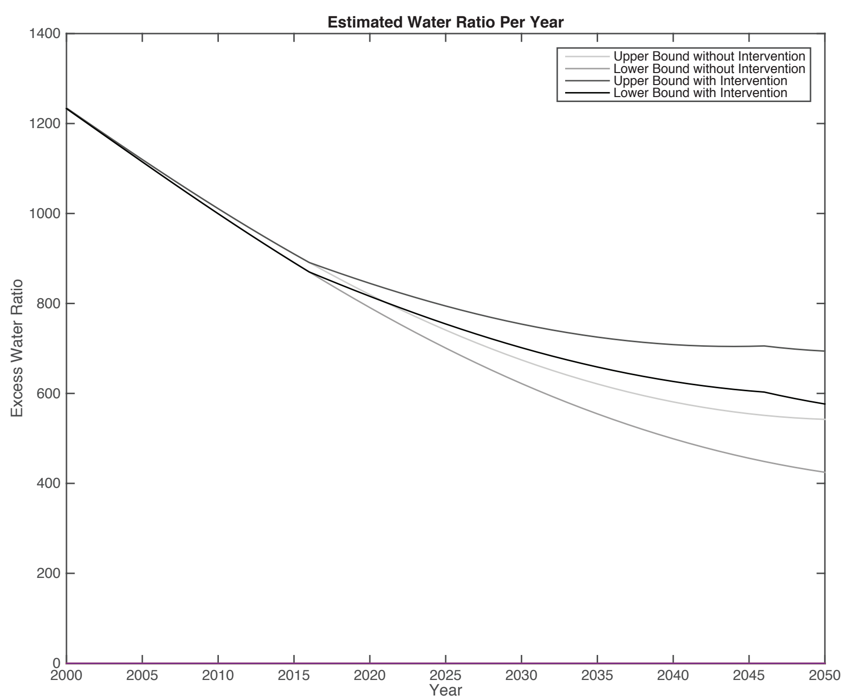

Figure 5. India's projected excess water ratio with and without millet interventions, 2000 to 2050.

Conclusion

We created the new metric of "excess water ratio" (EWR) that improves upon current measures by illustrating the extent to which water shortages impact an average individual. Taking India as a case study, we identified the components that contribute to the EWR and predicted their growth rates so as to extrapolate the growth rate of water needs in India over the next 15 years. Our results illustrate that at current growth rates, the average excess water per capita will be half of the current value by 2031.

We concluded by exploring intervention possibilities to develop long-term solutions for India's water issues. We first looked at strategies that increase the supply of water, but found that these techniques were expensive and did very little to offset the rapidly increasing water demands. When we turned to attempts to decrease the demand for water, such as switching some crop production to the water-efficient grain millet, we found that these could be much more effective in the long term, assuming that they are properly implemented by the government.

Fundamentally though, we conclude that more drastic societal changes will need to be adopted to decrease India's water demand enough to matter.

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Judges' Commentary: Water Scarcity

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Introduction

The ICM continued to challenge students to address real-world problems concerning environmental science in Problem E. This year, teams sought to identify and understand the drivers of water scarcity in order to create a model to predict the ability of a region to provide clean water to meet the needs of its population. Teams were asked to research and then create intervention strategies for a water-vulnerable region to mitigate its water crisis. The teams had to consider both environmental constraints on water supply and how social factors influence availability and distribution of clean water. Due to the interdisciplinary nature of the Problem E, the teams choosing this problem had to leverage the strengths and skills of their individual members as they navigated this challenge

The problem statement is given in the contest report earlier in this issue.

Judges' Criteria

The general framework used to evaluate submissions for the environmental science problem is described here. The judges that utilized this

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framework included representatives from a diverse set of fields including sustainability, biology, geography, applied mathematics, statistics, and engineering. Their main objective in the ICM problem judging was to find and evaluate modeling that includes good science and leads to measurable and viable solutions. The judges were looking for papers that clearly communicated each of the following elements:

- An understanding of the complexity of the problem, including the social and environmental drivers taking into account both physical and economic scarcity.
- The development of a meaningful model incorporating the dynamic nature of the problem affected by both supply and demand; and then the utilization of this model to determine the chosen region's ability to provide clean water to meet its needs, both before and after implementation of intervention strategies.
- A relevant and feasible set of intervention strategies tailored specifically to the region chosen.

Each paper was evaluated using a common assessment guide. In the sections below, we offer commentary of the critical components of the environmental science problem and highlight the innovation seen in this year's submissions.

Executive Summary

As in past years, it remained important that the executive summary succinctly and clearly explain the highlights of the submissions. The executive summary should contain brief descriptions of both the problem and the bottom-line results. The description of the problem must be written in the team's own voice and not taken directly from the problem statement. Better papers had a well-connected and concise description of the methodology, results, and recommendations.

Researching the Problem

Judges were looking for insight into a team's knowledge concerning the critical aspects of water scarcity that were incorporated into the model, as well as the specific drivers of water scarcity within a team's region of focus. The judges sought to understand the resources that teams used to obtain what they considered to be the relevant factors.

In the analysis of the primary causes of water scarcity, the judges expected a discussion of factors associated the growing rates of consumption in addition to physical and economic scarcity as indicated in the problem statement. This discussion should lead teams to differentiation between supply and demand constraints which include not only environmental factors but also social influences on availability and distribution of this resource. Most importantly, the judges were looking for the interpretation that drove the selection of a team's input factors. The explanations of why a factor was included weighed more heavily with the judges than the actual factor itself or even the number of factors chosen for inclusion. We wanted to gain insight into the team's motivation for selecting and utilizing the particular factors in order to gauge a team's true understanding of the complexity of the environmental crisis concerning water throughout the world.

The background presented on the region of focus was critical in the judges' assessment of a team's completion of the second requirement. Better teams introduced the water scarcity of the country or region of choice in general and then addressed the details according to the factors included in their model. Teams that chose a smaller, more homogeneous region or nation were more successful in this analysis.

Developing the Model

The judges determined that a well-researched and developed model should include an explanation of the reasoning behind the chosen approach as well as the assumptions used in developing the model. Outstanding teams motivated their model with background research.

The inclusion of assumptions used in developing a model was importation in evaluating the submissions. The better solutions explained why key assumptions were made, as well as how they affected the model development. Since this problem is so extensive and there were so many factors to consider associated with water scarcity and the ability of a nation to provide for its population's needs, a common assumption in many strong submissions was that the inputs used were correctly chosen to represent the complex nature of the real world situation. Strong teams realized that their initial model included assumptions that could be changed to add some complexity or address some of the weaknesses in the model based on initial results.

The critical aspect of this challenge was to create a model that defined the ability of a nation to deliver water to meet the needs of the population. Judges were impressed by the variety of ways that teams chose to create this metric. Some teams combined their factors without weights, treating all equally, while others chose mathematically rigorous weighting methods or even a hierarchical approach. We saw such a range of approaches and applaud teams for their innovation. The judges read papers from teams that developed completely original models, while other teams leveraged and improved upon models available in the literature. The best teams created a unique model and then conducted verification by testing it against a known metric identified through their research. Regardless, the expectation remained that the teams cite work that is not their own.

We want to caution some teams from over-modeling. A verified, simpler model may be better than going one step further in order to demonstrate increased mathematical knowledge or incorporation of an advanced method. Teams that developed a strongly researched, well explained model with details of its strengths and weaknesses were judged highly.

Testing and Using the Model

After working hard to develop their models, the majority of teams validated their models and then developed intervention strategies to assist a region or nation in mitigating their water scarcity problem. The application of the intervention strategies needed to be incorporated in order to determine a projection of the effectiveness of the strategies long-term.

Even a well-developed model will not produce useful results unless the inputs are reasonable. Judges were impressed with teams that discriminated between objective and subjective input parameters, especially when teams proposed and implemented methods to address the subjective nature of certain parameters. As an added challenge, teams encountered the problem of missing data. Judges looked for the usage of effective methods for handling missing data.

Validation and sensitivity analysis often set a great paper apart from just a good report. Validation is an important part of the modeling process, as it can instill confidence in results or help identify weaknesses in the model. Several papers presented a range of models from simple to complex and used a validation approach to justify the selection of one of those choices, considering the trade-offs. Many of the strong papers, at a minimum, conducted a validation based on another commonly-accepted published measure in order to compare. Additionally, sensitivity analyses can be done in a variety of ways; so judges were looking closely at the rationale behind each team's approach. Some teams revisited early simplifying assumptions, while others assessed the relative impacts of different types of improvements. There is no one way; but teams that attempted a sensitivity analysis in order to determine the robustness, flexibility, or accuracy of their model demonstrated to the judges a higher level of knowledge concerning the impact and usefulness of their model.

Judges appreciated the discussions that teams presented on the variety of intervention strategies they considered. An explanation of possible strategies and then justification or analysis of strengths and weaknesses for those implemented was preferred. Teams that truly extended themselves and did not confine themselves to standard or already-implemented strategies were praised by the judges. We saw innovative intervention plans that were truly tailored to the specific region in crisis.

Once the intervention plans were determined, implemented, and analyzed for effectiveness or cost, the intent of the problem was to utilize the model of Task 1 to determine long-term impacts. Judges understood the need to implement forecasting methodologies but were discouraged when they saw teams adopt completely new models in order to determine the effect of their intervention strategies.

The problem statement required teams to detail the strengths and weaknesses of their model. Outstanding teams not only analyzed the strengths and weaknesses of their model but also of their data, intervention strategies, and assumptions as well. Judges encourage providing such analysis throughout the submission vs. putting it at the end of their report as a seeming afterthought. Strengths and weaknesses are relevant to the entire modeling process.

Presenting the Results

Every year, the judges seek to highlight submissions that offer a balance of sound mathematics with well written justifications. The strongest submissions have a clear organizational structure with equations coupled with explanations and, when appropriate, graphics to help convey complicated ideas, with appropriate citations completed to give appropriate credit to past problem solvers.

Outstanding papers include clearly presented ideas which are introduced in a logical sequence with transitions between topics to link the document together. The subtasks within the problem statement provide the start of a logical sequence to answer the questions. Of course, the spelling and grammar must be correct so as not to inhibit the judges understanding of the approach. Additionally, when Outstanding teams presented equations or steps within their model or analysis, they also included justifications for their approach. Judges continued to look for explanations within the document vs. just including a variable list as an appendix.

The judges understood both the time- and the page-limit constraints. It can be challenging to convey the results of a weekend of intense modeling in a 20-page report. However, with effective use of diagrams, graphs and tables, many strong teams overcame this part of the challenge. These Outstanding papers included graphical visualizations with accompanied interpretations.

Earlier, we emphasized the need for teams to conduct the appropriate research of the topic and possible mathematical approaches to solving complex problems. When conducting the research and using the ideas gained through research, it is imperative that a team's submission include a list of references used. Additionally, in-text citations allow a team to credit specific portions of their paper, such as a quotation or the support for a certain assertion. Plagiarism goes against the contest rules and the spirit of the competition.

Problem Challenges

Due to the nature of the problem, the competing teams used varying modeling techniques focusing on different aspects of water scarcity and selected diverse target regions for analysis. As a result, the submissions provided great innovations and excitement for the judging panel.

Most papers offered sound models but there were several common reasons that teams did not reach the final judging. These papers generally suffered from shortcomings in one of three categories:

- answering the problem as specified,
- making true connections to the real world, and
- effective communication.

Some teams did not answer all the questions as specified in the problem by either leaving out relevant factors that affect both supply and demand or failing to provide any explanation or discussion for a specified task.

Additionally, some teams offered models that were not sufficiently structured to address the question of water scarcity for a region. Other papers did not draw meaningful connections between the mathematical modeling inputs or outputs and their significance in the context of intervention plans for a target nation.

More often, effective communication was the most significant discriminator in determining which papers reached the final judging stage. Some teams did not clearly communicate the models or the rationale behind them or failed to provide descriptions and explanations of techniques and instead provided lists of equations, tables, values, results.

Discussion of Outstanding Papers

Each of the five Outstanding papers used a different methodology in addressing the problem of providing clean water to meet the needs of a population in a comprehensive way. These Outstanding papers were generally well written and provided clear explanations of their modeling procedures. Some demonstrated unique and innovative approaches, distinguishing themselves from other papers. Others were noteworthy for either their thoroughness of their modeling or for the significance of their results. Some provided well-thought-out, implementable intervention plans, perfectly tailored to the chosen region. The summaries for the Outstanding papers for the environmental problem follow.

Brown University, Providence, RI: "A Model for Projected Water Needs and Intervention Strategies in India"

While many teams were content to use the established Water Scarcity Index (WSI) as a metric, this team proposed a new metric to measure a region's water scarcity, the Excess Water Ratio (EWR). The EWR incorporates a different view of water scarcity by considering how much unused water is available per person, enabling the population of a country or region to be taken into account when considering the water situation. In addition, by dividing water use into separate categories for industrial use, agricultural use, personal use, and ecological demands, the EWR metric more thoroughly captures the various factors that affect a region's water supply.

The most impressive feature of this paper is the development of innovative ideas for interventions to improve water supply in the future. The two most thoughtful interventions are the proposals to affect societal changes in food consumption, and by changing food production to emphasize more water efficient crops, as shown in **Figure 1**.

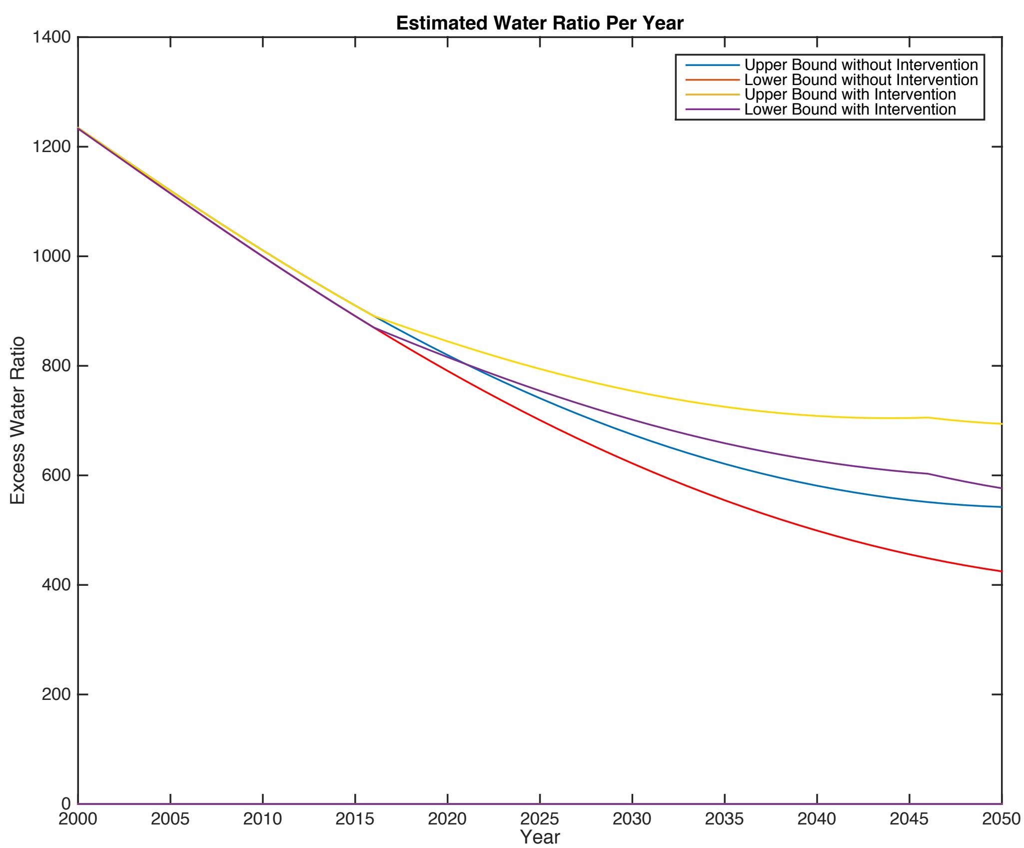

Figure 1. India's projected excess water ratio with and without millet interventions, 2000 to 2050.

The team incorporated the fact that 92% of India's water use goes to agricultural purposes, and recognized that they could gain the most by improvements in that area. They thoroughly discuss the strengths and challenges in incorporating these interventions. While the team proposes some more-standard interventions, such as watershed development and wastewater treatment, these also were well-researched and used data from current implementations of these techniques in India to predict cost, effects of the intervention, and time frame for implementation.

The paper is exceptionally well-researched, demonstrating a strong depth of understanding of current issues and practices involving water in India. For each course of action proposed, the team thoroughly analyzes the impact and discusses the strengths and weaknesses of the course of action based on their research and grounded their recommendations in that analysis. The paper is extremely well written, makes excellent use of references, and presents results with clear graphics, all of which combined to make this paper stand out.

NC School of Science and Mathematics, Durham, NC: "Where's My Water? Global Water Scarcity and Haiti's Water Crisis"

The Outstanding submission by the North Carolina School of Mathematics and Sciences was unlike any other seen by the judges this year. Instead of treating each task as a separate requirement, this team treats the overall problem of water scarcity as a project. The judges appreciated their interesting and very well written submission as well as the effort they demonstrated in tackling the problem of water scarcity by developing three different models which could be applied globally and then demonstrating the model's output, specifically using Haiti.

The team begins their submission with a history of Haiti entitled "Rags to Riches," as they explain how Haiti went from having it all to having the lowest access rates to improved water and sanitation. This upfront analysis is accompanied by common interventions currently seen in Haiti, analyzed according to the team's developed metric for a country's success in delivering needed water to their population. Their metric incorporates economic and environmental costs, as well as the ability to be self-sustainable and socially viable.

In each step of their modeling process for all three models, the team motivates the analysis, demonstrates them mathematically, explains them for the general case, then apply them specifically to Haiti, including detailed reasonable assumptions and justifications. This is followed by a sensitivity analysis. This approach is tremendous and was appreciated by the judges.

or the first model, they develop a systems network model, demonstrated in **Figure 2**, which creates differential equations for each of the six main factors of their model. This characterizes water flow by taking into account different sources of water and all varied uses of water. From there, it is applied to Haiti to understand that both the physical and social infrastructure for transportation and dissemination of potable water need to be highlighted.

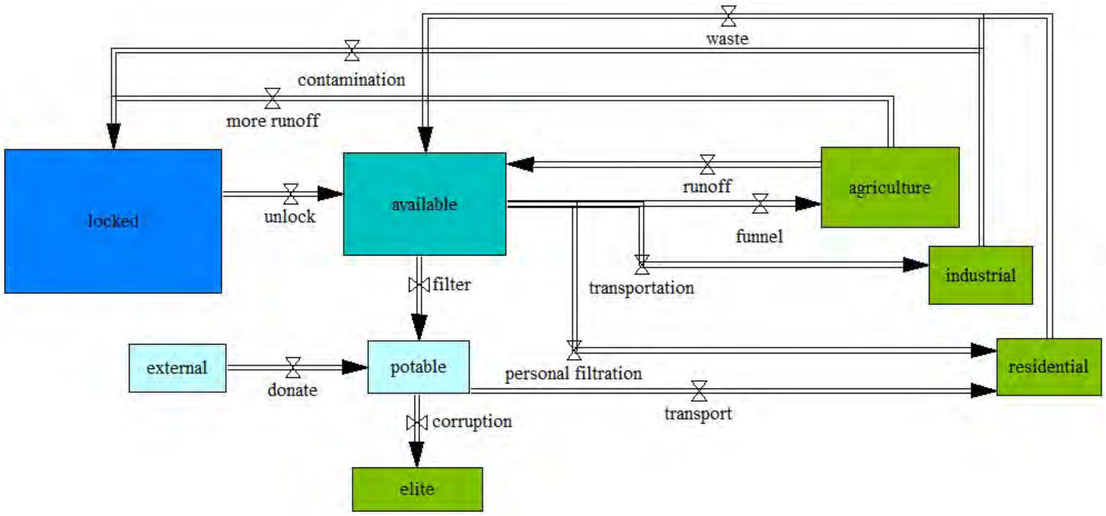

Figure 2. Systems network model of the team from North Carolina School of Science and Mathematics.

The team then examines uniquely-tailored intervention strategies for Haiti. Their first effort was to determine an optimal solution to their initial general success metric through particle swarm optimization. Then, they utilized agent-based network modeling to determine the best method for implementing a clean-water distribution system, the most critical of their intervention strategies for Haiti. Finally, the team compared current invention strategies to their proposed innovative solution using both a short- and a long-term planning horizon.

Specifically, in the discussion of water scarcity, the judges appreciated the understanding of the problem as a whole. The team looked into the cultural aspects and fairness of wealth and poverty when examining water scarcity and how solutions would be accepted within a society. When applied to Haiti, the team really understood the challenges of a water distribution network in such a nation. The judges appreciated the considerations of control of distribution nodes, presence of NGOs, infectious disease spread, the effectiveness of the government, and the operation of gangs. Overall, this was the most unique modeling the judges had seen, and the incorporation of such tailored innovative solutions was superior. The team from the North Carolina School of Mathematics and Sciences worked hard to convince us that they had good models that worked well for Haiti and could be applied globally.

United States Military Academy, West Point, NY: "Are We Heading Towards a Thirsty Planet?"

The team from the United States Military Academy provides an exceptional report focusing on water scarcity in Egypt which not only contains an extraordinarily well-written summary but also provides excellent discussion on the issue of water scarcity as well as an innovative policy recommendation for intervention. The USMA team began by analyzing the dynamics of water supply and demand through a simple flow model as shown in **Figure 3**. Each component of the model was then further developed and broken down into several individual models. Water deficit was calculated by dividing demand (or outflow) by supply (or inflow).

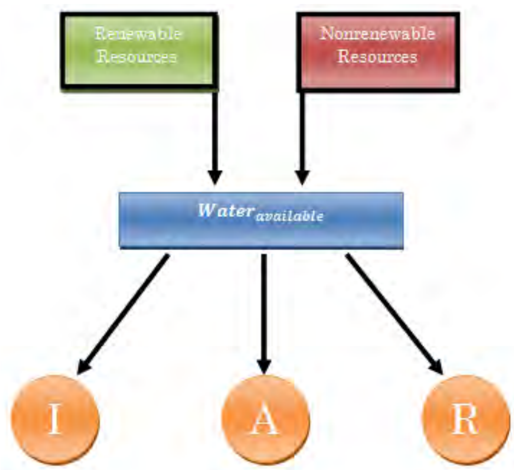

Figure 3. USMA supply and demand flow model.

Thoughtful assumptions were made concerning water recycling and artificial replenishment which added to the complexity of the model. Components such as population, industrial consumption and agricultural consumption were modeled in order to make predictions. The team goes on to provide excellent discussion of the drivers of water scarcity in Egypt, later incorporated into their intervention plan. Judges were impressed by the team's conversation about population and the fact that water consumption was not just tied directly to population but instead was broken into three separate models. Unlike many teams, the USMA team adjusted for climate change in their predictive models. They created two models, one which accounted for climate change and one which did not.

The report incorporates a well-thought-out intervention plan appropriate for the geographic region and takes specific drivers of water scarcity into account. Their intervention plan includes replacing part of the domestic crop production with international imports. This idea intrigued the judges because it was a unique idea that also makes sense for the region. The team not only addresses the impact that the intervention would have on future water scarcity but also provides nice justification and explanations for each aspect of the intervention plan.

The USMA team's ability to clearly communicate their ideas and results in a concise and thorough way pleased the judges. This, along with their inventive intervention plan, earned them an Outstanding ranking.

University of Colorado Denver, Denver, CO: "Tackling Water Scarcity: Modeling Water Access in India Using MultipleRegression Analysis"

This paper stood out because it did an exceptional job of assessing water access in India. The team uses a particularly well-thought-out structure for their intervention plan, taking account of all the critical variables that do, in fact, shape India's water crisis. They put their finger squarely on the fact, that, despite all the debates about population change, populations will certainly increase in this part of the world. One direct implication of this population growth rate is that demand for clean drinking water will increase as well. And, for all that GDP is a grossly flawed indicator of development, investment in water infrastructure is certainly tightly tied to increases in national wealth.

The team submitted a very well-written data modeling paper with excellent descriptions of their modeling process and well-chosen visualization. The statistical approach is all encompassing, with a series of detailed multiple linear regressions in which the team chose the best subset of attributes based on an adjusted R^2 value. Those included in the model are shown in **Figure 4**.

What was clearest to the judges when reading this submission was that the team did an excellent job in analyzing the nature, scale, and scope of India's water crisis. They showed a strong grasp of the realities that undergird the story of modern-day development in India. Overall, their model and recommendations were all inclusive and very innovative.

While there was some discussion amongst the judges about the extent to which the team's proposed interventions were, in fact realistic, the complete package that was their intervention plan was clearly well-thought-out and—within the limits of their assumptions—entirely defensible. The team went so far as to include a future work section in which they identified not only the weaknesses in their model but exactly how they could tackle those weaknesses.

Xiamen University, China: "Are We Heading Towards a Thirsty Planet?"

This paper was chosen largely based on its model development, including discussion of existing models in the literature, and strong data-based validation of the proposed model. The team develops two metrics, the

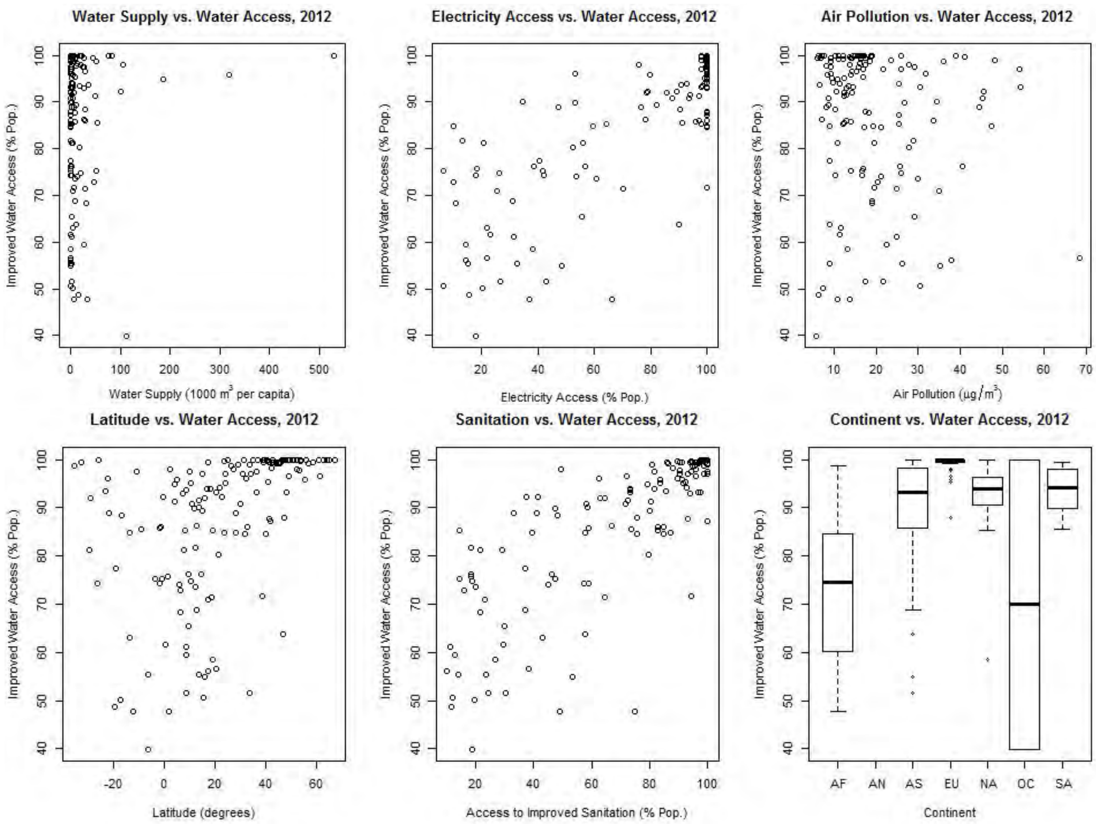

Figure 4. Data analysis for chosen attributes of the model.

Physical Scarcity Metric (PSM) and Economic Scarcity Metric (ESM), which are combined into a Total Scarcity Metric (TSM)—the ability of a country to provide clean water to its people. The main factors considered in this model are divided into technology, infrastructure, and human factors, with emphasis on the social—which was appreciated by the judges.

The team conducted extensive research that was highlighted in their literature review, where four known indices are explained and evaluated. After assessing the strengths and weaknesses of each of these measures, the team's TSM is developed using the mathematical technique of Grey Relational Analysis. To combine the PSM and ESM, the team develops an innovative solution with relative weights depending on the different country being assessed.

This paper distinguished itself in its thorough use of data in the verification of the model. Four different online data sources were used, ultimately resulting in the use of 83 countries' data. Using this data and Grey Relational Analysis, weights were found for the factors included. The following figure shows the resulting values of PSM and ESM for the 83 countries (**Figure 5**). Higher PSM and ESM correspond to more severe water scarcity. The team then compares their calculation to the UN Water Scarcity Map, with the resulting conclusion that the developed model matches the UN results well, noting possible reasons for some of the deviations. Following this analysis, the paper includes an extensive sensitivity analysis for the relative weight of PSM and ESM, choosing eight countries of varying values, as labeled in **Figure 5**. This team consistently assesses their work throughout the paper, a quality not seen among many other teams' papers.

Though the judges thought this paper was excellent overall, they had some reservations about the interventions proposed by the team which were fairly standard among those proposed by other teams. Overall, the judges recognize this team's outstanding efforts including comparisons of countries, nice explanations of mathematical techniques, extensive literature review which was used to inform the development of the metric and thorough validation of the model based on available data.

Recommendations for Future Participants

For those attempting the environmental problem in next year's competition, the judges recommend focusing on three areas. The first involves making a plan for the weekend and conducting the critical initial research. Next, solve the problem and all the subtasks that were outlined in the problem statement. Last, ensure you present your solutions and recommendations thoughtfully with explanations and interpretations.

Make a Plan

Have a plan for your 96 hours and then adjust as needed in order to ensure a completed solution and submission. Every year, there are submissions that do a tremendous job on one aspect of the problem but then are unable to complete their solution, obviously due to a lack of time or lack of coordination of the plan. To coordinate your plan, leverage the strengths of individual team members. The more your team can synchronize the efforts of its members and integrate the writing into a seamless paper, the stronger your final submission will be. Incorporate time into the plan for the best writer to edit and ensure smooth transitions throughout the document. Lastly, ensure that research is the first aspect of your plan. It is important to do the research up front and understand the context of the complex interdisciplinary problem. The judges do not expect the teams to be experts in all the aspects of a particular problem, but we do expect you to read about the environmental situation so that you ensure that you know what you are actually modeling.

Solve the Problem

Since time is short, all initial efforts must be dedicated to answering all the questions that are asked in the problem statement. Outstanding teams always address all aspects as required and then often go beyond for a particular aspect. Additionally, remember that a simple model can be just as effective as a complex one! As noted in the discussion of this year's Outstanding papers, a simple model that is nicely researched, explained, and implemented impresses the judges when coupled with excellent contextual real-world interpretation of the environmental crisis we are trying to solve.

Interpret and Present

Remember that the motivation for this competition is the real-world environmental problem. Therefore, the model itself is not the solution. Outstanding teams always use their models to produce interpretable applicable results as well as a recommendation for a solution. Throughout your process, explain what you are doing and why. The judges desire to read the explanations behind what a team is doing and the descriptions of why vs. a list of equations and numbers without words. If you are using information from other sources in your model or analysis, ensure that you use references for that information and then cite them accordingly. Please ensure that you give appropriate credit to the sources used throughout your research.

About the Authors

Kristin Arney is pursuing her Ph.D. in Industrial Engineering at the University of Washington. Kristin began her military career after graduating with a B.S. in Mathematics from Lafayette College. During her career, she has served in assignments all over the globe, received her M.S. in Operations Research from North Carolina State University, and taught as an Assistant Professor at the United States Military Academy at West Point where she will return and join the faculty in January 2017.

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Modeling the Syrian Refugee Crisis with Agents and Systems

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Abstract

We model refugee immigration policies in light of the current European refugee crisis. We develop a metric to determine the capacity of a country to host refugees, by assessing economic and physical information about the country relative to others.

We analyze the flow of Syrian refugees to and through Europe using agent-based modeling. We study the distribution of resources among countries for handling refugees and consider countries' attitudes towards hosting refugees. Our model also supports testing of sudden influxes of refugees, considers assistance of other countries outside Europe, compares ideal and realistic support from certain countries, and predicts the effects of contagious disease. The model is also scalable, and so can handle large numbers of refugees.

Our model produces realistic and interesting results when different factors are considered and also provides information useful in policy planning.

Using an agent-based model, we determined a fair distribution of resources and optimization of refugee flow that accepts over 93% of the total refugees over 91% of the time with 95% confidence.

We also develop a separate deterministic rate-based model that explores the effects of endogenous and exogenous events using system dynamics. This model incorporates a stock-and-flow structure and feedback loops in a rate-based simulation. Using this system dynamic model, we study the balance of endogenous setbacks with both negative and positive exogenous events, such as a negative anti-immigration bomb threat or a positive piece of viral media. We study the delaying effects of an endogenous issue, such as a problem with Eurodac, the fingerprinting identification system used in processing asylum application, and find that positive exogenous events of certain magnitudes could counter these delaying effects.

By incorporating known numerical values about refugee movement into both stochastic agent-based modeling and rate-based deterministic modeling, we shed light on the most influential factors in refugee migration and develop a policy to fairly settle 1 million Syrian refugees in safe-haven countries.

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Introduction

Recent conflict in the Middle East has caused an increase of migration to Europe. Refugees travel to Europe over multiple water routes, with a few routes experiencing heavy traffic, namely those via the West, Central, and Eastern Mediterranean. Travel over these bodies of water and crossing international borders involves many risks for refugees, but in 2015 an estimated 1 million refugees entered Europe to escape violence or threat of death elsewhere [BBC News 2016].

To accommodate these refugees, European countries have established a quota system to deal with the 715,000 asylum applicants; however, only a small percentage of requests are granted, and many refugees that are legitimately fleeing life-threatening situations are delayed in resettling to a safe-haven country or denied asylum entirely. In the past, burdening of host countries has varied in the quota systems used for small-scale redistributions of refugees already present in European countries. Those countries burdened the most worry about their ability to host the number of refugees assigned to them and wish for the movement and resettlement of refugees to be fairer.

Assumptions, Decisions, and Findings

- **We focus on Syrian refugees.** In 2015, more refugees fled from Syria than any other country. With no resolution to the war in the near future, the Syrian crisis will likely continue to dominate the refugee scene.
- **Our plan mainly concerns European countries and Turkey.** As of now, around 4 million Syrian refugees reside in neighboring countries in the Middle East, a number far greater than the population of refugees in Europe, estimated to be a little more than one million. The UN has enacted a regional plan through 2017 to assist these countries, which include Turkey, Lebanon, Iraq, and Egypt. On the other hand, the refugee situation in Greece is continuing to deteriorate; and because Turkey is the main path that refugees take to Europe, it plays a major role in our plan.
- **Hungary and Greece will not accept additional refugees in a realistic scenario.** The combination of a recent economic collapse and the huge influx of refugees from Turkey have incapacitated Greece. Hungary, the route of choice for many refugees going to Germany, does not support resettlement plans proposed by the EU [Than and Nasralla 2015].
- **Refugees do not choose which countries they are settled in;** they are directed by the UN High Commissioner for Refugees (UNHCR) and other organizing groups. Ideally, everyone would be able to choose

where to go, but this is not possible. Saving more lives and being fair to hosting countries overrides choice.

- **We consider the three most popular routes to Europe.** The vast majority of Syrian refugees attempt to reach Europe by land routes through Turkey, Syria's next door neighbor, and subsequently sailing to Greece. Others take the most dangerous route—traveling by land to the North African coast and then sailing over the Mediterranean, and a very small number cross over to Spain after reaching Morocco. Though refugees may take many variations of these routes, we condense their travel to these main three routes for the purposes of modeling. While sources report six routes through which refugees enter the European Union (EU), two are from non-EU European countries to EU countries (the West-Balkan-to Greece and Albania-to-Greece routes) and one is primarily frequented by Asian refugees (the East Borders route) [BBC News 2016].

Modeling Refugee Immigration

Overview of Modeling

It is important to assess the refugee-hosting capacities of countries in order to avoid overburdening them and exhausting their resources. We create a capacity metric to find the number of refugees that a country should take in. Our metric takes into account a country's economic and physical ability to support refugees.

We first create an agent-based model of refugee movement. Each agent is given information and reacts according only to what they know, and the overall system is created through the interactions of many individual agents. Agent-based modeling is commonly used to model dynamic behavior, such as schools of fish or erosion of cliffsides, and is applicable to refugee immigration [Majid 2011]. We use different agents to represent the countries, the refugees, and the routes between countries. We incorporate refugee- and country-oriented logic in our programming and include data for the refugees' path choices and for the decisions by the countries to accept individual refugees. The result is a dynamic, time-dependent complex system that incorporates stochastic and real-life data, representing the displacement, resource-consumption, and settlement of Syrian refugees into safe-haven countries across Europe.

Next, we create a system dynamic simulation and used it to explore the effects of endogenous and exogenous factors on the movement of refugees leaving Syria through various routes and being processed for asylum in different countries. This simulation incorporates data on travel routes as well as numerical values representing qualitative factors:

- "European hospitality," or the public attitude towards accepting refugees;

- endogenous events, such as delays in the refugee registration process, result in increased processing times; and
- exogenous events, such as threats or trends in media, modify "European hospitality."

We simulate Syrian refugees settling in European countries by using interacting feedback loops in a stock-and-flow model of movement, and we incorporate quantitative modification due to endogenous and exogenous changes.

Country Capacity

The following metric of ours determines a country's capacity to hold refugees. We consider as equal factors the country's percentage among all refugee-accepting countries of gross domestic product (GDP), population, and land area. Below is our equation for the country's capacity:

$$\frac{1}{3}\,(\text{GDP\%} + \text{population\%} + \text{land area\%}) \times (\text{total number of refugees}),$$

where the percentages are the country's percentages of the totals for the resettlement countries. This metric is similar to that proposed by the European Commission; theirs proposes different weights and also takes into account unemployment in a host country and its number of asylum-seekers in the previous year [Friedman 2015].

Both economic and physical aspects of a country should be considered in determining its refugee capacity. If a country is economically weak or incapable, we should not designate a large number of refugees to settle there. A country with a small population would not have the volunteers or work force needed to support many refugees. Additionally, if a country is small in area (such as Luxembourg), our metric should not direct it to hold many refugees.

Application of the Metric

We considered 15 European countries: France, Spain, Switzerland, Germany, Belgium, the United Kingdom, Norway, Sweden, Austria, Italy, Hungary, Serbia, Bulgaria, Greece, and Turkey. We apply the metric to data for each country to calculate capacities for a total of 1 million refugees. [EDITOR'S NOTE: We omit the table of capacities, noting only that Turkey's is the largest at 138,000, and Germany's—despite it actually taking in close to 1 million migrants in 2015—is only 121,000.]

To extend the model to include China and the United States, instead of applying the metric, we set the two of them combined to take 10% of refugees, or 50,000 each. It would not be sensible to base their responsibility to host refugees on the size of their land areas, or—due to to their large distance from Syria—to consider them at the same level of responsibility or capability as European countries.

Refugee Movement Model

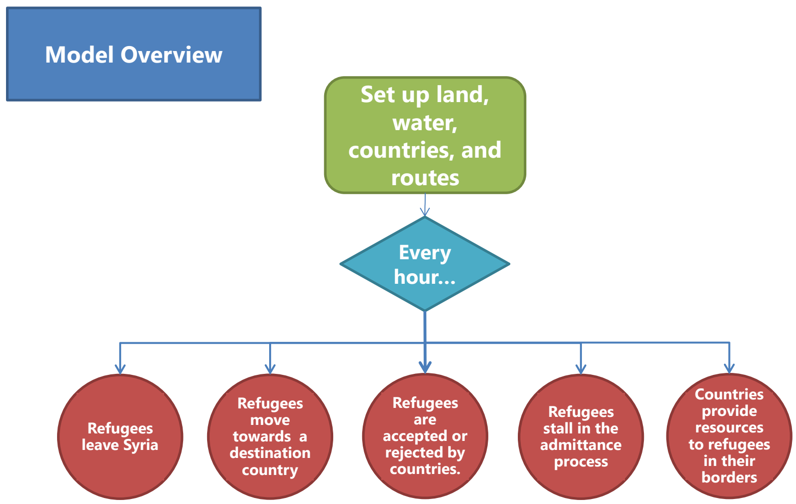

Figure 1. Overview of agent-based model.

We created a NetLogo program to model the resource expenditure and movement involved in refugee resettlement. The model sets up a map including European safe-haven countries and other relevant countries, primarily using three objects of interest: countries, refugees, and routes. **Figure 1** shows the design of the model.

NetLogo operates by executing actions every tick, over time; we scale movement, distances, and rates so that each tick is the equivalent of one hour.

Figure 2 gives a sample screenshot. The background is black, except for patches (in blue) indicating bodies of water. Circular targets (in yellow) indicate countries potentially accepting refugees. Xs (in orange) indicate countries not accepting refugees; Morocco, Libya, and Syria start off not accepting refugees, since they are not countries where refugees ultimately want to go. Line segments indicate border connections (green), water routes (blue), and land routes (brown).

Each "refugee" in the program represents 1,000 people. Refugees are "created" in Syria and leave at a rate of 3 per day [BBC News 2016]. They use the logic of **Figure 3** to choose a country to travel to and start traveling.

Once they reach a country, they have a chance of being accepted, as detailed in **Figure 4**; and if they are, they are removed from the program.

Over time, countries change their willingness to accept refugees, through the process detailed in **Figure 5**.

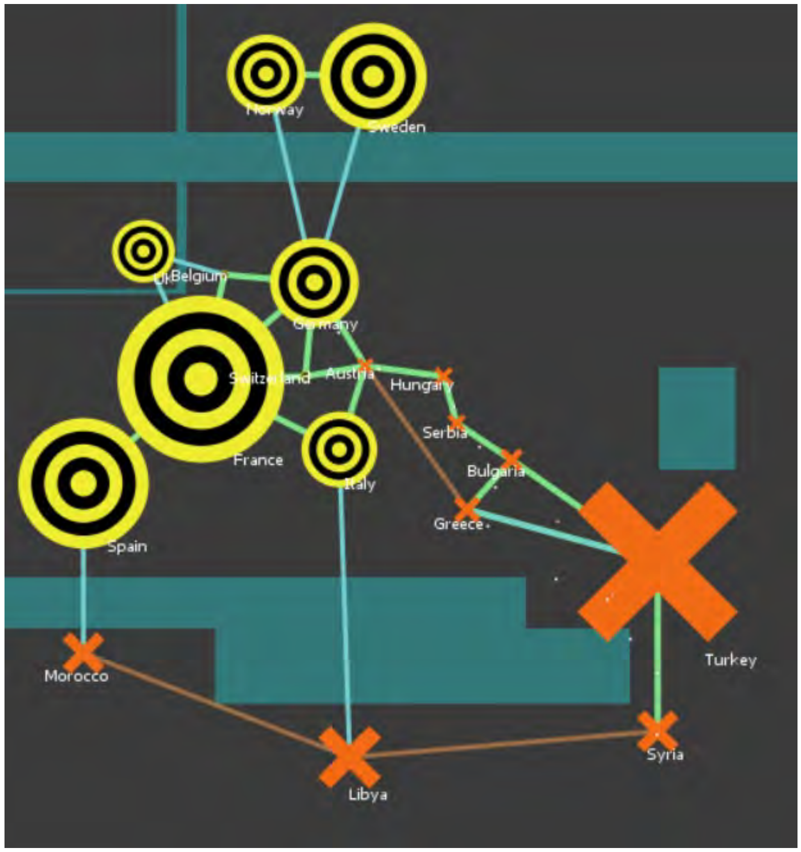

Figure 2. Sample screenshot of NetLogo model.

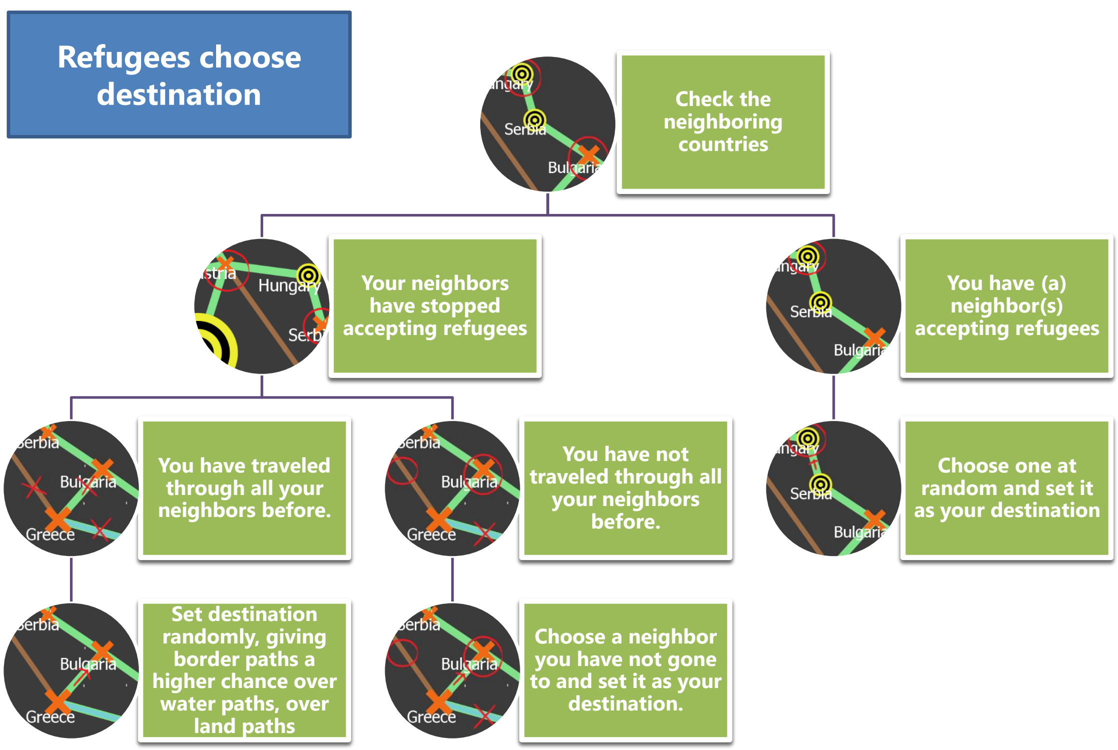

Figure 3. Flowchart of how refugees choose destinations.

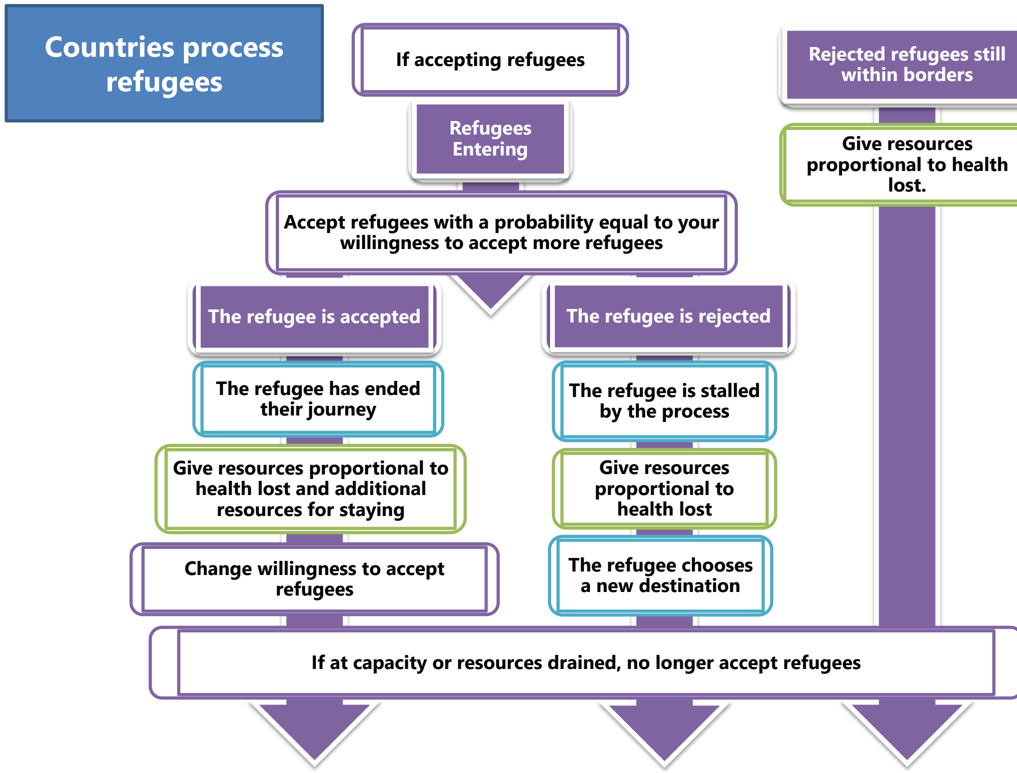

Figure 4. Flowchart of how countries process refugees.

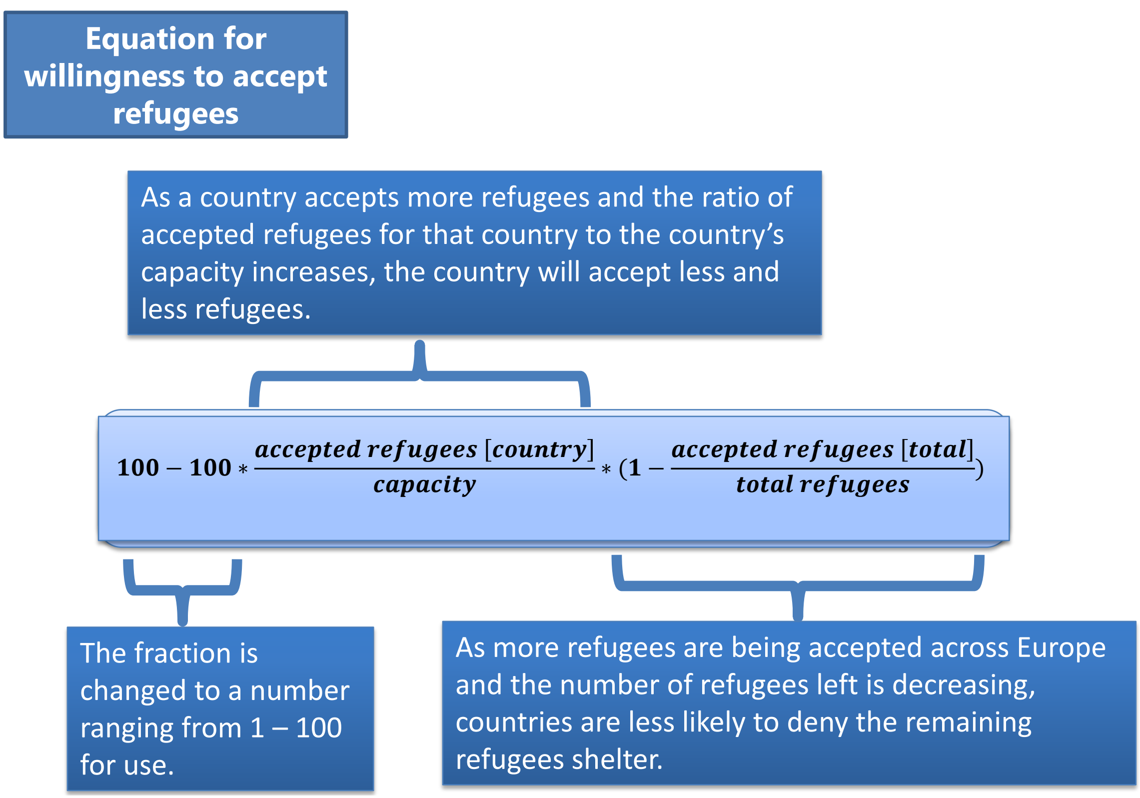

Figure 5. Calculation of a country's willingness to accept refugees.

A refugee not accepted in a country is stalled there for a random duration of up to 30 days, then chooses another country and continues traveling. Refugees who leave a country and return later to the same country have another chance of being accepted.

Countries provide "resources" to all refugees passing through their borders and to refugees whom they admit for settlement. "Resources" is our simplification of factors that could include food, water, shelter, medical attention, or transportation. For our purposes, refugees who do not gain resources for long periods of time "die"; and countries are the only providers of resources. Countries stop accepting refugees if they reach capacity or if they run out of resources. The model runs until 95% of the initial 1,000 refugees are settled in some country or have perished from sickness or lack of resources.

Model Flexibility

The program includes

- a toggle for including China or the U.S. as accepting refugees;
- a toggle for "realism," i.e., Hungary and Greece not accepting refugees (unless otherwise specified, our results are for "realism" on);
- a button for a sudden increase in refugees due to exogenous events;
- accommodation for disease. Sliders can adjust the the initial chance of a refugee in a group developing disease, the rate of disease spread among that group of refugees, the average duration, and the chance of recovery (unless otherwise specified, our results are for no disease).

Further Details of the Model

We considered all the major countries in Europe but include in the model only 15 countries, after considering each country's capacity and expressed interest and activity in accepting refugees [Friedman 2015]. Considering the major routes to Europe led us to include Morocco and Libya in the model [BBC News 2016].

In the course of runs of the model, countries are aware of whether their neighbors are accepting refugees.

Refugees who seek to travel over water are assumed to find transport to do so.

When refugees reach their desired destination, they have a chance of being rejected eventually, meanwhile staying in the country and waiting for the result. The model formulates this waiting time as uniformly distributed over a range up to the maximum processing time [European Commission, Migration and Home Affairs 2015].

A refugee's health has a chance of decreasing slightly with every tick. While refugees are in a country and draining that country's resources, they recover health, and the country's resources decrease by an amount proportional to the refugee's health gained. Even if the country is no longer accepting refugees, it still feeds and shelters those passing through, provided resources remain. Sliders in the program indicate the country's resources, which slowly decrease as the model runs.

Human Factors Model

We created a system dynamics model to explore the effects of exogenous and endogenous events on the rates of refugee processing and status approval from Spain, Italy, and Turkey, the three main entry points through which Middle Eastern refugees enter Europe.

The majority of Syrians who want to leave the Middle East for Europe travel through Spain, Italy, and Turkey via the Western Mediterranean, Central Mediterranean, and Eastern Mediterranean routes.

In our program, the time step is one day. Every day, Syrians enter the box "Syrians that want to leave" (**Figure 6**, on p. 204). From there, appropriate numbers leave for Spain, Italy, or Turkey. Once Syrians arrive in one of these three countries, the processing times for an application for asylum and the numbers of Syrians determine the "Spain to total," "Italy to total," and "Turkey to total" rates. Each rate is also modified by "European hospitality," a multiplier between 0 and 1 that represents changing European public attitude on accepting refugees. As total refugees in Europe increase, the rate of asylum acceptance decreases. [EDITOR'S NOTE: We omit details of the underlying equations of the model.]

This model allows for an exogenous event occurring on a specific day during the iteration. The event has either a positive or negative effect on European hospitality, which then affects the rate of refugees entering the "total refugees in Europe" box.

The "delay due to sudden endogenous event" represents an increase in processing times, which could be due to a technical issue with Eurodac (the biometric database used in processing asylum seekers) [European Parliamentary Research Service Blog 2015], a delay by the bodies that review asylum applications, or some other UNHCR-wide internal delay.

Further Details of the Model

The system dynamics model uses data from recent sources for the attempt and death rates for each of the three main routes to leave Syria for Europe, as well as the reported or self-set processing times for these countries' asylum application processes. The rate of Syrians entering the box

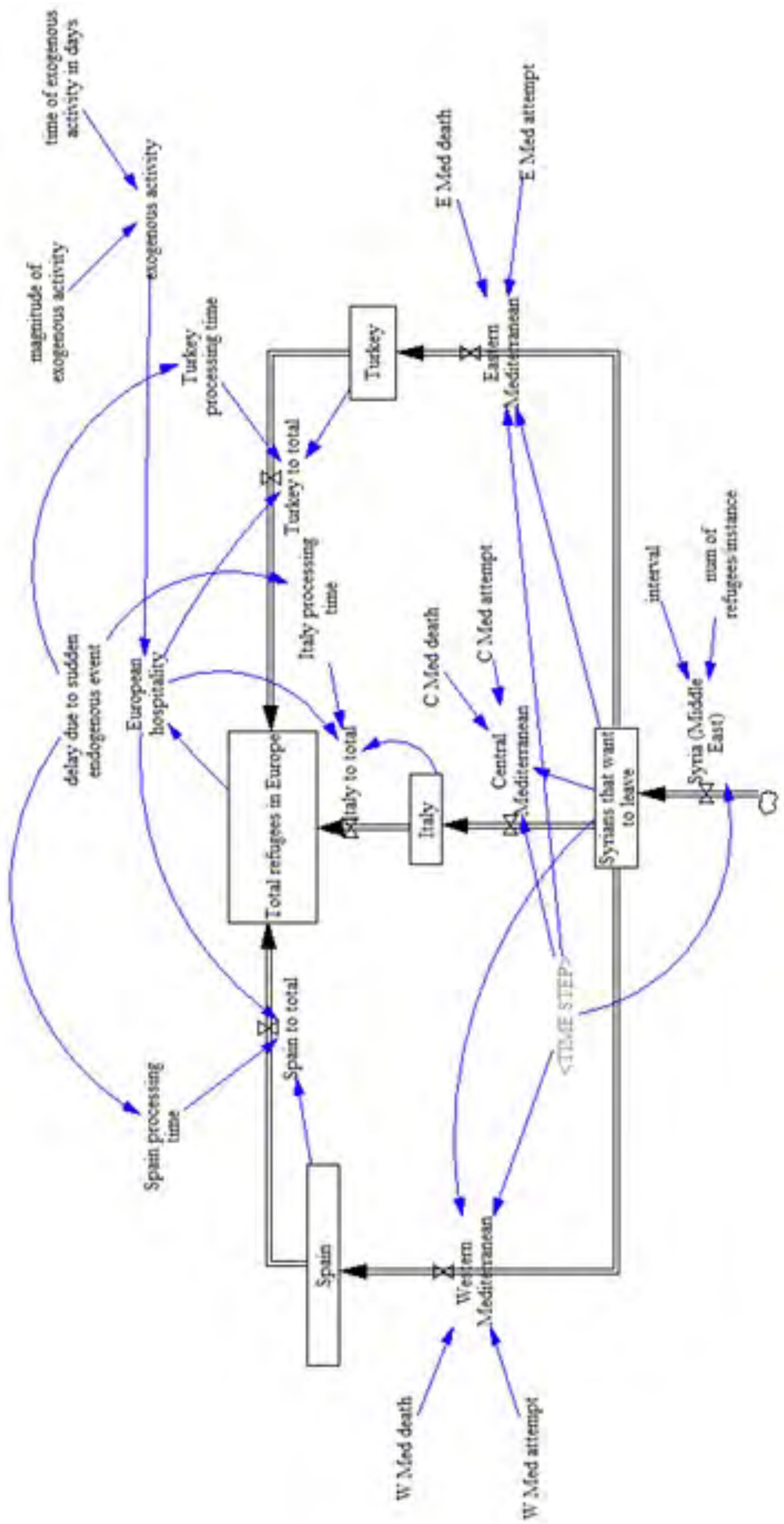

Figure 6. Vensim system dynamics model.

"Syrians that want to leave" is calculated from the estimated value of 1 million Syrians entering Europe in 2015 [BBC News 2016].

However, unlike the case in 2015 (with overrunning of borders), in the model every person must enter "Total refugees in Europe" through approval for asylum. In fact, not every Syrian applies for asylum in the first EU country entered (as prescribed in the Dublin Regulation); and there are reports of refugees applying for asylum in multiple countries (e.g., when Spain takes too long to process their case, they may move on to try in France, too).

Additionally, there is no delay in Syrians being "transported" between countries' box variables. In other words, a Syrian enters "Syrians that want to leave" one day, travels to a country within a day, then the next day is considered for asylum (repeatedly, until admitted or the rate becomes 0 because European hospitality is 0).

Results and Discussion

Refugee Movement Model

Determining Resource Distribution

How should resources, from individual countries and international aid, be distributed for the benefit of refugees?

We ran 30 trials for each of several sets of initial conditions.

First, we tested how much resources each country would use up if allowed unlimited resources (no resettlement in China, the U.S., Hungary, or Greece, and no disease). Turkey consumed, on average, almost twice as much in resources as the next country (France), accounting for 29% of total resources expended.

We then scaled resources to the refugee capacity of each country. This strategy ran successfully in only 4 out of 30 runs; the other 26 trials failed to settle a minimum of 95% of the refugees.

Finally, we set the resource value of a country to the amount needed for its refugee capacity plus one standard deviation of that amount. Then 24 out of 30 runs were successful in settling all the refugees, with no country running out of resources.

With success defined as at least 93% of refugees successfully settling, we can say with 95% confidence that our resource allocation allows for success over 91% of the time. [EDITOR'S NOTE: We omit the statistical details and the resource values.]

Dynamics of the System

We ran trials to test the impact of extraneous dynamics (events involving special circumstances), exogenous events, and scalability, using the resource distribution that we found above.

Our criteria were mean time to settle 95% of refugees and mean total cost of resources. Our conclusions are:

- Including Hungary, Greece, the U.S., and/or China as accepting refugees makes a negligible difference in settling time (which averaged 325 days).
- Including the U.S. or China as accepting refugees reduces resource costs by about 6% each.
- The effect of disease can be devastating on the population of refugees, and sick refugees drain country resources much faster than healthy refugees: All of the countries run out of resources and shut down early. Increasing the percentage of refugees who are initially sick has far more effect than increasing the infectiousness of the disease, indicating that refugee clumping while stalled in a country does not spread the disease drastically, but that having many sick refugees does impact the end result.
- Adding a sudden influx of refugees into the system has no visible impact. Each refugee handles their own situation and the system as a whole does not stop working. There is no significant change in average settlement time and the system runs rationally, taking in as many refugees as it can.

Scalability Testing

With 1,000 "refugees" (representing 1 million people), the program runs on our hardware at roughly 1,300 ticks per minute. With 10,000 "refugees," the program averages 19 sec between each tick.

Conversion of Model Elements to Monetary Units

The European Commission (EC) plan for relocation of Syrian refugees already in Europe (in Hungary, Greece, and Italy) calls 6,000 euros ($\approx$ 6,500 USD) to be given to a country for every refugee hosted [European Commission, Press Release Database 2015].

In our Netlogo model, the 1,000 "refugees" (representing 1 million people) used 1,261 resource units. For the following calculations, we treat one resource unit as the settlement cost for one "refugee" (but in the model, refugees also use resource units in passing through a country where they do not settle).

Scaling up and using the cost in the EC plan, the total cost for 1 million people would be around 6 billion euros, which suggests 5,000 euros as an approximate equivalence value for a single resource unit.

Human Factors Model

We ran our human factors model first on the base case of no consideration of the effect of refugee movement on European hospitality, no delay from endogenous events, and no exogenous activity modifying hospitality. Later simulations were run with European hospitality considered.

Our measure of comparison is the number of days to settle at least 95% of refugees.

Our results were:

- Base case: 350–375 days.
- Adding effect on European hospitality: 600–625 days.
- As expected, there is a decrease in the time when positive exogenous events occur, and an increase when negative exogenous events are introduced, or when an endogenous event causes a delay in processing time. [EDITOR'S NOTE: We omit the details and resulting values.]

It may take months or even years for consideration of an application for asylum, as a result of factors not included in our model (resources of the processing offices, backlog, scheduling of interview, etc.). Our European hospitality represents human sentiments that affect the acceptance rates for refugees into Europe.

Policy Recommendations

The preservation of human life and dignity supersedes other factors in considering an appropriate course of action for refugees. Based on this principle, we have formulated a plan to resettle the Syrian refugees that have entered the European continent and Turkey. Non-refoulement (a victim seeking asylum should never be returned to his attacker) and preventing discrimination are priorities, so the purpose of the plan is to give all those seeking a life away from violence and war a place to live without discrimination [Lauterpacht and Bethlehem 2003]. Since it is potentially discriminatory to distribute refugees to different regions based on race or religion, we exclude both those aspects from consideration.

To be fair to the current inhabitants of hosting countries in spreading the burden, our team developed a metric that takes into account geographic size, population, and economic stability of a country in determining the number of refugees a country should take. These capacity values should be requirements for the number of refugees each country should take in.

Because keeping families together is important, we recommend that family units be considered as a whole and sent only to countries with room for all family members. To facilitate this, we also recommend increasing the aforementioned capacities by 5%, to be used only to keep families together.

Through incorporating these capacity values into the NetLogo model, we have formulated how resources to care for refugees should be distributed. These values are different from capacities because resources are necessary not only when refugees have settled in a country, but also as they are moving to these designated countries. Since Turkey and countries in southeastern Europe are closest to Syria and have the greatest traffic, they will need the most resources.

For this plan to be feasible, the UN will need continued financial support from its donors. Most of the budget will be to provide resources to participating countries. A smaller portion will be set aside for improving the communication systems and bureaucratic infrastructure necessary for efficient international information exchange. Minimizing the time to register refugees and to make contact with other countries about available space will mean that refugees will settle sooner, and money will be saved since fewer resources are consumed in the meantime.

This model is very stable; but in the event of unusual exogenous events that would interfere with the plan, we recommend that the UN divert a small portion of the budget into an emergency fund. An example of external events that would negatively impact the system is the recent terrorist attacks in Paris. Several countries shut down immigration services for a period of time after the attack, due to suspicions of Syrian migrants, causing many refugees to be totally blocked from entry.

Another issue demanding the attention of the UN is safety of the routes taken to get to Europe and to travel through it. When registration policies are inefficient and European countries are trying to discourage people from coming through their borders, refugees have no choice but to turn to smugglers and other illegal methods of gaining entry to safe havens. Refugees then put themselves in grave danger while funding criminals. Recently the bodies of 71 refugees were found in an abandoned truck, likely belonging to a smuggler [Al Jazeera 2015]. Furthermore, even in less tragic cases, the money spent on fake passports and dangerous boat trips could instead go to funding resettlement. Previously, Italy funded a project called Mare Nostrum that made routes for refugees safer and rescued 150,000 migrants [Ministero della Difesa 2014]. This project was discontinued in 2014, but we recommend that the UN revitalize such efforts.

Strengths and Weaknesses

Refugee Movement Model

Strengths

- **The model is flexible, time-dependent, and dynamic.** The model considers many factors such as resources, disease-spreading, exogenous events that strain the system, capacity, and every refugee's decisions, and the agent-based modeling structure allows easy addition of further metrics or shifts in the dynamics of the crisis. Furthermore, the tick-based logic of NetLogo guarantees that the simulation is time-dependent and everything runs at the same rate, working together to create a dynamic complex system.

- **The model contains stochastic elements.** The model is not deterministic, meaning that different runs produce different results, and we can take note of the variability in settlement time. We can also vary parameter values to reflect different conditions, produce a data set of total run times for condition, and see the implications of change in these choices and how much they affect the end result.
- **Agent-based modeling closely represents human behavior.** Since each "refugee" in the model makes its own stochastic decisions, the paths of the model "refugees" simulate the paths of real-life human refugees. Also, the countries in the model react to "refugee" flows in a realistic manner as well. The behavior is not uniform, nor is it arbitrary, creating a more-realistic representation of the situation in Europe and Syria. Running many trials allows us to see overall trends even though the decisions made by each "refugee" may be different every time.
- **The model considers multiple aspects of refugee support.** A "country" not only provides resources to a "refugee" that is accepted and granted asylum but also supplies "resources" to "refugees" who apply and are declined or are passing through and cannot be fit into the country's capacity. This is representative of the actual resources needed by refugees traveling to and across Europe—they need resources not only to settle, but also need immediate food, shelter, treatment, and other resources as they travel.

Weaknesses

- **The model is strict in exactly what the countries and refugees know.** "Countries" are unaware of the status of "countries" beyond their immediate neighbors. Similarly, "refugees" are aware only of countries one country away from them, and of the paths from the country they are currently in. Turkey cannot tell "refugees" that Switzerland has room for them, and a "refugee" in Austria would not know if France is still accepting refugees before the "refugee" travels to a country neighboring France, for example, Germany.
- **The model assumes durability and accessibility of resources.** In addition to assuming that all refugees who choose to travel by water have access to transport, we assume that distributing resources to countries once (at the start of the simulation) is sufficient to model consumption of resources over time, ignoring food decay or shelter spots opening and closing over time.

Strengths and Weaknesses

Human Factors Model

Strengths

- **The model incorporates general public sentiment.** The changing value of European hospitality represent human sentiments. While there is no simple quantitative measure of this variable nor of its influence on refugee movement, it must be taken into account because it impacts the system significantly.
- **The model allows for endogenous delays and sudden exogenous events.** Exogenous events can be distilled to a net negative or positive influence on rates of asylum acceptance and consequently on settlement time.
- **The stock-and-flow structure of the model simulates the movement of refugees from Syria to Europe.** A compartmental model is a suitable representation of the stages in an individual refugee's journey.

Weaknesses

- **In the model, countries are equally affected by changes in public attitude and endogenous/exogenous events.** Spain, Italy, and Turkey are all modified by the same ratios when European hospitality or endogenous/exogenous events occur. If there were a bombing in France, then Spain or Italy would likely respond with a more negative reaction in acceptance rate compared to Turkey, since the former two are closer to France and could feel more concern that refugees entering through their processes could be connected to a negative exogenous event in France. In reality, Spain, Italy, and Turkey would have different reactions depending on the public sentiments of other countries, as well as multiple endogenous and exogenous events of different magnitudes.
- **The model does not directly incorporate delays and realistic times for exogenous events into the rate of refugee movement.** Processing time affects a country's rate of accepting refugees into Europe; but "refugees" are hindered by probability or rates, instead of delays in obtaining transportation from Syria to Spain/Italy/Turkey or delays waiting for paperwork processing. Additionally, there may be some delay in the effects of exogenous events; for example, a social media trend might take a couple days before it reaches peak, but it will affect the rates of entry both before and after the peak.

The Two Models Combined

Strengths

- **Our models incorporate real data collected from recent sources.** By basing the rates of route selection, refugee deaths, and processing times on research, our model is more representative of the actual situation than one created with arbitrary values. Additionally, our metric for resource distribution was applied to current country data.

- **Our models consider non-ideal complications and realistic modifications.** Our models allow for changes and depletion of resources, changes in public attitude and countries' acceptance rates of refugees, and other facets that add to the complex nature of the refugee crisis.

Weakness

- **Our models do not incorporate certain factors, such as wealth or religion, that are reported to affect refugee movement.** Many Syrians pay smugglers or fees for traveling, and some countries want to confiscate valuables from refugees (to help pay for the cost of settlement) [Matthews 2016] while others refuse to accept refugees of certain religions.

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Appendix: Letter to the United Nations

We, the ICM-RUN (RefUgee-aNalytics) team, were tasked with helping the UN develop a better understanding of the factors involved with facilitating the movement of refugees from countries of origin into safe-haven countries. Through

- devising a metric to determine countries' capacities to host refugees, and
- the development, programming, testing, and analysis of two mathematical models,

we have created a plan that will allow for near optimal distribution of 1 million refugees throughout Europe.

We calculated maximum capacities of countries within Europe as well as Turkey to handle the flow of incoming refugees. The bulk of resources such as food, water, and immediate medical care will be most effective if pre-positioned in Turkey, France, Germany, and Italy. Furthermore, refugee families should never have to be separated, and so we created flexibility in our capacity determinations to allow family members to stay together.

According to our plan, dedicating small portions of the budget to causes other than immediate needs will also be beneficial for the refugees. We recommend that projects designed to make escape routes for refugees safe and not life-threatening, such as Italy's Mare Nostrum plan, be re-implemented so that the daunting journeys refugees currently undertake will not be so dangerous.

An emergency fund should be dedicated to creating positive media attention to counteract the potential effects of negative events (such as a terrorist attack) on public opinion. This could facilitate viral campaigns or promotional advertisement encouraging people to volunteer or otherwise assuring the European public that hosting refugees is not a dangerous risk. Increasing public awareness and sympathy for the refugee cause will increase the support for this plan, and will hopefully encourage the participation of other countries.

Despite the distance of China and the U.S. from Syria, and aside from acting as host countries, both can offer resources and many potentially willing volunteers and supporters. While there is higher cost to transport refugees to these two countries, our model indicates that there would be a 12% decrease in cost of resources if 10% of refugees resettle in China and the U.S.

Not only does our plan seek to save millions of lives of refugees, it is also beneficial to the inhabitants of hosting countries. Much of the burden safe-haven countries is caused by illegal immigration, which refugees often resort to when a country does not provide resources for their survival. Properly distributing resources and improving the registration process will mean that refugees will be able to integrate more quickly into society.

We hope that you will adopt our policy recommendations so as to maximize the safety and movement efficiency of the refugees fleeing violence, while being fair to hosting safe-haven countries.

Advisor Daniel J. Teague with team members Sicheng Zeng, Anna Hattle, and Katherine Shulin Yang.

Judges' Commentary: Refugee Immigration Policies

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Introduction

This year's ICM introduced the first problem that explicitly focused on policy modeling. Public policy is the system that produces laws, regulations, courses of action, policies, and funding priorities concerning governmental issues. Individuals and groups attempt to influence public policy. Therefore, policy modeling must take special efforts to overcome system and political biases to build fair and unbiased models to analyze complex situations and issues to ultimately make good recommendations.

It is often the dynamic and challenging human element that makes policy modeling so challenging. The ICM considers policy modeling as the process where, based on information and realistic assumptions, recommendations are made from the results of a model that can then be tested and/or validated, in order to advance understanding of an issue, build a new system, and/or recommend a policy decision. Policy issues often require the modeler to incorporate social and political science knowledge and perspectives to engage accurately with such a complex real-world issue. The culmination of the modeling process is usually a policy paper prepared by the modeler for the decision maker that contains the most cogent results of the policy model and explains and anticipates the model's implementation in the context of the human elements and the political situations.

We hope that by adding policy modeling to the ICM, we increase awareness about social science modeling that leads to more student experience in solving challenging social problems. The ICM policy modeling problem provides opportunity for students to experience interdisciplinary model-

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ing (combining quantitative and qualitative perspectives) to solve some of society's most challenging and important social issues.

The problem statement is given in the contest report earlier in this issue.

Judges' Criteria

This year's problem involved modeling refugee immigration policies relevant to the on-going migration of people from Syria and the rest of Middle East to Europe. The problem statement is given in the contest report earlier in this issue. The judging goal of this ICM policy modeling problem is to evaluate teams' performance of good science that leads to viable policy recommendations. Getting good data to build and evaluate the models are challenges for this problem. Some of the issues the judges considered for the modeling team members are:

- Do they develop a means for producing a good policy recommendation?
- Do they find and use viable data and do they provide a visualization of their model and framework?
- Do they determine the specific factors which can enable or inhibit the safe and efficient movement of refugees? Do they develop a set of measures and parameters and justify why they should be included in the analysis of this crisis?
- Do they create a model of refugee movement that would incorporate projected flows of refugees across the six travel routes with consideration of transportation routes/accessibility, safety, and resource capacities?
- Do they identify the environmental factors that change over time, and show how these factors can be incorporated into the model to account for these dynamic elements? Do they determine how to incorporate resource availability and flow in their model?
- Do they prioritize the health and safety of refugees and of the local populations?
- Do they consider what parameters of the model would likely shift or change in a major exogenous event? What are the cascading effects on the movement of refugees in neighboring countries?
- Do they discuss the scaling of their model in an expanded crisis?
- Do they discuss what policies need to be in place to manage issues such as disease control, childbirth, and education?
- Do they discuss assumptions, strengths, weaknesses, and sensitivity of their models?
- Did they find and use good data to help their modeling and analysis?

- Is the Executive Summary clear and concise?
- Is the policy recommendation clear and concise?
- Is there good visualization of results?
- Do the models utilize policy science and immigration research factors?

Discussion of the Outstanding Papers

Renmin University of China: "Dual Goal Network Planning Model"

This team used a network optimization approach to develop a Dual Goal Network Planning Model. Their model attempts to optimize refugee movement along the routes with least difficulty and maximize living quality of the receiving country. The team chose 5 source nodes that represented the countries of emigration in Northern Africa and Middle East and 11 sink nodes that represented receiving countries in Europe (see **Figure 1**).

Figure 1. Map of the Renmin University team's source and sink nodes.

Then they abstracted the movement routes into a network where the length of the edges between the nodes represents transport accessibility of each route segment between any two nodes. The transport accessibility is developed from a compound measure of death rate, transport distance, and transport time. They develop a living quality index and use a minimum-cost network-flow model to develop a transport accessibility matrix.

Finally, the team uses goal programming to optimize the two objectives:

- maximize total living quality index, and
- minimize total accessibility index.

Assumptions made throughout their modeling are reasonable, and a number of them are relaxed to evaluate the effects.

The team's living quality index combines the receiving country's GDP, cereal production, pension spending, healthcare spending, and number of doctors per 1,000 inhabitants into one measure using principal components analysis. The index contains 80% of information of original five metrics. Additionally, they constrain refugee capacity of each country to be less than 0.5% of the country's population.

The dynamic component of their model allows the team to assess compounding effects of refugee influx on the living quality index. Their analysis of exogenous events is thorough, especially the mention of the cascading effects of the refugee movement. However, it would have been even better to discuss cascading effects at border closings.

Analysis of their model revealed that it is not quite scalable (at least, not out to an order of magnitude scale of $10\times$), due to the capacity constraints. Perhaps the team should have looked at other countries not utilized in the model as an option to receive the overflow of refugees. However, the team provides an insightful discussion on the change of the parameters and new challenges and constraints of their model due to a dramatic increase in the number of refugees. Moreover, the team provides insights on the role of NGOs in such a large-scale event.

The team's policy recommendations use findings from their modeling and transform the results into implementable strategies. Following are the policy suggestions advised by the team:

- Strengthen the construction of infrastructure and increase the supply of basic necessities and subsidies.
- Devote more efforts to the patrol and rescue of refugees in the Mediterranean area.
- Support countries on the front line and inhibit unilateral border-crossing.
- Make changes to the current Dublin system, and consider a fairly shared refugee intake plan.
- Embrace the multicultural aspects and emphasize considerations about the local people's welfare.

The final policy suggestion, however, would benefit from a direct support from the model. The team's argument rests on the effects of refugees through their living quality index, but religious and cultural differences were not directly included in it.

Shandong University: "Modeling to Refugee Policies"

The team optimized a control variable algorithm to build a model using factors such as psychological condition of refugees, resources, policies of the receiving countries, capacities of the receiving countries, and exogenous events such as natural disasters or terrorism. They further utilize a small-world network algorithm to analyze the flow of refugees into Europe. The team introduces a dynamic element to the problem by making resource factors, such as financial and material resources, become dynamic variables. The team expands on the role of NGOs in the crises as the primary providers of basic needs. The model's assumptions are to ignore countries with low volume of refugees as well as time delays associated with the movement of refugees.

An interesting component is the inclusion of religious beliefs and habits. The team stresses the importance of disparity between the receiving countries' religious beliefs and cultural habits and those of the refugees. They highlighted that this factor is particularly important in integrating the refugees into the local population.

The team report addresses the following exogenous events: border crossings, wars, and violence among refugee receiving and exporting countries, and natural disasters. The developed model is scalable and the team offers enhancements and new parameters to further strengthen the utility and scalability of the model. A strength of the report is the discussion on stability and sensitivity analysis of the model. The team assessed their model as low in sensitivity and high in stability.

The model uses the following influence factors:

- psychological condition of refugees;
- faith of the refugees;
- material and financial resources of the receiving country;
- refugee policy of the receiving country;
- refugee capacity of the receiving country;
- exogenous events: natural disasters and terrorist acts.

Finally, the team's policy recommendations are feasible and include three main suggestions:

- Give priority to cultural restraint and religion.
- Establish a "safe zone" for the refugees as a buffer in case of conflict between bordering countries.

- Provide more doctors and psychologists at border crossings and within the refugee receiving countries.

Sun Yat-Sen University, China: "Towards a Hopeful Journey"

This team uses network analysis and cellular automata to simulate refugee migration into Europe and then to build good management policies and a viable feedback system. The team establishes a set of metrics and indices to consider relevant factors in refugee migration. The six migration routes considered included 14 countries. Because they assume that refugees get limited information, they initially built a random migration model. However, using a Matlab-constructed simulation of this network flow, their initial results were inconsistent with data that they found to check their model.

As good modelers, they adjusted their assumptions and revised their model. Their new version was a gravity model that analyzes the factors affecting the migration of refugees. They integrate their factors into what they called the Attraction Index. Through statistical weighting, they produce a more accurate population distribution for the routes and used it to build and optimize a flow distribution model. Using their new model, they could expand the scale and capacities of nodes and edges. Their innovative modeling continued as they used a cellular automaton simulation of the migration progress of refugees to further refine the dynamics of the flow.

This team's policy discussion and recommendation try to play up the importance of the empathy that the receiving population of each country had to develop to accommodate the refugees and their impact on local living conditions. Unfortunately, this empathy element is not present or reinforced by their models. Additionally, the team noticed that they could not reliably scale up their model because of the fast saturation of the existing migration routes.

As part of their basic measures, they assemble a Safety Index, Environmental Acceptance Measure, and a Transportation Index, which take into account transportation cost, travel time, distance, and traffic conditions. Through the Environmental Acceptance Measure they could judge the danger of a route for groups and people, especially vulnerable ones, such as children, pregnant women, the elderly, and the disabled. Their measure of Environmental Acceptance consists of:

- resource abundance,
- economic condition, and
- religious and culture acceptance.

This team did a good job in identifying and describing the fundamental assumptions that they made. Some of the elements on this list were:

- Refugees migrate in groups

- The migration of refugees is irreversible and there will be no possibility of return to the home before arriving at their destinations.
- Refugees are sensible and can adjust their routes.

The dynamic simulation model of refugee migration based on a cellular automaton showed various elements of the migration. The results of their simulation are shown in **Figure 2**.

When the issues of scaling and sensitivity were addressed, the team realized that more countries were needed to accept refugees. So the team added Canada, the U.S., and China to expand the migration and checked the scalability of their work with more routes and locations. **Figure 3** shows the new results with Canada, the U.S., and China added to the destination list.

As part of the task on the effects of exogenous events, the team also considers the outbreak of the diseases and illness such as the newly-discovered Zika virus. If migration nodes and links are shut down from a disease outbreak, what will happen to people and places involved in the disease? The modelers also looked at the effects of a terrorist attack—especially the cascading effects of changes in refugee policy of a country where terrorism is blamed on refugees that then has the potential to cause attitude to change in neighboring countries as well.

This team also provides a good analysis of their effort. They list the strengths and weaknesses of their modeling and their results. They like how their models were verified by data that they found in the literature. One of the weaknesses discussed is that the distances in their models are approximated by straight lines, not real travel distances. They also ignore geological barriers on the routes, so they felt that there were errors in calculating the travel times and distances.

Overall, this was a strong modeling effort; and the team is congratulated on being selected as the INFORMS Prize winner for this problem.

North Carolina School of Science and Mathematics, NC: "ICM-RUN to Safe Countries"

This team models refugee immigration movements, policies, and issues of the current Syrian-European refugee crisis. They develop a creative measure for the capability of a country to host refugees by assessing economic and physical data (relative to other host countries). A resource distribution is also computed and analyzed using their measure. Their dynamic model simulates the flow of Syrian refugees to Europe using agent-based modeling (NetLogo). Using system dynamics and social constructs, the team also considers several countries' attitudes towards hosting refugees. Through the use of these general network structures, their model is able to simulate sudden influxes of refugees, the addition of host countries, changes in levels of support from countries, and the effects of an outbreak

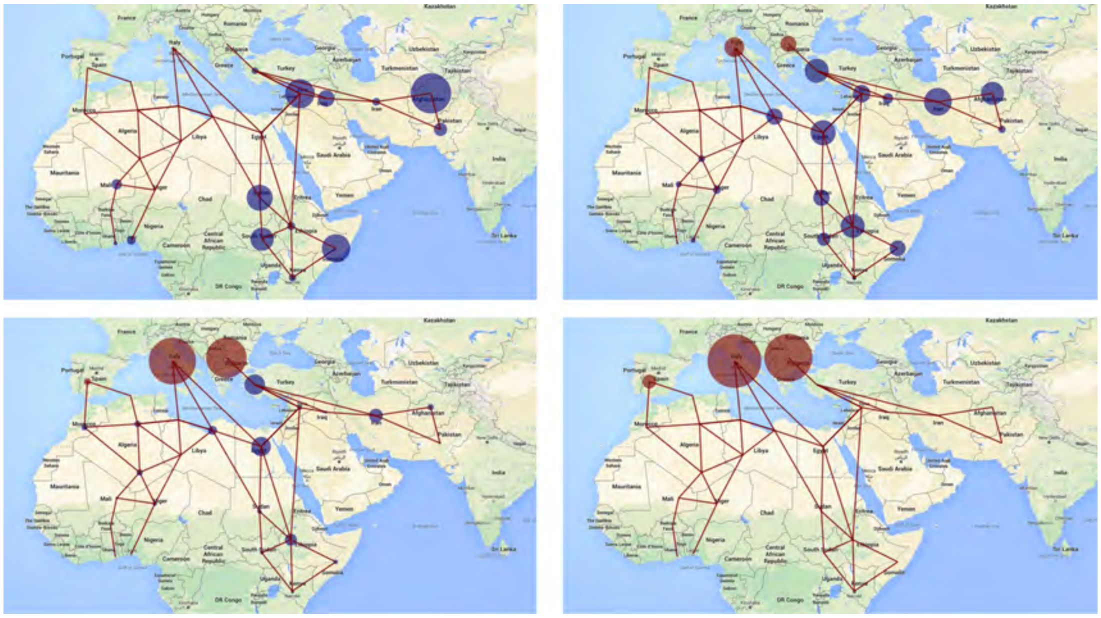

Figure 2. Refugee flow in the network model.

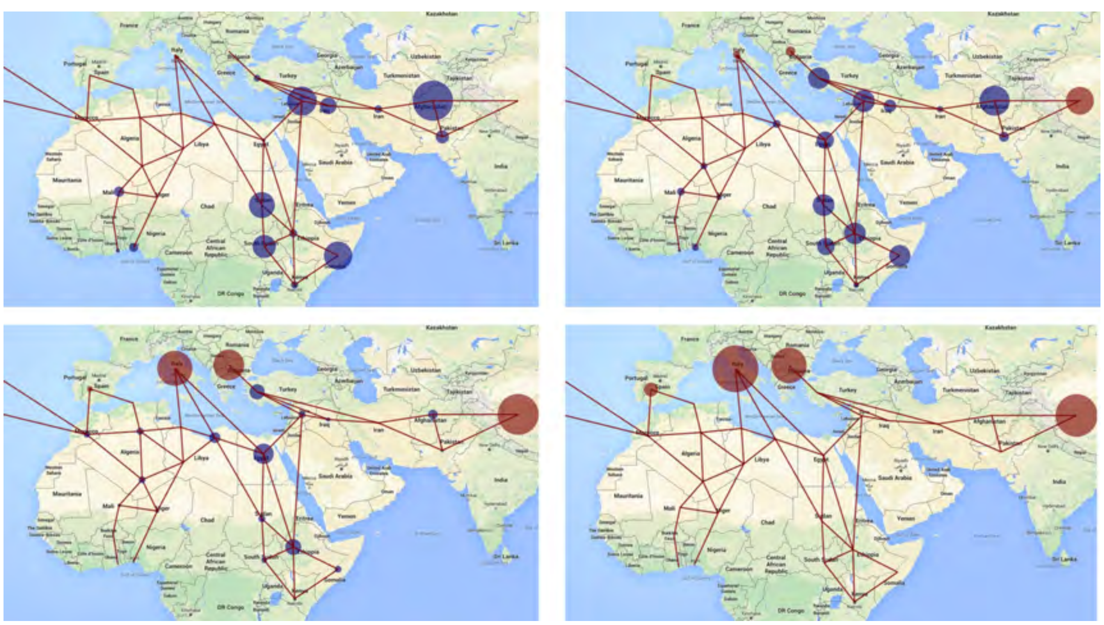

Figure 3. Refugee flow in the network model with the U.S., Canada, and China added as recipient countries.

of contagious disease. Their model is scalable, and therefore is useful in conducting policy planning. The dynamics of their NetLogo model help determine distribution of resources and optimization of refugee flow.

This team also develops a deterministic rate-based model to consider endogenous and exogenous events. They use a standard modeling structure of stock-and-flow with various feedback loops. Using their system dynamic model, they study both positive and negative events that could directly affect the rates of refugee entry into Europe. This was one of the few teams that studied the negative effects of delays and dynamic obstacles, such as the delays caused by the use of EURODAC, the fingerprinting identification system for processing asylum applicants. They also attempt to counter these negative effects by planning for positive events and implementing them in the simulation. In their simulation, they were able to take advantage of positive exogenous factors to achieve 95% of 1 million refugees being accepted in Europe within a specified time, even with endogenous delays continuously affecting the process.

Some of the most effective elements of this team's report are an extensive restatement of the problem in their own words; a very thorough itemization and analysis of assumptions, decisions, and findings; strong graphics of their network; solid analysis of their models strengths and weaknesses; and many pages with charts of various modeling results. The judges recognized the outstanding policy modeling and interdisciplinary problem solving performed by this team and awarded them the Rachel Carson Award, which honors an American conservationist whose book *Silent Spring* [Carson 1962] initiated the global environmental movement and whose work spanned many disciplines concerned with the local and global environments.

Future Trends in Interdisciplinary and Policy Modeling

The ICM tries to mimic some of the elements of real-life problem solving. Real-life problem solving is inherently interdisciplinary through its need to combine concepts, models, methods, knowledge, and perspectives of various disciplines in sciences, humanities, and arts. To develop students who are prepared to solve real world problems, disciplinary problem solving must be supplemented with broader, less restricted, more interdisciplinary and realistic problem solving. Real problems are often layered, multi-scaled, dynamic, and/or multi-dimensional. Policy modeling has become a popular way to inform decision makers of potential priorities and determine the what-if effects of different scenarios or decisions.

There is more to modeling than a templated structured mathematical process with quantitative measures and linear components. In particular, interdisciplinary modeling can include many types of knowledge and perspectives. Quite often the assembly and pathways from which the policy model is built or implemented are artistic and lead to qualitative models. Good problem solving thus involves making appropriate assumptions that lead to quantitative or qualitative models using scientific or artistic methods. Many viable models are hybrid—containing quantitative, qualitative, scientific, and artistic elements—and incorporate many different disciplinary and interdisciplinary structures and processes.

We have discovered many perspectives and terms being used in the area of interdisciplinarity. For instance, the term "antidisciplinary" is not just used to define a way that is opposite of the normal disciplinary approach. The MIT Media lab uses the term to indicate working in spaces that simply do not fit into any existing academic discipline or interdiscipline [Ito 2016].

Conclusion

As judges for this year's policy modeling problem, we hope that the teams that wrestled with the immigration problem experienced some of the policy modeling elements described in the previous paragraphs. Perhaps as they worked, questions such as these arose: Where should a qualitative structure or process enter in the modeling? What disciplines of study help with this model's context? What assumptions are necessary or appropriate? What data do we need to test the validity or verify the models utility?

The judges of this problem are excited about the future prospects of policy modeling in the ICM. Next year's ICM will continue to offer students an opportunity to perform policy modeling and analysis. The judges expect even better performance in this area as experiences with this type of problem increase.

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About the Authors

Chris Arney is a Professor of Mathematics at the United States Military Academy. His Ph.D. is in mathematics from Rensselaer Polytechnic Institute. He served as a Dean and acting Vice President for Academic Affairs at the College of Saint Rose in Albany and had various tenures as division chief and program manager at the Army Research Office in Research Triangle Park, NC, where he performed research in cooperative systems, information networks, and artificial intelligence. His current research and academic interest is cyberspace, social networks, philosophy of science, interdisciplinary modeling, and diversity. Chris is the founding Director of the ICM.

Yulia Tyshchuk graduated from Rensselaer Polytechnic Institute with a Ph.D. in Decisions Sciences and Engineering Systems. During her Ph.D. studies, she was a member of the Army-funded SCNARC (Social Cognitive Network Academic Research Center) research team and assisted in completion of successful grant proposals for National Science Foundation, Department of Homeland Security, and Army Research Laboratory. Her research interests include understanding, modeling, and predicting human behavior as expressed on electronic media as well as incorporating network models in the studies of team composition and performance. Her current research includes the study of the effects of simulations on learning, team performance, cyber team composition, and emergence of leadership.

Teaching Modeling and Advising a Team

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Introduction

The two authors of this article have been highly successful ICM advisors: Daniel Teague at the high school level and Gary Olson at the university level. This article presents the courses, events, preparations, and support provided to the ICM teams at their respective schools.

High School Modeling Course

The NC School of Science and Mathematics (NCSSM) has been teaching a curriculum focused on mathematical modeling since 1985. As a part of that curriculum, we offer a formal course in mathematical modeling to seniors. There were three major influences leading to our decision to focus on modeling. The most important was the good fortune to have Henry Pollak, then director of the Mathematics and Statistics Research Center at Bell Labs, on our Board of Trustees. Henry spent many hours with the mathematics department encouraging us to consider mathematical modeling as a fundamental component of the mathematics program. The second and third came simultaneously at the Joint Meetings of the AMS and MAA. Frank Giordano and Maury Weir gave a minicourse on mathematical modeling and a winning MCM team gave a presentation of their paper at that meeting. I [Daniel Teague] attended both and came away with the idea that "my kids would enjoy the MCM challenge" and I thought they could do reasonably well in the competition.

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All students competing in the MCM/ICM challenge at NCSSM take the modeling course during the fall term. These students are concurrently taking calculus or have completed calculus prior to enrolling, but none of the assigned problems require the use of calculus or differential equations. This one-term course is almost entirely problem-based, with very little new content being taught. The only formal mathematical instruction is comprised of one week each on

- methods of data analysis,
- Markov processes, and
- an introduction to agent-based models.

The goal of the modeling course is not learning new mathematical content, but to learn how to use profitably whatever mathematics the student already knows (though students will obviously learn some new mathematics from their partners as they develop their models).

Students will obviously learn some new mathematical ideas from their partners. However, the course is not primarily focused on learning new mathematical content, but on using profitably whatever mathematics they know. Students in the course are concurrently taking calculus or have completed calculus prior to enrolling, but none of the problems that they are given require the use of calculus or differential equations.

Problems in the course are of varying lengths. Short problems may take one or two class periods, including a short presentation of their ideas to the class. For example, we might consider the problem of redistricting the state of North Carolina based on the most current census. State law requires that all districts be as compact as possible. So, the students might be asked to develop a metric to measure compactness. This activity represents one of the steps that students would need to take in a larger problem.

A medium problem might take two to three days and have some modified form of presentation. An example is the driving-for-gas problem. In some areas, local radio stations report on the location of the gas station with the lowest price per gallon for regular gas. Of course, that station may be across town from where you are driving. Is it worth the drive out of your way for less expensive gas? If you know the locations and the prices at all gasoline stations, at which station should you buy your gas? Develop a model that can be used in an app that will tell drivers how far they should be willing to drive based on the specifications of their car. Turn in four Powerpoint slides, one with the essential assumptions used in your model, one with the mathematical model, and two showing potential screenshots from a smartphone app based on your model. The first screenshot requests essential information from the user and the second is the app's response to that information. In this problem, rather than taking the time to write a formal paper, the students present both their model and their idea for how it could be used in a mobile app.

The long problems typically take a week to 10 days for students to work. They typically require a formal paper written in MCM/ICM format. Past MCM/ICM problems are often used for these assignments. The groups will receive extensive feedback on both their modeling and their written presentation of their work. Most of the feedback is on the clarity of their presentation including their explanation of what they have done and why they believe their work captures important features of the process or phenomenon being modeled.

Other Preparations for the Contest

Following the modeling course, most students take a course in Complex Systems, which extends the agent-based modeling approach and introduces dynamical systems. They also work together on projects in all of their science classes, so they are very comfortable with open-ended problems and negotiating the team-work aspects of the MCM/ICM challenge. As high school students, there are many disadvantages NCSSM teams face in the MCM/ICM competition. Primary among them is a very limited mathematical base to use in their modeling. However, their lack of mathematical firepower can be an advantage, since the focus of their work must be on using simple mathematics in a creative way. It is the modeling, not the mathematics, that stands out in their work. Another advantage is the opportunity to compete in the HiMCM competition prior to MCM/ICM. In addition to the experience for the students, this gives their coach an opportunity to select teams based on their HiMCM performance. Over the years since 1985, the MCM/ICM competition has been the highlight of their high school experience for many NCSSM students. Whether their work was deemed Outstanding, Finalist, Meritorious, Honorable Mention, or Successful, the richness and intensity of the MCM/ICM experience has been life-changing for some, and memorable for all.

Choosing Teams at the University Level

One of the most important elements for constructing a successful competition team is to start planning and generating excitement and interest about the competition early on. I [Gary Olson] am a great cheerleader for the competition with our students, but I can only reach a small subset of those at our university who might be interested. Therefore, it is important for me to reach out to other faculty in our department and other departments and colleges at our university to help in recruitment. Through email, phone calls, and office visits, I solicit names of students whom faculty think might be a good fit for the competition and also target specific classes to visit and give a brief five-minute introduction to the competition. Once

I have identified interested students I often use them to help recruit their friends and classmates who might be interested. Through these efforts I am usually able to generate a large list of potential students to recruit.

Once the groups of interested students are identified, I hold an informational meeting early on to help the students learn more about the competition and to help me learn more about the students. During this session, I give out a survey that helps me identify the different skill sets for each student. In particular, I'm interested in what mathematical backgrounds they have, what familiarity they have with programming languages, which students are confident in their writing abilities, and if any students have colleagues they prefer working with. I also make time for a small conference with each student to determine more about their particular interests and skills. This information helps me identify which students would potentially complement each other for the contest. In terms of team composition, I generally strive to match up one student who is confident and experienced with programming with one student who is confident they can lead the writing effort for the team and a third student who can fill in different roles and complement the skills of the others.

Preparing the Team

Once the teams have been formed, the competition preparations begin. I prefer to have my teams solidified in the fall so that they can begin meeting together as a team for the competition training sessions. At our university, we do not focus on mathematical preparations during our training but rather on interpersonal skills, community building, competition time management, and brainstorming sessions for previous problems. Some of the trainings are done as a large group with all of the teams participating, but the majority of the training is work done by the team itself. Once we have identified the teams, we have an informational meeting where we first introduce all of the students and start getting to know one another. Once we are all on a first name basis, I begin by giving them more information about the competition (background information and history of the contest, more information about each of the different problems and information about the different types of interdisciplinary problems that are possible).

After the initial meeting, I encourage the teams to meet together as a group in a nonmathematical setting (i.e., it cannot be on campus!). Many of the students who compete do not know some of their teammates when we start, so we want to encourage them to get to know one another, become comfortable conversing with one another and sharing ideas and thoughts, and to some extent help them to start building a friendship. After the teams have met outside of the department for community building (coffee shop, library, baseball game, etc.), we bring them together again for a training session that details how to handle interpersonal relationships during the competition and potential conflict. I feel that for many teams the biggest pitfalls during the contest occur because of interpersonal conflict. We focus a large amount of our training sessions on how to work with one another in a group, how to respectfully listen and disagree, and what steps can be taken to recover when a conflict has occurred.

The next phase of our training involves allowing teams the opportunity to practice brainstorming and working together. I have them choose two or three sessions where they can meet together for a two-hour time block and I give them all of the contest problems from a given year. Their task is first to practice the process of going through and choosing a problem and then to begin work on the initial brainstorming of ideas for the contest problem. In-depth models cannot be developed in a two-hour time frame; however, it allows the team to start working together early and develop a familiarity and comfort level with one another that will ultimately benefit their actual competition experience.

Guiding the Teams' Experiences

To kick off the competition, we hold a pizza party in the department an hour before the contest problems go live. This allows the teams to have a chance to settle into their rooms a bit and for me to give any last-minute advice/preparations before the clock starts to tick. Once the problems go live, the teams separate into their respective rooms and the work begins. We reserve separate rooms in our department for each team for the entirety of the 96 hours to give them privacy, a central location, and space to work. While the teams are brainstorming and choosing a problem, I go and stock the kitchen with all sorts of food to fuel them throughout the weekend. While the students are allowed to request specific items, the competition mainstay items are fruit, Oreos, a plethora of junk food, and lots and lots of caffeine. During the competition we also arrange for team dinners on Friday, Saturday, and Sunday night. These dinners are provided by faculty in our department and allow each team a chance to take a break from the problem and get out of the department for a change of scenery. It also allows them the opportunity to get to know some of the faculty members in our department on a more personal level than what would previously be possible. Faculty members have also commented that it is a fun way for them to get to know our undergraduates while also providing support for the competition.

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About the Authors

Dan Teague has been teaching mathematics at the North Carolina School of Science and Mathematics since 1982 and mathematical modeling since 1985. Under his mentorship, North Carolina School of Science and Mathematics teams have earned six Outstanding rankings in the ICM, including two in 2016, in the Water Scarcity Problem and the Refugee Immigration Policies Problem. Dan has served as the Second Vice-President of the Mathematical Association of America, as Chair of the MAA SIGMAA on Teaching Advanced High School Mathematics, and twice as the MAA Governor-at-Large for High Schools. Dan has also served on the AP Statistics Test Development Committee and two terms on the US National Commission on Mathematics Education.

Gary Olson is a senior instructor in the Dept. of Mathematical and Statistical Sciences at the University of Colorado Denver. He serves as the director of service courses in mathematics and teaches both mathematics courses for undergraduates and professional development courses for in-service middle school teachers. He is interested in inquiry-based learning, teaching-assistant training and models, and online learning strategies for mathematics. He is also actively involved with the MCM and ICM mathematical modeling competitions and undergraduate student activities. As an undergraduate, he received an Outstanding ranking in the ICM as a student team member at Carroll College, Montana. In 2016, a team that he advised at the University of Colorado Denver was an Outstanding team in the Water Scarcity Problem.