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From the Editor

When in early March I wrote this item for the April issue, I did not expect the COVID-19 pandemic to have significant scientific consequences beyond the cancellation of a possibly large number of meetings. Instead, it has led to the closure of most University research labs, worldwide, for several months.

Many young people have seen the start of their research delayed, some have moved on to other pursuits and may never return. Others that were planning to work in a different country are now unable to travel or even get visas, and have to alter their plans.

All of these will have negative long term consequences. Even worse of course was the hasty and mistaken decision to interrupt the schooling of small children and teenagers. Only a few countries escaped the panic.

From the science and society point of view it was sad to see all the hasty decisions made by University officials. These are too often untrained in science and tend to be, by and large, timid and easily scared people, afraid to make the wrong decision and sheltering behind bloated committees of unqualified people. Not understanding what was involved they were too easily swayed into believing worst case scenarios, however unrealistic. There has lately been somewhat of a reaction, which I hope continues. Among the Big Ten schools, the President of Purdue, a person of non-academic background, has recently given a good example of leadership.

Oriol T. Valls, the current P&S newsletter editor, is a Condensed Matter theorist.

Paradoxically, the closure of so many institutions, accompanied by an improvised switch to second rate online instruction, has produced a considerable amount of overwork, arising from inefficiencies. This has made it difficult to obtain contributions to this issue. However, several members of the Board of Editors have stepped up and provided timely contributions to this issue. I am extremely grateful to them.

But for the future, contributions from you, the readers, are needed. There should be no lack of pertinent and timely topics. Articles and suggestions for articles should be sent to me, and also letters to the editor. Book reviews should go to the reviews editor directly (ahobson@uark.edu). Content is **not peer reviewed and opinions given are the author's only, not necessarily mine, nor the Forum's or, a fortiori, not the APS's either.**

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FPS 2020 April Meeting Online Sessions

Although the 2020 April meeting scheduled for Washington DC could not take place in person, most sessions were available online and the videos are available. You will need to login to your APS account. You can see the following Forum on Physics and Society sessions:

Session C08: Science and National Security

- Science, Security, and Pandemics – *Laurie Garett*
- Climate Change and National Security – *Rod Schoonover*
- Cyber Issues and National Security – *Herb Lin*

Available at: aps-april.onlineeventpro.freeman.com/live-stream/15336080/C08

Session H08: Invited talk by former NSF Director France Córdova

Available at: aps-april.onlineeventpro.freeman.com/live-stream/15336088/H08

Session Q08: Response of Physics to the Coronavirus Pandemic

- Developing Mechanical Ventilators – *Reiner Kruecken*
- Repurposing Physics Infrastructure – *Stephen Streiffer*
- Big Data and Open Science to Fight COVID-19 – *Savannah Thais*

Available at: aps-april.onlineeventpro.freeman.com/live-stream/15336095/Q08

Session Y07: Intersection of Science and Politics

- Science and Politics in the US Congress – *James Jensen*
- Role of Non-Governmental Organizations in Science and Politics – *David Goldston*
- Role of Scientific Societies in Science and Politics – *Mary Woolley*

Available at: aps-april.onlineeventpro.freeman.com/live-stream/15336087/Y07

ARTICLES

Lessons from Epidemiological Models

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TWO OR GREATER IS BAD

In early February I attended a presentation by Myron Cohen. Cohen is the chief architect of a clinical trial recognized as *Science* journal's 2011 Breakthrough of the Year. The trial showed remarkable success for a new protocol to prevent transmission from HIV infected people to non-infected sexual partners. This breakthrough was the culmination of three decades of Cohen's inspiring work to reduce the horrific toll HIV exacts on humanity.

At the end of his talk, Cohen offered to take questions on his HIV research or on the novel coronavirus outbreak. Not surprisingly most of the questions pertained to the latter, given its currency in the news. Cohen said several things that stuck with me. He said not to travel to Asia until we have a better understanding of the virus (even though at that time there were few confirmed cases outside China). He also said prophetically that epidemiologists are greatly concerned for the safety of health care workers and the potential for community spread, since estimates of the reproduction R_0number were between 2 and 5.

That last statement got me to sit up and take notice. It's been 15 years since I taught nonlinear dynamics, but I remember enough to know $R_0 \geq 2$ is bad. Really bad. I dusted off Strogatz' *Nonlinear Dynamics and Chaos* (*1*) and looked up the SIR model, which describes the dynamics of an unconstrained epidemic. I also read the Wikipedia page on *Compartmental Models in Epidemiology* (*2*). These resources are excellent background to understand how epidemiological models can be applied to the COVID-19 pandemic. A couple examples which stand out: Goldenfeld and Maslov using an SEIR model to inform policymakers in Illinois (*3*), and Maier and Brockmann (*4*) introducing the SIR-X model, which provides important insights into the effects of containment measures.

In this article I'll first provide a brief summary of the SIR model, then discuss lessons from slightly more involved models applied to COVID-19, and end with some open questions.

THE SIR MODEL

The SIR model posits a total population comprised of three compartments (i.e. types of individuals) with respect to an infectious disease: susceptible to infection, infectious, and removed from the transmission process, either through recovery with conferred immunity or by death. The model can be written as a third-order system of nonlinear ordinary differential equations with time-dependent variables $S(t)$, $I(t)$, and $R(t)$ representing the fraction of the population in each compartment:

$$\partial_t S = -\alpha SI \qquad (1)$$

$$\partial_t I = \alpha SI - \beta I \qquad (2)$$

$$\partial_t R = \beta I \qquad (3)$$

where ∂_t means differentiation with respect to time, and positive constants α and β represent the transmission and removal rates. The ratio of these rates defines the reproduction number

$$R_0 = \alpha/\beta \qquad (4)$$

(By perhaps unfortunate convention $R(t)$ is used to represent the dynamic variable for the removed fraction, and to represent a parameter.) The inverse of these constants, α^{-1} and β^{-1}, are the time between transmissions, when most of the population is susceptible, and the duration of infectiousness, respectively. The ratio of the latter to the former time equals R_0 and represents the mean number of new infections which result from an infectious person's interactions with susceptible people during the early part of an outbreak, which is a good way to conceptualize the meaning of R_0.

The model assumes people can only change compartments irreversibly from S to I to R and the population is well-mixed so that susceptible and infectious people interact at a rate proportional to the size of these groups and each interaction has a constant probability of transmission. The model also assumes the rate at which infectious people are removed (i.e. recover or die) is constant, and the time a person is infectious coincides with the time he or she is infected. For a real population these may be poor assumptions. For example, voluntary changes in population behavior and government interventions such as requiring people to shelter in place reduce interactions between susceptible and infectious people. Also, people may vary in infectiousness, or those who recover may not acquire full immunity and be completely removed from the transmission process. The SIR model illustrates the fundamental dynamics of an unconstrained outbreak without the complications of a real-world epidemic. Other epidemiological models contain various more realistic assumptions.

The initial condition of most interest is when almost the entire population is susceptible with only a few people infectious, as when a viral infection is introduced from a wild animal or a handful of infectious people travel to an uninfected region. Setting the initial susceptible fraction to its approximate value and integrating Eq. (2) yields $S_{in}=1$

$$I(t) \cong I_{in}\, e^{(R_0-1)\beta t} \qquad (5)$$

as the approximate behavior of I when the system first starts evolving. Eq. (5) shows $R_0=1$ is the threshold for an outbreak, with initial exponential growth for $R_0>1$ and exponential decay for $R_0<1$. This makes sense, since a reproduction number greater than unity means on average each infectious person transmits more than one new infection when the population is mostly susceptible.

Since R plays no role in the dynamics of S and I, the SIR model is equivalent to a second-order system consisting of Eqs. (1) and (2). (Solving this system for S and I, the fraction removed can be determined from $R=1-S-I$.) Dividing Eq. (2) by Eq. (1), separating variables and integrating, and then substituting approximate initial values of $S_{in}=1$ and $I_{in}=0$ gives the trajectories (i.e. solution curves) in the phase plane which intersect the point $(S,I)=(1,0)$:

$$I = 1 - S + R_0^{-1} \ln S \qquad (6)$$

The system has fixed points (S^*,I^*) when $\partial_t S = \partial_t I = 0$, which occurs when $I^*=0$, and can be found by setting Eq. (6) equal to zero and solving for S^* as a function of R_0. For $R_0=2$, the minimum estimate for COVID-19 given by Cohen, $(S^*,I^*)=(1,0)$ and $(0.2,0)$. Trajectories in the phase plane flow from the former to the latter fixed point, since the dynamics of the system can only irreversibly reduce S, while I initially grows nearly exponentially, so long as $R_0>1$, before peaking and then decreasing to zero, at which point the epidemic is over. A nonzero fraction of infectious people is enough to spark an epidemic. With $R_0=2$ only 20% of those susceptible at the start of the outbreak would escape infection. This simple model provides a sobering back of the envelope estimate of the devastating effect an unconstrained epidemic running its course could have on a population.

Taking the derivative of I with respect to S in Eq. (6) and setting it equal to zero yields $S=R_0^{-1}$ when I peaks. For $R_0=2$, at the peak of infection 50% of the population is still susceptible, 15% is infectious, and 35% is removed from the transmission process. Such a peak could massively overwhelm healthcare systems for a disease such as COVID-19 in which even a small percentage of those infected become critically ill.

Numerical solutions of the SIR model depend on the size of the initial infectious fraction. A solution with $I_{in}=10^{-6}$ and $R_0=2$ shows I peaking after a time of about $13\beta^{-1}$. For β^{-1} of roughly 10 days, as for COVID-19, this would mean peaking four months after an outbreak begins, if the disease is left to spread unconstrained.

STAY AT HOME

According to *APS News* (3), just before spring break in early March at the University of Illinois, Urbana-Champaign, UIUC physicists Goldenfeld and Maslov collaborated on an SEIR model of COVID-19. An SEIR model, which is only slightly more involved than the SIR model, uses an additional compartment E (for exposed) when a disease has a nonnegligible latency period during which an infected individual is not yet infectious, and assumes people move irreversibly from S to E to I to R. According to the model, which took just a few hours to analyze, if students returned to campus after spring break, there would be a huge wave of infections. Alerting university administrators to the model's results led to a rapid decision to move classes online. Eleven days later, citing Goldenfeld and Maslov's modeling as part of the rationale, the governor of Illinois issued a statewide stay-at-home order.

An obvious question is, based on epidemiological modeling to what extent do containment measures such as a stay-at-home order flatten the curve?

THE SIR-X MODEL

According to the SIR model, if a population could be constrained to avoid all interaction between susceptible and infectious people (i.e. effectively α=0), then no new infections would occur, and all infectious people would be removed and the epidemic completely suppressed after a time of β^{-1}. Unfortunately, the danger posed by an outbreak typically goes unrecognized until a substantial number of people have been infected, at which point it may not be practical to identify all infectious individuals, including those who are asymptomatic, and prevent their interaction with those who are susceptible. Instead, as happened with COVID-19, it becomes necessary to implement blunter measures to reduce interaction, such as population-wide isolation through stay-at-home orders as well as quarantine of symptomatic infectious individuals. Maier and Brockmann include the effects of containment policies that deplete the susceptible and infectious fractions of a population, thereby reducing their interaction, by introducing the SIR-X model (4):

$$\partial_t S= -\alpha SI-\kappa_0 S \tag{7}$$

$$\partial_t I= \alpha SI- \beta \mathrm{I}-\kappa_0 I-\kappa I \tag{8}$$

$$\partial_t R= \beta I+\kappa_0 S \tag{9}$$

$$\partial_t X=(\kappa+\kappa_0)I \tag{10}$$

For this model, physical distancing measures applied to the whole population deplete individuals from both the S and I compartments at the same rate κ_0. Additionally, quarantining of those who test positive or are symptomatic depletes infectious individuals at a rate κ. Both κ_0 and κ are positive constants. There is an additional compartment X which quantifies infectious individuals who have been separated from the transmission process by containment or quarantine. The model assumes this new fraction of the population $X(t)$ is proportional to confirmed cases of a disease.

The effective reproduction number is then

$$R(_{0,\mathrm{eff}})=\alpha/(\beta+\kappa_0+\kappa) \tag{11}$$

The key result of the SIR-X model is that the explosiveness of an outbreak is damped because $R(_{0,\mathrm{eff}})<R_0$. Protection of the susceptible fraction of the population by containment and quarantine leads to initial subexponential growth for $X(t)$, with a power law scaling t^{μ}, for a wide range of model parameters. After a period of algebraic growth, saturation sets in, primarily as a consequence of the separation of those who are susceptible from unidentified infectious individuals, leading to a lower peak that occurs earlier than the peak for an unconstrained epidemic. The curve is flattened. This contrasts with initial exponential growth of confirmed cases for an outbreak with little containment, which is expected from the SIR model and observed for some epidemics such as the Ebola outbreak in West Africa.

Remarkably, using the parsimonious SIR-X model Maier and Brockmann are able to reproduce quantitative growth behavior observed in data from the COVID-19 epidemic in nine Chinese provinces including Hubei Province, the epicenter of the outbreak. The parameter choices that best fit the data are a reproduction number R_0=6.2 for an unconstrained epidemic and a mean duration of infectiousness of $\beta^{-1}=8d$. The model's growth curves follow the observed scaling of data for the provinces with exponents $\mu\approx 2$. However, wide variations in parameter choices produce similar scaling and thus the model doesn't permit inference of specific parameter values. More sophisticated epidemiological models coupled with serological studies are needed to yield reliable estimates for epidemiological parameters.

Nonetheless, the SIR-X model's mathematical form for the growth of confirmed cases implies that the observed subexponential growth is a result of basic epidemiological processes, caused by a balance between transmission and containment. It offers a guide to judge the expected effectiveness of various containment measures from voluntary stay-at-home advisories up to mandatory curfews and hard lockdowns, as was used in China and some European nations in response to COVID-19. Containment efforts can be evaluated by whether the resulting growth of cases exhibits power law scaling and, if so, by the size of the exponent.

OPEN QUESTIONS

The epidemiological models discussed above offer important lessons that can be used to inform public health policy on a basic level. The SIR and SEIR models show that doing nothing allows for explosive growth with potentially devastating consequences. The SIR-X model shows that containment measures and quarantine procedures produce a predictable flattening of the curve with algebraic instead of exponential growth.

But these simple models leave many questions unanswered for a real-world disease such as COVID-19 that need to be addressed by more sophisticated models. How many cases of infection go unidentified through lack of testing, particularly of asymptomatic individuals who are nonetheless infectious? Does the transmission rate for those with documented infections differ from the rate for those with unidentified infections or for symptomatic versus asymptomatic infectious individuals? What is the average latency period and average duration of infection and by how much do these vary? Is there a seasonality effect on the reproduction number? Is immunity conferred through infection and how variable and long lasting is the strength of acquired immunity? How does susceptibility to and severity of infection vary based on medical history, geographical location, socioeconomic status, and genetics? How do real populations of susceptible and infectious individuals interact to make transmission more or less likely? Determining which epidemiological models best answer these and other questions when compared to data from serological studies will better prepare us to respond to the next potential pandemic.

Science provides the exit strategy from epidemics. Testing, therapeutics, vaccine development, and, importantly, epidemiological modeling are essential. Hopefully, one lesson from COVID-19 is the unequivocal need for modeling to inform public health policy.

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An Unscientific Look at Science During the Pandemic

Maury Goodman, Argonne National Lab

Since the beginning of the current pandemic, the popular media has been filled with comments about “listening to the scientists”, often with an additional mention of medical professionals. And a sign that I saw on the web, probably from one of the “Marches for Science” that have taken place the last few years, read “Every disaster movie starts with a politician ignoring a scientist.” Is America listening to the scientific community right now? It appears to me that most of it is. The community of scientists doesn’t speak with one voice, but those that have something to say about how to handle the pandemic are getting a huge opportunity to have their voices heard and influence public policy.

The situation is a reminder of the history and purpose of the forum on Physics and Society. It was scientists who developed nuclear weapons, and since there were so many implications for society and public policy, many of which depended on an understanding of the laws of physics, the early members of our organization felt that discussions of those implications deserved a place in the structure of the American Physical Society. And when it was called for, physicists needed to not just discuss these issues among themselves, but also needed to raise them within our governmental structure and with the public at large. On some of those issues, the scientific community got its point across, while on others it did not.

How should we react as scientists when we hear that so many people are looking to us for answers that affect their daily lives? Physicists can easily frame some of the questions: How far do water droplets that might carry a virus travel when we talk, cough or sneeze? How long do the relevant water droplets remain suspended in the air? How effective are face masks of various compositions in protecting an individual or protecting those around him or her? These are questions for

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which a physicist's input could help provide answers. But as a practical matter these questions may be more appropriately answered by the medical community. This opportunity to be listened to makes me feel impotent, with nothing of value to say.

During one of the earliest press conferences, I heard Dr. Fauci respond to almost every question with a response that didn't answer the question. Many of his responses were along the lines of "it depends". I felt this would be quite frustrating for a public that wanted answers. Yet his calm and reasoned demeanor seems to have struck a positive vibe with the nation at large, as we struggled to totally change our daily habits to respond to a problem with more unknowns than knowns. When there are future problems that cause the public to turn to the Physics community for input, this lesson may be an important one.

Another oft-repeated statement about the situation we are in is that "nobody predicted this." An interesting book that I've just read is *Factfulness* by Hans Rosling, with the subtitle, "Ten reasons we're wrong about the world – and why things are better than you think." The main point of the book is that despite an unending chorus of doom and gloom, many important things in our world are improving significantly, from poverty rates, immunization rates, education, child mortality, life expectancy, deaths from armed conflicts, etc. (I challenge readers to take the 13-question test on pages 3-5 of the introduction. Be prepared for a surprise.) But near the end of the book he admits that there are pressing global risks that we do need to address, and his first stated concern is a global pandemic. He writes, "The world is more ready to deal with flu than it has in the past, but (many poor people) still live in societies where it can be difficult to intervene rapidly against an aggressively spreading disease." Hans Rosling passed away in 2017, the year the book was published. It would have been interesting to hear his thoughts on the COVID-19 situation.

Now we are waiting for the development of a vaccine, which if I understand the press reports, might or might not ever happen. Jim Gaffigan, a comedian whose family response to the stay-at-home orders has been chronicled weekly on the CBS Sunday morning show, ended one segment with "… we're counting on you nerds to solve it. Go Science!"

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REVIEWS

What Lies Beneath: The Understatement of Existential Climate Risk

David Spratt & Ian Dunlop, published by Breakthrough online.org.au, National Centre for Climate Restoration, Melbourne, Australia, 2017.

What Lies Beneath by David Spratt & Ian Dunlop is a brief (40 page) report prepared by the National Centre for Climate Restoration (also called Breakthrough), an Australian think tank dedicated to climate restoration. The report is organized in three sections: Risk Understatement, Scientific Understatement, and Political Understatement. Each section comprises a series of 1 – 3 page overviews of specific topics that highlight that section's thesis. Noted climate expert Joachim Schellnhuber wrote the book's Foreword.

The Risk Understatement section focuses on the definition of risk and how it shapes our response to global climate change. Specifically, although extreme events (e.g. ice sheet collapses, permafrost feedbacks, and other tipping points) are unlikely, their impact is very large. Thus, since risk is the product of likelihood and impact, the risk from such extreme events is high and is often underestimated within both the public and scientific communities.

The Scientific Understatement section suggests that the scientific community is underestimating global climate change. For example, semi-empirical climate models often suggest larger changes in the global temperature relative to fully-coupled models. Likewise, the current climate sensitivity (change in global temperature occurring if greenhouse gases doubled in concentration) estimate of 3°C suggested by the IPCC report may be too low by not accounting for changes in climate sensitivity as the Earth warms. Additionally, sea-level rise has historically followed the highest IPCC projections instead of the mean projection. Using this evidence, Spratt and Dunlop suggest that scientists are being too cautious and underestimating the impact of global warming.

The final section, Political Understatement, focuses on the need for consensus and timescale of the IPCC report generating process. By requiring consensus, the report is necessarily more conservative in estimating risk. Moreover, the long timescale associated with generating the report often leads to exclusion of the most recent data. Based on these arguments, Spratt and Dunlop advocate a very rapid decrease in global carbon emissions.

His report is freely available (breakthroughonline.org.au/whatliesbeneath) and worth reading in that it reframes the actual risk of global climate change by noting that even unlikely events pose a major risk due to their large impact. Moreover, the report includes extensive citations, allowing for further exploration. The only criticism of this report is that the "fat-tail" of the probability distribution generated by climate models is highly susceptible to model parameters. Similarly, the impact of extreme events also has a large degree of uncertainty. Thus, the risk of such events is difficult to accurately estimate. Regardless, *What Lies Beneath* is an excellent addition to the climate change discussion.

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Crossing the Red Line: The Nuclear Option

Gerald E. Marsh (Hackensack, NJ, World Scientific, 2019). ISBN 978-9813276826 (hardcover), $20.

Gerald Marsh will be familiar to *P&S* readers for his numerous contributions on topics such as missile defense, climate change, and nuclear power and proliferation. Now retired, Marsh served as a consultant to the Department of Defense on nuclear policy in the Reagan, Bush, and Clinton administrations, with the United States' Strategic Arms Reductions Talks delegation, and worked in the Strategic & Theatre Nuclear Warfare Division of the Office of the Chief of Naval Operations from 1983-93. In this book, he addresses the incentives for developing nations to develop nuclear weapons, the expertise needed to do so, and technical aspects of ballistic missiles. North Korea is the main example, but every nuclear power appears. While this volume runs to 240 pages, one-half of it is Appendices, the text is double-spaced, and there are numerous photographs, drawings, and graphs. Several sections are reproductions of articles or material drawn from *P&S* or other sources. There is no bibliography, but there are a number of footnotes with references.

Chapters 1-4 cover background material: The origins of nuclear weapons, the Cold War, the Nuclear Non-Proliferation Treaty (NPT), why developing countries want nuclear weapons, and how their spread might be controlled. Marsh sees the motivations for developing countries to acquire nuclear weapons as being to have a regional advantage (Iran, North Korea), or to prevent interference by more developed nations. For a regional player such as North Korea to threaten the United States, however, it will need to lighten existing warheads for use on its missiles. As to thwarting proliferation, Marsh views the NPT as flawed in that countries can acquire nuclear technology for ostensibly peaceful purposes, but then withdraw from the treaty, and advocates that it be strengthened via better intelligence-gathering.

Chapters 5-9 examine the history and current status of the North Korean nuclear and missile programs and the physics of rocketry. The treatment of plutonium production draws heavily from Carson Mark, Frank von Hippel, and Edwin Lyman's well-known paper on the properties of reactor-grade plutonium which appeared in *Science and Global Security*. The key graphic is a plot of what payload masses could be delivered to various distances by the current Hwasong-15 missile. While American cities lie within the achievable range, the payload capacity is apparently still too low, and Marsh feels that ICBM-level warheads are beyond what North Korea could achieve in the next decade without an extensive testing program. But North Korea should not be underestimated: It took them only about a decade to go from a sub-kiloton detonation to one of 120 kt. If Japan and South Korea develop their own nuclear weapons over fears that America will not come to their defense in a regional crisis, there will be further nuclear proliferation.

Chapters 10-12 return to the issue of nuclear proliferation. Here I learned some things of which I was unaware: That Israel may have conducted three tests in the 1979 Vela incident, and that Israeli agents likely destroyed two reactor cores in France destined for shipment to Iraq. There are also speculations on how proliferation may have enhanced stability: There has been no (overt) Arab-Israeli war since 1973, nor a China-India-Pakistan conflict since 1999. But while Marsh sees the China-India-Pakistan triangle as stabilizing, he believes that if Iran were to develop a bomb and Saudi Arabia were to follow suit, the resulting Israel-Iran-Saudi triangle would be unstable due to the presence of radical Islamism. If proliferation is to be controlled by international law and enforcement, nations will have to give up some sovereignty; Marsh makes no comments on convincing existing nuclear powers to give up their stockpiles. As to negotiations with North Korea, Marsh feels that the requirements will need to include a formal end to the Korean War, a non-aggression treaty, an end to sanctions in return for the dismantlement of the North Korean weapons program, and that country's return to the NPT.

Appendix A runs to 72 pages, and is a reproduction of a paper on North Korean missiles and US missile defense by Theodore Postol which appeared in *P&S*. Appendix B, also drawn from a *P&S* article, deals with the possibility of nuclear terrorism; Marsh feels that the danger of a reactor-grade weapon is overblown in view of the radioactivity involved and the difficulty of fabricating a high-explosive assembly. Appendix C is a brief background on China, mostly focusing on conflicting claims in the South China Sea. Appendix D is a history of Islamic terrorism that really has nothing to do with nuclear weapons or missiles.

Overall, I don't know what to make of this book. Events in North Korea will likely quickly render it out of date. It is not clear what audience Marsh has in mind. If his target group is policy-makers, the discussions seem brief and inconclusive, and I doubt that such readers would be interested in, say, a derivation of the rocket equation from first principles. For technical readers, much of what Marsh relates is already available in the *P&S* articles he cites. Existing volumes such as the Proceedings of the 2017 FPS conference on Nuclear Weapons and Related Security Issues offer deeper analyses of both policy and technical issues (*P&S*, April 2018). Some facts lack much in the way of context. For example, it is remarked that the plutonium core of the *Fat Man* bomb weighed only about 6 kilograms, but that the bomb as a whole weighed in at over 4600 kilograms; no explanation of the difference is offered. The caption to a photograph of W88 warheads points out that the tips of the missiles appear different from the material of their bodies, but offers no speculation on why. My impression is that the chapters seem more like summaries of talking points used to provide background for a student seminar, not attempts at deeper analyses. For those who want to buy this book, it's worth noting that the electronic version lists at a considerably lower price than the hardcover one.

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