Externalities, public goods, and infectious diseases

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Abstract
COVID-19 has been mutating so fast that existing political and economic systems may not be able to control it without (a) getting *many* more people vaccinated and complying with other public health measures like masks, *and* (b) more effective vaccines than currently available. This article discusses externalities and other economic phenomena associated with managing infectious diseases. The history of COVID-19 suggests that a better understanding of these issues might help economists make better contributions to improving the effectiveness of public health measures for this and other infectious diseases. It also suggests that urgent action can help save lives and improve the international economy. The economic question for public health is to design public policy to minimize the present value of the burden of disease in perpetuity at some reasonable discount rate. This has implications for (i) pricing of tests, treatments, vaccines and other risk-reduction protocols and (ii) public health monitoring, especially for infectious diseases like influenza and future novel diseases like COVID-19, which experts claim are becoming more frequent as humans increasingly interact with ecologies that have traditionally been more isolated. It also raises questions about whether it might be wise to separate new product development in these areas from testing and production. Also, to help communicate the need for compliance with public health measures, society might require everyone who travels to carry liability insurance to cover losses suffered by others directly or indirectly infected from them.[1]

The urgency of faster spreading variants of COVID-19

Before discussing economic considerations of infectious diseases, we feel a need to first summarize the urgency that we perceive in the spread of COVID-19 as we are writing this: The speed with which faster spreading variants of COVID-19 have been appearing suggests that humanity may not be able to control this disease without moving *much* faster to (a) get an effective vaccine to anyone any place in the world willing to be vaccinated, and (b) convince more anti-vaxxers[2] and anti-maskers[3] to do their part to protect others whom they will likely infect if they get this disease.

[1] Parts of this work are available in Wikiversity "Externalities, contagious diseases, and news" (https://en.wikiversity.org/wiki/Externalities,_contagious_diseases_and_news); accessed 30 August 2021.

[2] See the discussion of vaccine hesitancy below, esp. incl. "liability insurance for contagious diseases".

[3] References on "Mask refusal" are discussed in the Wikipedia article with that title, accessed 19 September 2021.

Even that may not be enough without more effective countermeasures than what we have right now, according to data summarized in Figure 1, which plots the "Basic reproduction number,"[4] R_0, for the original Wuhan variant, along with the variant that took Europe by storm in early-to-mid 2020 and the Alpha and Delta variants, along with estimates of the uncertainties. As this is being written, the most virulent, deadly, and least understood variant is Delta.[5] Its basic reproduction number has been estimated at between 5 and 8.[6] If it's 8, that means that we will need 87.5 percent (= 1-1/8) of humanity immune or otherwise protected from exposure to this disease to stop the number of new cases from growing. That's the "Herd Immunity Threshold" axis on the right hand side of Figure 1.[7]

It will *not* be enough to get 87.5 percent of humanity vaccinated with the current vaccines, because no vaccine is perfect. If 100 percent of humanity were newly vaccinated with a vaccine that is 90 percent effective, we would be just barely above that 87.5 percent figure. The Pfizer and Moderna vaccines were reportedly 90 percent effective a month after the second dose.[8] More recent research "found that the efficacy of the Pfizer-BioNTech vaccine against hospitalization fell from 91 percent to 77 percent after a four-month period following the second shot. The Moderna vaccine showed no decline over the same period."[9]

But it's worse than that, because a new variant worse than Delta could already be circulating, but scientists have not yet collected enough data to identify it as such; this is indicated by the red question marks (**?**) near the upper right of Figure 1. The risk of worse variants is proportional to the total number of cases. That's why it's so urgent to get as many people as possible vaccinated and complying with other public health protocols like masking.

This is not a minority position. Two-thirds of the epidemiologists surveyed in March 2021 thought that we had "a year or less before the virus mutates to the extent that the majority of first-generation vaccines are rendered ineffective and new or modified vaccines are required."[10] Harvey et al. (2021) are

[4] The "Basic reproduction number" "is the expected number of cases directly generated by one case in a population where all individuals are susceptible", according to the Wikipedia article with that title, accessed 19 September 2021. This concept has been used routinely in epidemiology since 1952. It is, however, quite difficult to estimate, which explains the wide range of uncertainty in the estimates of R_0 for the variants of COVID-19 considered in Figure 1.

[5] Since this was submitted for review but before it is being published, the Omicron variant has been identified as a major problem. However, we are unaware of any credible studies of its basic reproductive number. In addition, the primary concern in this analysis is the economics of infectious diseases. We are therefore not discussing Omicron extensively in this article.

[6] Gallagher (2021). Liu and Rocklöv (2021) "identified five studies, which estimated the basic reproductive number for Delta [ranging] from 3.2 to 8, with a mean of 5.08." We could revise Figure 1 and Appendix 1 using this information. We will not do so here, because the changes would not alter the main point of this article, namely the importance of considering externalities, public goods, free riders and the commons in setting public policy for infectious diseases. For detailed planning regarding COVID-19, it might make sense to expand these analyses.

[7] See Wikipedia on "Herd immunity" and references cited therein, accessed 19 September 2021.

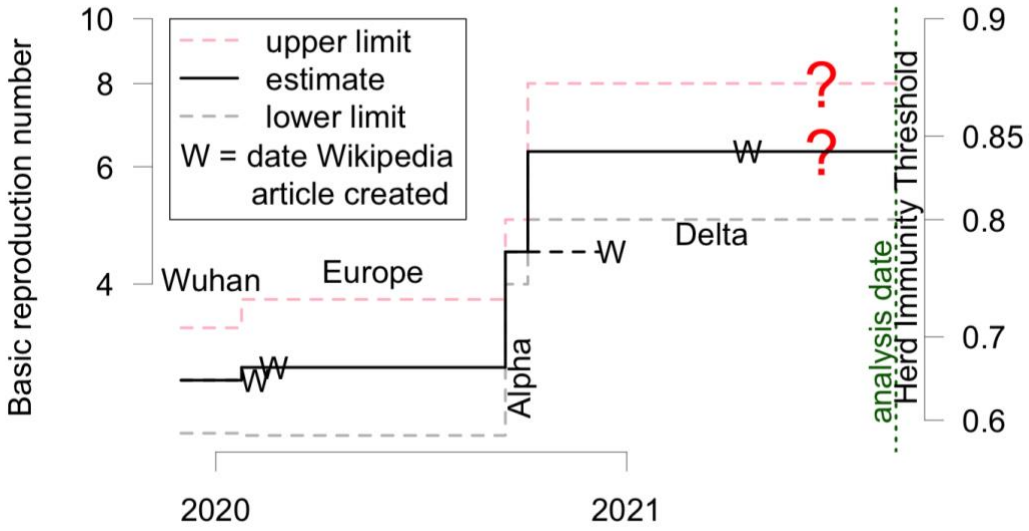
[8] Wikipedia on "COVID-19 vaccine" cites multiple sources giving different numbers for the efficacies of the different vaccines. This article cited sources saying, "In Phase III trials, several COVID-19 vaccines have demonstrated efficacy as high as 95% in preventing symptomatic COVID-19 infections." However, "real-world vaccine effectiveness (RWE)" is lower. A 6 May 2021 Tweet from @sputnikvaccine claimed 80 percent efficacy from one shot (https://twitter.com/sputnikvaccine/status/1390274722487746563), accessed 30 August 2021. See also Thompson et al. (2021) and Wikipedia on "vaccine efficacy", accessed 19 September 2021.

[9] Mandavilli (2021).

[10] Ellyatt (2021).

concerned about "immune escape": As strains develop that are resistant to a vaccine, they will increasingly threaten people who have already been vaccinated.

Figure 1. Fastest spreading variants of COVID-19



Note: The axis on the left is the basic reproduction number, R_0, which is the number of people in a susceptible population infected by each infected individual. The axis on the right is the associated Herd Immunity Threshold = $1-1/R_0$ = the proportion of the population that must be immune to control the disease. The dashed lines indicate the published limits for the Wuhan, Alpha and Delta variants. For the Wuhan variant, this is a 95 percent confidence interval derived from a meta-analysis of other published studies. Our source for the Alpha and Delta limits did not state a confidence level; we assumed 95 percent. We also assumed that the estimates of R_0 follow a lognormal distribution, which allows us to impute standard errors for the estimated values of $\log(R_0)$ as 0.093, 0.057 and 0.12 for Wuhan, Alpha, and Delta, respectively. We use the latter number to estimate the uncertainty in the estimated R_0 for the early phases of the pandemic in Europe. "W" indicates the date of creation of the Wikipedia article for each variant, which is a measure of when it became "notable". Each such Wikipedia article contains references suggesting dates when the first case of that variant seems to have appeared, which we used for the start of each horizontal line segment. The question marks "**?**" on the plot indicate that new variant(s) may already be spreading faster than Delta but have not yet been identified as such.[11]

Harvey et al. (2021) claimed that between December 2019 and October 2020, the virus was "acquiring approximately two mutations per month in the global population."[12] That's grossly misleading, because the mutation rate is *not* a function of time: It's proportional to the number of patients infected and spreading a disease.[13] COVID tends to linger longer and generate more mutations in patients whose

[11] The numbers for this plot and references for them are summarized in Appendix 1. This plot was initially prepared before the appearance of Omicron. It could be updated at any time that credible estimates of R_0 for it are available. That's not a serious priority for the purposes of this paper, because the issue here is the general theory of the economics of infectious diseases, not restricted to COVID.

[12] Harvey et al. (2021).

[13] In living organisms, the error rates in copying DNA have been estimated at between 10^{-4} and 10^{-5} per base or "letter" in the DNA sequence. See Milo and Phillips (undated). However, many living organisms have mechanisms for finding and fixing errors. And many of the errors that don't get corrected cannot function. Of those that continue to function, only a few are more transmissible or more virulent (with either a higher risk of death or long-term disability).

natural defenses have been suppressed by drugs to fight cancer, manage autoimmune disorders like rheumatoid arthritis, or keep transplanted organs from being rejected, or who have untreated or poorly treated HIV.[14] COVID reportedly underwent 32 genetic changes in 216 days (approximately seven months), in one HIV patient, averaging 6.75 days between mutations.[15] Another HIV patient generated 5 COVID mutations in 15 days, averaging 3 days between mutations.[16] Shah (2022) insists that accurate analyses of the evolution of diseases like COVID should consider exchanges both to and from non-human hosts.

If the number of new cases per unit time is cut in half or by a factor of 10 or a million, the number of new variants per unit time will also be cut by approximately the same factor. We estimate that there has been at least one new viable variant for each 600 cases, and it could be one for every 60 cases or less.[17]

Conversely, legal structures that encourage media organizations to disseminate content contradicted by the available evidence *increase* the risks associated with this disease and contribute to deaths of millions by COVID.[18]

To repeat the basic message of Figure 1, existing vaccines may not be adequate by themselves, even if 100 percent of humanity were vaccinated. On the other hand, testing that is sufficiently rapid and accurate combined with effective quarantine / isolation of people testing positive[19] might be enough if adequately enforced, even without a vaccine. Generally available masks may not be enough unless combined with other measures like existing vaccines.[20]

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[14] Tribune Content Agency (2021).

[15] Keyser (2021).

[16] Allday (2021).

[17] The estimate of "at least one new viable variant for each 600 cases" is based on rounding up the ratio of 290 million cases by January 2021 to 512,000 unique SARS-COV-2 sequences reported by that time. The 512,000 number came from the Wikipedia article on "Phylogenetic Assignment of Named Global Outbreak Lineages", which claimed that more than 512,000 unique SARS-COV-2 sequences had been reported to open, international databases as of January 2021, all or nearly all of which could transmit the disease to another human. Unfortunately, no reference was given for that number. The actual number of unique sequences is almost certainly higher, because many parts of the world are not submitting sequences to the international database. The figure of almost 290 million cases by January 2021 came from the Wikipedia article on "COVID-19 pandemic cases", accessed 12 September 2021, which were extracted from the World Health Organization, "Coronavirus disease (COVID-19) Weekly Epidemiological Update and Weekly Operational Update" (https://www.who.int/emergencies/diseases/novel-coronavirus-2019/situation-reports). 290,000,000 / 512,000 = 566. Round up to get one new variant for each 600 people with COVID-19.

[18] Numerous publications document how Facebook, Twitter, Microsoft, Google, and other Internet companies make money from clicks: The veracity of the content is not a consideration. Worse, people are more likely to click on something outrageous if it's consistent with their preconceptions. This seems to have been a major driver, if not the primary driver, of the increase in political polarization seen in many countries around the world since Facebook was founded in 2004. See, for example, Vaidhyanathan (2018), Zuboff (2019, 2021), and McMaster (2020). McMaster, President Trump's second National Security Advisor, said Russia is using this to divide and weaken America and other countries, substantively degrading their national security. See also the Wikiversity article on "International Conflict Observatory" and other references cited therein (https://en.wikiversity.org/wiki/International_Conflict_Observatory), accessed 27 September 2021.

[19] Krueger (2021).

[20] See Wikipedia "Face masks during the COVID-19 pandemic" and references cited therein. Wikipedia "N95 respirator" discusses the N95 US standard and comparable standards in other parts of the world. Wikipedia "Face masks during the COVID-19 pandemic" describes supply problems; all articles accessed 28 September 2021.

The COVID-19 pandemic is costing trillions of US dollars and millions of lives. How much of that could be saved by accelerating the international negotiations required to get a vaccine to every human on the planet willing to accept it? And how much of that might be appropriately described as a transaction cost?

For centuries, the Black Death removed the most susceptible people from the gene pool.[21] That reduced the R_0 for the bubonic plague. We don't want to wait that long. As noted below, malaria has been dramatically reduced in many countries without a vaccine by adding insecticide-treated bed nets, insecticide spraying in homes, rapid diagnostic tests, free preventive treatment for people at risk of the disease, and more effective medicines for those who had fallen ill to the more traditional efforts to reduce mosquitos. Countries with high rates of malaria lack the political will to expand the use of these proven techniques, according to experts in the WHO.[22] All these techniques carry substantial positive externalities for others.

Public Health: Overview

Laurie Garrett (2000, p. 11) wrote that public health is "a practical system ... rooted in two fundamental scientific tenets: the germ theory of disease and the understanding that preventing disease in the weakest elements of society ensured protection for the strongest (and richest)". She also reported that, "Vital statistics data from England, Wales, and Sweden show that in 1700 the average male lived just twenty-seven to thirty years. By 1971 male life expectancy reached seventy-five years. ... [In] the United States ... less than 4 percent of the total improvement in life expectancy since the 1700s can be attributed to twentieth century advances in medical care. It is a matter of considerable academic debate which factors were most responsible for the spectacular improvements in life expectancy and infant mortality seen in the United States and Western Europe between 1700 and 1900." Factors mentioned include improved sewers, clean water, education and government responses to epidemics.[23]

Even when direct access to improved sewers, clean water, education and government responses to epidemics is not universal, people who do not have such access may still benefit when diseases circulate less and other goods and services become easier to obtain.[24]
The better sewers, water, education, and government response to epidemics that contributed to this increase in life expectancy all carry positive externalities; an externality is a cost or benefit for a third party who did not agree to it. Pollution is a negative externality.[25] Goods with positive externalities that

[21] Wikipedia on "Bubonic plague" says it has been killing humans for thousands of years including between 25 and 60 percent of the European population in the fourteenth century. "From 2010 to 2015 there were 3248 documented cases reported worldwide, including 584 deaths", according to "Plague: Key facts", World Health Organization, 31 October 2017 (https://www.who.int/en/news-room/fact-sheets/detail/plague). Sichone et al. (2020) estimated R_0 = 1.75 with a 95 percent confidence interval ranging from 1.51 to 1.98. Its R_0 was almost certainly much higher in the fourteenth century with the living conditions and existing genetic diversity in Europe at that time. Websites accessed 19 September 2021.

[22] World Health Organization (2020) and Alonso (2021).

[23] Garrett (2000, p. 10).

[24] While not directly relevant to the present discussion, we note that most of the innovations that contributed to those improvements in life expectancy since 1700 "would have died in the cradle but for persuaders and activists who championed the innovation and policies", according to Pinker (2021) and Johnson (2021a, b).

[25] Wikipedia, "Externality", accessed 26 August 2021.

are consumed on a sufficiently large scale become part of the commons, defined as the cultural and natural resources accessible to all members of a society and held in common, not owned privately.[26] The commons are enjoyed by all, including people who never lifted a finger to obtain the improvements in quality of life they enjoy as a result.

The total economic value of externalities is huge, almost certainly several times the gross world product. Constanza et al. (2014) estimated that ecoservices, only one class of externalities, "contribute more than twice as much to human well-being as" the gross world product.[27]

The present article discusses negative and positive externalities associated with public health. Media and messages that *discourage* compliance with public health measures carry *negative* externalities, increasing the burden of disease shared by all and contributing negatively to the commons. Public health systems for testing, diagnosing, tracking / monitoring, treating, vaccinating for and limiting the transmission of infectious diseases carry huge *positive* externalities, as described herein. Anti-vax propaganda and effective public health efforts can both be considered part of the commons, contributing negatively or positively to the well-being of all.

Paying for an effective public health program encounters the classic free rider problem, like any other economic transaction with positive externalities. The smallpox eradication program provides an extreme example of the benefits of the eradication of a disease.

[26] Wikipedia "Commons" says, "The commons is the cultural and natural resources accessible to all members of a society, including natural materials such as air, water, and a habitable earth. These resources are held in common, not owned privately." The traditional literature on the "commons" discussed environmental resources, use of land and water. More recent literature extends the idea to include cultural, intellectual, digital, urban and knowledge commons, all of which are "accessible to all ..., not owned privately." Website accessed 19 September 2021.

[27] Costanza et al. (2014) estimated the value of the externalities associated with ecoservices. They noted that they had considered only a portion of known externalities. The real numbers could easily be twice as large. This could mean that if all the externalities were properly considered, the real economy could easily be five times as large as documented in the gross world product. Similarly, Austin (2021) explained how this means that the world's economic and political leaders are being pushed to do things that are massively counterproductive, driving climate change into a major crisis because the world's leading economists are focusing on the wrong things, pretending externalities are negligible, when the global expert consensus is that these externalities will ultimately prove to be catastrophic. Austin suggests that we need Pigovian taxes to reverse the problems that the largest negative externalities are creating with the international economy and ecology. Properly internalizing these costs on an actuarial basis might make it easier to communicate to the public the economics of alternative public policies.

Free riding on smallpox eradication

One example of extremely positive externalities is the smallpox eradication program of the 1960s and 1970s. In the mid-1960s the global disease burden of smallpox was estimated at between 10 and 15 million cases costing roughly $1.35 billion (USD) annually in the losses from sickness and death plus the cost of vaccinating people. The eradication campaign spent on average $23 million for each of the 13 years between 1967 and 1979 totaling $300 million. International donors provided $98 million, while $200 million came from the endemic countries.[28]

Documentation we've seen describing the smallpox eradication program does not mention any fee charged to those who were vaccinated, but it was very likely zero, especially in the latter stages of the campaign. If the price had been higher, fewer people would likely have been vaccinated when they did, which likely would have extended the duration and increased the total cost of the program. And they presumably did not *pay* people to get vaccinated, which could have generated an industry of poor people getting vaccinated repeatedly for the money.

One important aspect of this for the present discussion is that everyone alive today benefits from that $300 million program that ended in 1979. This has been an incredibly valuable public good and part of the commons. We are not even asked to pay a penny today for the benefits (positive externalities) we derive now from that program, which ended over 40 years ago. Some of us would not even be here. Some of us born before 1979 would have died from smallpox without it. Others born more recently would not have been born, because one of their parents or grandparents would have died from smallpox before they were conceived. The rest of us would have a shorter life expectancy and higher cost of health care, because of the costs of vaccinating and otherwise managing smallpox that were eliminated, presumably in perpetuity, by that program. Every human alive today is free riding on that program paid in full almost two generations[29] ago. Everyone alive today benefits, and none pay anything anymore. Any competent actuary could quantify the benefits in increased life expectancy and reduced burden of disease from a program like this.

Similarly, any consortium of countries that experienced, e.g., 10 percent of that total annual cost of $1.35 billion could have paid the entire $300 million and gotten their money back every 2.22 years (= $300 million divided by 10 percent of $1.35 billion) in perpetuity. The United States, the largest contributor to the program, has reportedly recouped its investment every 26 days since then in money not spent on (a) vaccinations and (b) the costs of incidence. If the US had paid the entire $300 million, they still would be getting an incredible return on that investment, ignoring the benefits to the rest of humanity. *The transaction costs of obtaining financing for similar programs for other contagious diseases are huge.*

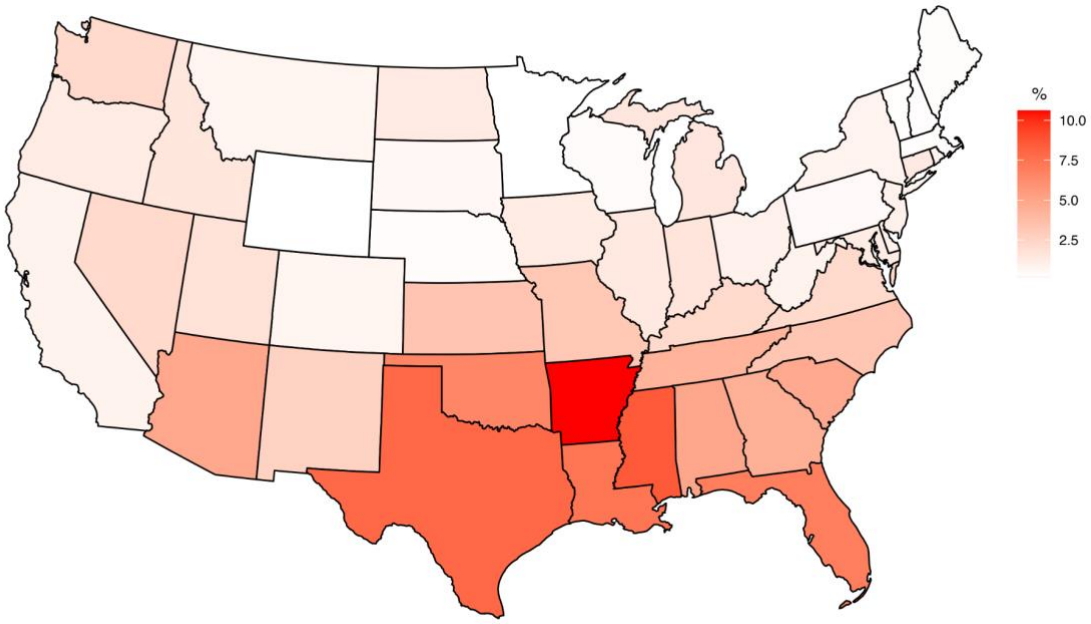
[28] Seymour (undated). A billion dollars divided by 10 million cases is only $100 per case. That suggests that either that $1.35 billion is conservative or the 10 to 15 million cases was a gross overestimate. See also Ochmann and Roser (2018).

[29] Wikipedia on "Generation" says it is, "generally considered to be about 20–30 years, during which children are born and grow up, become adults, and begin to have children." Accessed 17 September 2021.

Malaria[30]

Meade and Emch (2010, p. 119) said, "The experience of the United States illustrates some of the complex forms of cultural interaction with the biotic disease system. Originally malaria was an Old World disease. The British brought *P. vivax*[31] to North America, and the slaves they imported brought *P. falciparum*[32] from Africa. ... Malaria was *the* American disease of the late 19th century." The 1890 US Census reported 880 thousand deaths, of which 2.1 percent were attributed to "malarial fever". Numbers were reported for each of what are now the 48 contiguous states of the US plus the District of Columbia[33] with percentages ranging from 0.2 in Minnesota and Wyoming to 10.6 in Arkansas; see Figure 2.

Figure 2. Malaria as a percent of all deaths in the US[34] in 1890



[30] Malaria is a mosquito-borne infectious disease that affects humans and other animals. It is caused by single-celled protozoal parasites of the *Plasmodium* group. Five species of *Plasmodium* can infect and be spread by humans. See Wikipedia "Malaria" and references cited therein. Accessed 5 September 2021.

[31] *Plasmodium vivax* is less virulent than *P. falciparum* but still leads to death in humans in some cases. See Wikipedia *P. vivax* and sources cited therein. Accessed 5 September 2021.

[32] *Plasmodium falciparum* is the deadliest of the 5 species of *Plasmodium* that cause malaria in humans. See Wikipedia on *P. falciparum*, accessed 10 September 2021.

[33] In the District of Columbia (DC), whose geographical area is too small to show on this map, 1.6 percent of all deaths in reported 1890 were attributed to malaria. DC is between Virginia and Maryland, where 2.2 and 1.2 percent of deaths, respectively, were reportedly due to malaria. Thus, DC is consistent with the image in Figure 2.

[34] Data from Billings (1894). Image modeled after Figure 4.4 in Meade and Emch (2010, p. 120); it is available on Wikimedia Commons, "File:Malaria as a percent of Deaths in the US in 1890.svg", accessed 10 September 2021. In 1890 what is now Oklahoma was split between "Oklahoma" (roughly the western half of the current state of Oklahoma) and "Indian territory". Those two were combined when Oklahoma was admitted as a state and were combined in preparing this Figure.

The incidence of malaria has since been dramatically reduced in the US without a vaccine primarily by methods that have nothing to do with how the disease is treated once diagnosed. The expansion of agriculture in the North often involved clearing forests and draining swamps, reducing the breeding area for the mosquitoes that communicate the disease from one host to another. Moreover, since most mosquito species feed at night, dawn or dusk,[35] improvements in the construction of houses reduced the ability of mosquitos to feed on humans, especially in the North. The opposite happened in parts of the South: The breeding area increased where rice was grown, and housing was less likely to have glass in windows and other barriers to entry for mosquitos.[36] By the 1930s, malaria had become concentrated in 13 southeastern states.[37]

In 1940 the US Department of War asked the Public Health Service (PHS) to create a "Malaria Control in War Areas (MCWA)" program, which organized public health activities near military facilities, most of which were in the South. Early in 1942 the PHS obtained funds for an independent malaria control program for military installations and war industries in 15 southeastern states and the Caribbean. This program focused primarily on larvicide. They started with Paris green, which was soon replaced by diesel oil. Starting in 1942 diesel was replaced by DDT. In 1947 the MCWA was replaced by the "National Malaria Eradication Program (NMEP)".[38] This program did *not eradicate* malaria, but it did reduce the incidence to between 1300 and 1500 cases annually,[39] making it a minor rather than a leading cause of death in the US.[40]

The primary purpose of discussing malaria here is that its incidence has been dramatically reduced in the developed world without a vaccine through action based in large part on an understanding of the etiology of the disease.[41] This is crudely analogous to routine hand washing since the understanding of the germ theory of disease and masking and social distancing for COVID-19.

More recent efforts to eradicate malaria have added newer technologies to the more traditional efforts to reduce mosquitos. These include insecticide-treated bed nets, insecticide spraying in homes, rapid diagnostic tests, free preventive treatment for people at risk of the disease, and more effective medicines for those who had fallen ill. Countries with high rates of malaria lack the political will to

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[35] Crans (1989).

[36] Meade and Emch (2010, p. 120).

[37] The Wikipedia article on, "National Malaria Eradication Program" says, "By the 1930s, malaria had become concentrated in 13" southeastern states. For this, they cite "Map 4 - Areas of the continental United States believed to be malarious in 1934-35" (https://commons.wikimedia.org/wiki/File:MalariaMap.jpg#%7B%7Bint%3Afiledesc%7D%7D) in Coates and Hoff, eds. (1963), accessed 18 September 2021. A visual inspection of that map identified the following states that might be considered southeastern: Texas, Oklahoma, Arkansas, Louisiana, Kentucky, Tennessee, Mississippi, Alabama, Florida, Georgia, South Carolina, North Carolina, and Virginia.

[38] Parascandola (1996).

[39] Taylor et al. (2012). See also Wikipedia, "National Malaria Eradication Program", accessed 10 September 2021.

[40] Malaria is spread exclusively through bites of infected *Anopheles* mosquitoes, according to WHO fact sheet No. 94 on Malaria, updated March 2014 (https://web.archive.org/web/20140903002027/http://www.who.int/mediacentre/factsheets/fs094/en/). A few cases have been reported of people catching malaria without going near a location where malaria is endemic, e.g., in airports with flights from such locations (Sanders 2021). Also, mosquito control seems also to have reduced the incidence of other diseases like yellow fever, which tend to be spread by different mosquitoes. Website accessed 19 September 2021.

[41] Cox (2010).

expand the use of these proven techniques, according to experts in the WHO.[42] All these techniques carry substantial positive externalities for others.

Malaria is infectious but not contagious. It does not normally spread from one human to another where there are no *Anopheles* mosquitoes to spread it. Thus, people who live in places with no *Anopheles* mosquitoes will not directly share in the externalities from improved malaria control, not counting the positive contributions to productivity of the international economy from a reduction in the burden of disease. This makes it different from contagious diseases like smallpox and COVID-19, for which transmission is (primarily if not exclusively) person-to-person.

Other infectious diseases

Table 1. Examples of infectious diseases[43]

Disease	Mode of transmission	Contagious?
COVID-19, influenza, smallpox	Aerosols, respiratory droplets	yes
malaria	mosquitos	no
polio	anal-oral	yes
dracunculiasis	water	no
yaws	skin-to-skin contact	yes

A 2001 analysis of what the United States saves through standard childhood vaccinations estimated that, after the costs to deliver the vaccines and the health care costs for the rare side effects that vaccines cause, society saves nearly $10 billion in direct medical costs, and $43 billion in indirect costs like lost worker productivity and permanent disability from disease for a total of $53 billion; this was the total life cycle cost for all the children born in 2001 discounted at 3 percent.[44] The US Gross Domestic Product in 2001 was $10.6 trillion with a population of 285 million.[45] Thus, the dollar value of the positive externalities of childhood vaccinations is roughly 0.5 percent of GDP[46] and $187 (almost $200) per person,[47] not counting the increased costs to public health systems due to an epidemic or pandemic.

Other eradication programs currently in progress target polio, dracunculiasis (Guinea worm), yaws (caused by a spirochete similar to syphilis) and malaria. Obstacles to eradication include the need to (a) upgrade public health systems in poor countries to avoid diverting the few trained health workers

[42] World Health Organization (2020) and Alonso (2021).

[43] See Wikipedia on "Basic reproduction number" and on the individual diseases. Accessed 19 September 2021.

[44] Zhou et al. (2005).

[45] Johnston and Williamson (2021).

[46] $53 billion saved as a percent of the $10.6 trillion = 0.5 percent.

[47] $53 billion divided by 285 million people = $187 per person.

from concerns that seem more pressing, and (b) guard against "reintroduction from areas where poverty, civil unrest, or lack of political will impede high vaccination coverage and sustain endemicity."[48]

Western military activities and support for corrupt regimes in Muslim countries on top of the legacy of colonial domination have reportedly contributed to boycotts of the polio vaccine and spikes in cases in Afghanistan, Pakistan,[49] Nigeria,[50] Kenya,[51] and elsewhere. An honest budget for the War in Afghanistan (2001–2021) should include the negative externalities from the increased burden of disease in the US and its allies. Their military operations in Afghanistan and elsewhere and other support for political corruption in Muslim countries are reflected in the resistance to vaccination efforts.

How to price goods to combat infectious diseases?

Public policy should minimize the present value of the disease burden in perpetuity at some reasonable discount rate. For most goods, when prices are reduced, demand increases. For many goods useful for managing infectious diseases like vaccines, tests, masks, and treatment, the benefits to others (positive externalities) exceed the marginal cost of producing and distributing an additional unit, at least in geographic regions where the disease is endemic. In such cases, the price to the consumer should probably be zero.[52]

This is more likely to be true for diseases that are contagious than those that are infectious but not contagious, as discussed with Table 1 above. The Delta variant of COVID-19 was first detected in India and is the rage worldwide as this is being written. Conversely, a person with malaria in a location without *Anopheles* mosquitoes is not likely to infect others. Similarly, someone ill with dracunculiasis is not likely to infect others in a location where sufficient care is taken to ensure the potability of the water that people drink.

More precisely, one possible pricing model might be the maximum of two numbers, as discussed in Appendix 2 below:

1. The marginal cost of producing an additional unit minus the average benefit to others. In some cases this could be negative, implying we should pay people to get vaccinated, tested or treated to minimize the spread of a contagious disease.
2. A minimum charge needed to limit waste: We may not wish to create an industry of people who get vaccinated or tested excessively. And for products like N95 masks, we may not want to subsidize uses in dusty environments that do not carry risks to others in the same way as we might subsidize uses that would more likely limit the spread of contagious diseases.

[48] Seymour (undated).

[49] Walsh (2007). In 2011 the Central Intelligence Agency of the US government (CIA) reportedly conducted a fake hepatitis B immunization campaign to collect blood samples from Osama bin Laden's Abbottabad compound to confirm the genetic identity of children living there before staging the attack during which he, a wife, a son, and two guests were killed, according to references cited in the Wikipedia article on "Killing of Osama bin Laden". See also Larson (2012) and *BBC News Online* (2011).

[50] Ghinai (2013).

[51] Njeru et al. (2016).

[52] World Health Organization (2020) and Alonso (2021).

For many products, the vast majority of the price to consumers is substantially higher than the *marginal* cost of producing an additional unit. For products without large positive externalities, this higher price is routinely justified to encourage people to take the risks involved with operating any business, especially if it involves developing new products. However, the current practice of granting patents for technology developed at public expense, as with the Moderna vaccine and under the Bayh-Dole act of 1980 may *reduce* rather than *increase* the general welfare -- and may actually be a major *obstacle* to controlling a disease like COVID-19.[53]

Humans susceptible to any disease would benefit from having their government pay those fixed costs whenever the positive externalities expected from the increased use of a good would reduce their risk of catching the disease enough to offset the tax subsidies. This would apply to vaccines, tests, masks, and treatments.

In many cases, this optimal price could be negative, suggesting we should pay people to get vaccinated, tested, or treated. For COVID-19 vaccinations, that has been done in some cases,[54] though Largent and Miller claim it "is morally suspect, likely unnecessary, and may be counterproductive."[55] However, when it is done, proof of identity is required to avoid creating an industry of people being vaccinated, tested, or treated unnecessarily multiple times.

For other goods with positive externalities, a positive price may be justified if they also have uses that do not carry the positive externalities associated with reducing the burden of disease, like N95 respirators. The general rule is that you and I should be willing to subsidize consumption of goods by others to the extent that such consumption benefits us. With goods with multiple uses only some of which carry such substantive benefits to others, we would like to subsidize only uses with positive externalities and not other uses when it is economically feasible to discriminate between uses.

A mathematical framework for modeling both the benefits and the costs of producing and distributing such goods is outlined in Appendix 2. In this framework, any patent and copyright royalties should be combined with the fixed costs and should *not* be included in the price to the consumer: Otherwise, they discourage uses that would benefit others and make it harder to recoup the costs of developing the product and of improvements that drive down production costs.[56]

[53] e.g., D. Baker (2016, esp. pp. 80-81); D. Baker et al. (2021).

[54] e.g., Oza (2021), Vavreck (2021), Morris (2021).

[55] Largent and Miller (2021).

[56] Patents and copyrights may have made good sense prior to the US Civil War when US federal government spending averaged roughly 2 percent of national income (Gross Domestic Product, GDP). However, there is substantial literature today insisting that patents, in particular, do not "promote the Progress of Science and useful Arts", as required in the US by the Copyright Clause in the Constitution, but rather do the opposite. D. Baker (2016, pp. 80-81) implied that the Bayh-Dole act of 1980 is on average an *obstacle* to the progress of science and the useful arts, because it allows universities, research institutions, private companies and individuals operating on government contracts to gain control of patents derived from work done on government contracts in ways that become obstacles to such progress without increasing research productivity enough to justify those grants. He notes further that the vast majority of the cost for vaccines, drugs, and diagnostic procedures in the US are for patent royalties, enforced the world over through the World Trade Organization. The marginal cost of producing an additional unit is almost negligible by comparison. We argue here that this patent enforcement threatens the health of people the world over, including in the US. See also D. Baker et al. (2021).

Another alternative is provided by the example of the COVID "Vaccine for the world", Corbevax,[57] whose developers have released the information on how to make it into the public domain, so it cannot be patented, and is currently being produced in India. These developers could not get funds from the government, which gave over a billion dollars to Moderna to help their vaccine development. Instead, they got $6 or $7 million raised from philanthropies.[58]

Public health programs should be managed as public goods. When successful, the results become part of the commons, enjoyed by all. One of the most successful public health programs was the smallpox eradication program, discussed above. We next consider who should pay to subsidize the distribution of goods with positive externalities like vaccines.

Who benefits and who pays?

As mentioned above in discussing smallpox eradication, any group of countries representing 10 percent of the global burden of smallpox in the mid-1960s would have recouped their investment every 2.22 years since if they had paid the entire cost of the program, and the US has reportedly recouped its contribution every 26 days since.

As this is being written, there seem to be three major bottlenecks to vaccinating everyone worldwide: (1) Vaccine hesitancy. (2) Production capacity. (3) Disputes about who should pay and how much. We are not prepared to discuss vaccine hesitancy, apart from the brief comments we already made in the section on "Other contagious diseases" above. And the limits on production capacity seem primarily tied to the economic need of the commercial vaccine producers to retain their intellectual property. This includes trade secrets that are not disclosed in their patent filings.[59]

The present situation calls to mind the evolution of fire-fighting services: when your house is burning down, it's a little late to start thinking about buying fire equipment or forming a fire department. That seems an apt analogy to the condition of the world today regarding COVID-19. After the 1666 Great Fire of London, fire insurance brigades were formed.[60] Each company had its own "fire mark", which was a durable plaque affixed to the outside of the building. Each fire brigade would only extinguish fires in buildings bearing their mark. In 1833 the political leaders in London decided they would all be safer if their ten independent fire brigades were merged.[61] Fires spread until controlled, regardless of source.

Similarly, on 29 December 2020, Acharya and Reddy claimed, "It's Time to Use Eminent Domain on the Coronavirus Vaccines: Respecting drug companies' intellectual property rights during a pandemic

[57] Salam (2022).

[58] *Democracy Now* (2022). This development was led by Dr. Peter Hotez, who's (2021) book advocates "vaccine diplomacy."

[59] The Wikipedia article on "Deployment of COVID-19 vaccines" cites multiple sources saying that vaccines like those available for COVID-19 are large, complex molecules, requiring considerable knowledge that is not disclosed in patent applications and not available in current generic manufacturing facilities. Website accessed 19 September 2021.

[60] Cote and Bugbee (1988). See also Wikipedia, "Fire department", accessed 19 September 2021.

[61] London Fire Brigade, "London's ten independent brigades all merged to form the London Fire Engine Establishment (LFEE)" (https://web.archive.org/web/20110903052849/http://www.london-fire.gov.uk/JamesBraidwoodAndTheLFEE.asp), accessed 19 September 2021.

doesn't make medical, or economic, sense." They suggest separating (1) research and vaccine development from (2) clinical trials and (3) production and distribution.

They wrote, "The easiest way to make vaccines truly available to all is to freely license every effective vaccine formula so that generic producers can manufacture the vaccine anywhere." They also noted that the results of clinical trials managed by people who stand to gain economically from the outcome are never as *credible* as when those who manage the clinical trials have no vested interest in the outcome.[62] Others argue that governments in the past have displayed insufficient interest in funding developments as risky as new vaccines and new drugs. Moreover, if governments expropriate the intellectual property rights in COVID vaccines, pharmaceutical firms may give up on saving lives and focus on inventing quality of life treatments like Pfizer's Viagra and Allergan's Botox, which are more profitable and less likely to be expropriated. In fact the vaccine sector had withered away to only a handful of companies by the turn of the 21st century and by 2021 had only recently begun to grow again.[63] However, it's not clear if that decline in the vaccine sector was a result of government action or that the major pharmaceutical companies recognized that *drugs that keep people alive without curing them tend to be much more profitable than either cures or vaccines.*

We cannot offer here any insights that will clearly support one option over the other. We do hope, however, that the information we provide will contribute to increasing the urgency of this discussion while hopefully providing some resources and perspectives that may not be as easily accessible elsewhere.

How much should countries spend on health? A 2003 discussion paper by William Savedoff for the World Health Organization notes that, "The range in per capita health spending across countries is larger than 100 to 1, and this translates into spending of anywhere between 1 percent to well over 10 percent of national income." Five percent of Gross Domestic Product (GDP) is mentioned as an unofficial target that has been used in some international comparisons and evaluations but was never officially approved. Savedoff mentioned a 1988 WHO resolution that does not mention 5 percent but does recommend taking action 'to reallocate existing resources more effectively, "reduce waste and increase efficient use of resources", etc.'[64]

It may also be worth reviewing the most recent Global Burden of Disease Study published by the World Health Organization (WHO).[65] This methodology has been developed since 1990 to help guide public health investments in areas of greatest long-term need. In such studies, disease burden is often expressed in terms of Disability-adjusted life years (DALYs).[66] DALYs can be expressed in US dollars (at Purchasing power parity, PPP) or any other currency by multiplying DALY components by the average annual income (Gross Domestic Product, GDP, per capita). However, investments even by poor countries should not be limited to selecting from currently existing options but should also consider investing in research to find lower cost and / or more effective approaches to these problems. Might we

[62] Acharya and Reddy (2020).

[63] Moore (2021).

[64] Savedoff (2003).

[65] *The Lancet: Latest global disease estimates reveal perfect storm of rising chronic diseases and public health failures fuelling COVID-19 pandemic*, University of Washington Institute for Health Metrics and Evaluation, 15 October 2020 (http://www.healthdata.org/news-release/lancet-latest-global-disease-estimates-reveal-perfect-storm-rising-chronic-diseases-and), accessed 19 September 2021.

[66] The World Health Organization (WHO) used age weighting and time discounting at 3 percent in DALYs prior to 2010 but discontinued using them starting in 2010. See Mathers and Stevens (2013).

find other examples like the eradication of smallpox that could show massive returns on investments that are miniscule compared with the burden of disease?

Some research has documented net positive return to society from free health care provided pregnant women and from improved child care that reduced health problems later in life while reducing crime and increasing academic achievement that led to higher incomes and taxes paid as those children entered the workforce[67] and increased rates of economic growth that would not be achieved without those increases in academic achievement.[68]

Vaccine cartel

Because of the urgency associated with the high mutation rate of COVID-19, any limits on the production of vaccines increase the risks to everyone, even those already vaccinated. In particular, when distribution is limited by demands for patent royalties, it threatens the health of all. It is "penny wise and pound foolish" and will almost certainly lead to more deaths among those already vaccinated. The disease burden among people in the developed world could cost *more* than if they had paid reasonable patent royalties for the entire world and otherwise worked to increase the speed of distribution of the vaccines.

The Health Global Access Project (Health GAP) has said, "Expanding Vaccine Manufacturing Capacity Solely Within the Pharma Cartel is a Recipe for Perpetual Vaccine Apartheid and Artificial Scarcity". In an "unusual pact between fierce rivals", J&J "will give Merck $268.8 million in U.S. taxpayer funding to use its capacity to manufacture J&J's vaccine. ... Every country in the world is up in arms about inadequate supplies of COVID-19 vaccines. Rich countries had tried to ensure against delayed vaccinations by advance purchases ... . For the rest of the world, including 130 countries that as of last week had received no vaccines, artificially limited supplies means waiting in line for years, more deaths, more social and economic disruption, and development of more contagious and vaccine-resistant variants. It is a recipe for a never-ending pandemic. The solution to the false supply scarcity should have been advance planning and early agreement to override patent protections ... . Instead vaccine monopolists schemed to maintain rigid control over supply, price, and distribution, both to increase profits and prioritize their monopolies at the risk of public health."[69]

The vast majority of the costs associated with many patented products is in the research; the unit costs of production are often a very small part of the cost and can be made even smaller as the cumulative production increases.[70] This increases the importance of considering having taxpayers pay any patent royalties for goods with positive externalities and not requiring the end user to think about whether they should pay the higher cost.[71]

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[67] Hendren and Sprung-Keyser (2020).

[68] e.g., Hanushek and Woessmann (2015).

[69] B. Baker (2021).

[70] Empirical research has documented "Experience curve effects" in producing a wide variety of goods, whereby each doubling of cumulative production tends to be accompanied by roughly a constant percentage reduction in the marginal cost of producing an additional unit. The Wikipedia article on "Experience curve effects" cites multiple sources documenting empirical support for this as well as limitation; accessed 19 September 2021.

[71] D. Baker (2016) further suggests that this implies that the development of such products should be funded directly by taxpayers with the results placed in the public domain. See D. Baker et al. (2021).

Public health monitoring

Public health programs are public goods, benefitting even people who are unaware of them. Scientists have estimated that there may be 1.7 million mystery viruses in wildlife with the potential to transfer to humans. In September 2019 the US decided to end an innovative program begun in 2009 that had identified 160 potentially dangerous coronaviruses. Dozens of scientists and analysts working to identify potential pandemics in countries around the world, including China, returned to the US in the three months before the first reports of COVID-19 from Wuhan. The supporters of that program suggest that the current COVID pandemic might have been managed much better if that program had not been cut.[72]

However, even without that program, in December 2019, before anyone outside of China had heard of COVID-19, Charity Dean reportedly saw a major problem from her monitoring of internet traffic for key words. Dean was the number 2 public health official in California but was unable to convince her manager that there was a problem. Instead, her manager excluded her from key meetings, apparently believing that Dean's claims were a waste of time. Eventually a couple of Silicon Valley executives got Dean's message through to Governor Newsom, who issued a stay-home order -- *after* COVID-19 was already a major problem in California.[73] In 28 September 2020 O'Leary and Storey described how they could predict "the number of people in the USA who will become infected and die from the coronavirus" using "the number of Google searches, Twitter tweets, and Wikipedia page views".[74] In fact this is a cheap way to monitor for all kinds of problems including emerging and evolving conflicts, natural disasters, and public health crises.

Public health officials in the US announced[75] in August 2020 that they were creating a new tool called the "National Wastewater Surveillance System (NWSS)" that would "include a portal for state, tribal, local, and territorial health departments to share wastewater testing data, helping public health officials better understand community spread" of conditions like COVID-19. For that in particular, they are asking wastewater treatment facilities to test "sewage for RNA from SARS-CoV-2". With this they can model which strains are active where as well as the emergence of new strains.[76]

Sadly, government agencies in the US and around the world have sometimes made pandemics worse by trying to suppress the dissemination of honest information. That was true in 1918, and it has been true with the current pandemic, contributing to increasing the global burden of disease. We would all be healthier if we improved monitoring and sharing of public health data while severely limiting the ability of government officials to censor or misrepresent what is being reported.[77]

The development in recent decades of electronic health records provide the promise of computer-assisted health care monitoring, suggesting additional tests and alternative therapies. They could also

[72] Milman (2020).

[73] Confessore (2021).

[74] O'Leary and Storey (2020).

[75] Danigelis (2020).

[76] *National Wastewater Surveillance System (NWSS)*, Centers for Disease Control and Prevention (https://www.cdc.gov/healthywater/surveillance/wastewater-surveillance/wastewater-surveillance.html), accessed 19 September 2021.

[77] e.g., Blackburn and Parker (2021), Blackburn et al. (2020), Tomori (2020), Agogo et al. (2019).

be used for public health monitoring and research. Unfortunately, there is a sad record of use of such data by people in business and government to track and punish their perceived enemies. This has been countered in the past by an emphasis on privacy, protected in the US by the Health Insurance Portability and Accountability Act (HIPAA). However, Graves (2014) suggests it may be wiser to drastically curtail the ability of government and corporate bureaucrats to keep secrets about harms they may cause to individuals and groups. That can be difficult to achieve in the US, where business lobbyists often write legislation, even prohibiting the public from knowing the origins and quality records of the companies that supply pharmaceuticals.[78] Further discussion of those issues is beyond the scope of the present work.

Testing for contagious diseases

One of the major obstacles to managing COVID-19 has been the availability of tests, especially early in the pandemic. Before entering a retail outlet in the US in March 2021, a store employee measured a shopper's temperature with a forehead scanner. It was reported as 70 °F (21 °C). That's Stage 3 hypothermia: That shopper would have been unconscious or dead, not trying to enter a retail outlet with that body temperature.

But a forehead fever thermometer in that context provides positive externalities, because it reduces the risk of people being exposed to a disease when shopping -- and it would be even better if it were reasonably accurate![79]

Diagnostic procedures with less error usually (a) make it easier to identify and manage contagious individuals and (b) increase the value of contact tracing. Both of these tend to reduce the spread of the condition. In addition, more accurate diagnostics make it easier to develop vaccines, treatment modalities, and other procedures for managing the spread of a disease. When a person with a contagious condition is diagnosed, steps are usually taken to reduce the number of others who would likely catch that disease.

Even if an outbreak occurs on the other side of the planet, more accurate diagnosis and better control limits the spread and with it the chances that you and I will catch that disease. Better control also on average reduces disruptions to the economy from people not producing as much when sick. If the disruptions are large enough, they can reduce the availability of seemingly unrelated products (like toilet paper in the US early in the COVID-19 pandemic)[80] and the cost of obtaining such. These positive externalities indicate that I would benefit from subsidizing the use of any such test procedure any place in the world if my subsidies increased the use of better diagnostic procedures enough to benefit me. That's also true with more effective treatment, as noted by the World Health Organization (2020) and Alonso (2021).

[78] "We know where our shirts are made, but not where our drugs are made, which is arguably more important," according to Ohio State Professor John Gray. To be precise, US law does not prohibit a private company from doing its own testing of pharmaceuticals and collecting data on the reliability of supplies. It does, however, largely prohibit the US Food and Drug Administration (F.D.A.) from sharing the information it has, according to Stockman (2021).

[79] The use of a malfunctioning forehead fever thermometer can carry positive externalities if its use convinces people who are not feeling well to avoid an enclosed space where they might infect someone else.

[80] Nguyen (2020).

Some contagious diseases could be eradicated if anyone who did not feel well had convenient access to a sufficiently accurate test. Such tests could help diagnose their condition and prescribe actions to maximize their rate of recovery while minimizing the chances of infecting others. This may not work if many people who are contagious are asymptomatic unless they are subjected to effective routine screening, e.g., when entering some public space like public transit, retail or office space.

There are in fact several research strains moving in this direction. Harvard Chemistry professor Whitesides predicts "Zero cost diagnostics" for almost any medical condition in the not-too-distant future.[81] These predictions are based on rates of improvement comparable to Moore's law, which has described the doubling of the number of transistors in a microprocessor almost every two years since 1970; it is named after Gordon Moore, co-founder of Fairchild Semiconductor and Intel, who first predicted something like this in 1965.
Moore's law is a special case of experience curve effects, which is an empirical observation that each time the cumulative production of almost anything doubles, the unit cost drops by roughly a constant percentage, with the rate of improvement varying between products and industries. While it is not clear what determines this rate of improvement, it is clear that providing more money to fund research by competent experts tends to increase the rate of progress. Both the Salk and Sabin polio vaccines were funded by the March of Dimes, founded in 1938 as the National Foundation for Infantile Paralysis by Franklin D. Roosevelt, himself a polio victim and president of the US at that time. Twenty years later, two different vaccines were being administered worldwide and have since come close to eradicating polio.

Whitesides has proposed developing specially treated paper for low-cost diagnosis of health problems, analogous to litmus paper, which has been used for roughly 700 years to test acidity. Others are developing "lab-on-a-chip" devices. Both types of products hold the promise of rapid, low cost diagnosis of almost anything, including DNA sequencing of previously unknown pathogens for pennies. In 2020 it cost $600 to sequence the genome for a single human, down from over $3 billion the first time it was done (1990-2003). A $100 genome is anticipated "soon"; a $10 genome is reportedly not far away. Harvard geneticist George Church predicated "one day sensors might 'sip the air' so that a genomic app on our phones can tell us if there's a pathogen lurking in a room." The human genome has 3 billion letters but SARS-CoV-2 has only about 30,000 letters. This makes it much easier and cheaper to sequence something like a SARS-CoV-2 sample than the genome from an individual human. The widespread availability of relatively inexpensive sequencing has allowed researchers to monitor the evolution of SARS-CoV-2 essentially in real time.[82]

Joseph DeRisi has developed a system called "IDseq" for "metagenomics", whose goal is to inventory all the viruses and living organisms in a sample of almost anything, e.g., bodily fluids or sewage. It does this by matching overlapping fragments of nucleotide sequences in the sample. The assembled genomes are then compared against a database of all the known sequences maintained by the National Center for Biotechnology Information (NCBI), part of the US government, to identify all known and previously unknown viruses and living organisms in the sample. This system has made major contributions to understanding many different diseases all over the world, including COVID.[83]

[81] Whitesides (2009). See also Diamandis and Kotler (2012) and the Wikiversity article on "Freedom and abundance" (https://en.wikiversity.org/wiki/Freedom_and_abundance), accessed 28 September 2021.

[82] Gertner (2021).

[83] Kahn (2021).

The global burden from influenza might be dramatically reduced through low cost testing of domestic pigs and fowl. Aquatic birds are reportedly the primary reservoir of the influenza A virus, which is responsible for most cases of severe illness, epidemics and pandemics in humans. Influenza also circulates among mammals, especially pigs, which have often facilitated the transmission to humans.[84]

Aaron Carroll, the chief health officer for Indiana University, said that a free COVID test should be mailed to each American each week until the pandemic is under control. Doing so would cost billions and save trillions. Germany is already doing this.[85] The present analysis says that decisions on how many free tests to produce and mail to whom should consider only the marginal costs of producing and distributing an additional unit. Those marginal costs are almost certainly a tiny fraction of the current sale price in the US. If we invoke eminent domain, as suggested by Acharya and Reddy (2020), cited above, we could pay the developers of such tests more than they could possibly make from patent royalties, place the testing technology in the public domain to create competition in producing such tests, and scale production to the need internationally. If we did, the unit costs of producing and distributing additional tests would almost certainly decline further. The major obstacle is US patent law, which in this case is clearly an obstacle to progress of science and the useful arts, in blatant violation of its purpose under the Copyright clause of the US Constitution.

Major obstacles to progress are sufficiently widespread understanding of (a) the benefits of research and (b) effective and efficient ways of managing research to benefit all.

A goal simpler than universal diagnosis might be reasonable diagnostics for known sexually transmitted infection (STI). Some organizations are already offering free testing for HIV and Hepatitis C at libraries, bars and other community locations.[86] Compliance might improve if tests for STIs could be as cheap and simple as testing blood oxygen level or using saliva or some other body fluid, e.g., a drop of blood like a glucose test. If anyone could do it discreetly in the presence of a potential partner, that could become standard practice worldwide: When one partner tested positive, they might still engage in intimate behaviour that was not high risk.[87] If use of such tests became sufficiently widespread, it could be combined with a program using 100 percent contact tracing to eradicate STIs. Chen (2021) described difficulties finding a homeless pregnant woman, so she could be treated for syphilis, for which she had tested positive, before passing that disease to her baby at birth. This search could be eliminated with a test that could produce a diagnosis before the pregnant woman left the clinic where she was tested.

Roughly 16 percent of the world population of 7.4 billion had a sexually transmitted infection other than HIV/AIDS in 2015.[88] It may be worse in the US. A 2008 study by the US Centers for Disease Control and Prevention (CDC) reported that a quarter of US teenage girls have at least one of four infections monitored in the study.[89]

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[84] Li et al. (2019) and Joseph et al. (2016).

[85] Aaron E. Carroll (2021).

[86] Merchant (2021).

[87] Krueger (2021) reported how rapid testing is being used to test for COVID before admitting people to a party.

[88] The figure of 16 percent was computed by dividing 1.146 billion people with sexually transmitted infections excluding HIV by 7.38 billion to get 0.155, approximately 16 percent. The 1.146 billion is from GBD 2015 Disease and Injury Incidence and Prevalence Collaborators, et al. (2016),.

[89] The four sexually transmitted infections monitored in the study were human papillomavirus (HPV), chlamydia, genital herpes and trichomoniasis. Almost half of the African Americans in the study were infected. Altman (2008).

Even people who are 100 percent monogamous would benefit from widely used and accurate test(s) for common STIs. Some partners are clandestinely unfaithful, and not all children are as sexually naive as their parents want them to be. Moreover, widespread use of such testing would reduce the likelihood that rape spreads STIs. In sum, such testing carries positive externalities, and a program to improve such tests and their use would be a public good.

Face masks and other interventions to limit contagious diseases

Face masks provide an interesting example of a product that can limit the spread of contagious diseases. How should they be priced? The general rule for pricing mentioned above is the minimum of (a) the marginal cost of production minus the benefit to society and (b) a minimum charge required to limit waste. In this case, "waste" could include otherwise legitimate use in applications like painting or working in a dusty environment, which do not carry the positive externalities associated with limiting the spread of a contagious disease. The public should not be expected to pay fixed costs like patent royalties for uses that do not produce such positive externalities. For an outline of mathematical modeling for such applications, see Appendix 2 below.

Treating infectious diseases

Much of the above discussion of tests and face masks also applies to treatment of infectious diseases: The human population might on average be healthier if everyone who had symptoms that might be due to an infectious disease were *required* to seek medical assistance *at public expense*. The World Health Organization (2020) and Alonso (2021) suggested that measures like this have already reduced the incidence of malaria, because people with the disease are less likely to feed mosquitos that would then infect other people.[90]

[90] The externalities associated with treating contagious diseases might tend to be greater than from treating diseases that are infectious but not contagious, as indicated above.

Vaccine hesitancy[91] and liability insurance for contagious diseases

Ropeik (2013) said:

> "A 2008 study in Michigan found that areas with 'exemption clusters' where more parents chose not to have their kids vaccinated were three times more likely to have outbreaks of pertussis than where vaccination rates matched the state average. ... A 2008 measles outbreak in San Diego triggered by an unvaccinated boy infected during a visit to Switzerland exposed 893 people... . Controlling the outbreak ... cost the community close to $900,000.[92] A similar case that year in Tucson, Arizona, infected 14 people ... with measles. The outbreak cost two hospitals nearly $800,000, and tens of thousands more were spent by the state and local health departments to track down the cases, quarantine and treat the sick cases, and notify the thousands of people who might have been exposed."[93]

Ropeik concluded, "society has the right and responsibility to establish laws, regulations, and choice frameworks that discourage vaccine refusal. ... [V]accine refusal costs society billions of dollars, both in direct health care costs and indirectly in lost productivity and public health spending to curtail disease outbreaks. ... [I]n many communities, vaccination rates, particularly for children, have dropped below thresholds necessary to maintain herd immunity. ... A study in the United States found that in places where it is harder to opt out, fewer people do."[94] On 4 May 2020 the US Senate Republican Policy Committee published a report on "Legal precedents for epidemic response", noting that states in the US, though perhaps not the federal government, have the authority to enforce measures such as quarantine and vaccinations "as long as those measures are reasonably tailored to fit the situation." They date in US history to the presidency of George Washington, following English common law from the sixteenth century.[95]

Becchetti and Salustri modeled disease progression in Italy with partial vaccination and concluded that herd immunity, a public good, could not be reached with the prevailing rates of noncompliance with vaccines without vaccinating people under 16 years of age, though the stress on the existing hospital system would be substantially reduced.[96]

A relatively simple solution to the problem of people refusing to get vaccinated might be to require the following:

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[91] The Wikipedia article on "Vaccine hesitancy" discusses "anti-vaxxers" including many of the reasons they give, while documenting the paucity of evidence to support those claims. The Wikipedia article on "Misinformation related to vaccination" cites multiple sources documenting unfounded reports circulating on social media. For more on that see the discussion below of legal structures that encourage media organizations to disseminate information contradicted by available evidence. (Wikipedia articles accessed 19 September 2021.)

[92] See also Sugerman et al. (2010).

[93] Chen et al. (2011).

[94] See also Wikipedia "Vaccine hesitancy", accessed 19 September 2021.

[95] Blunt (2020). On 23 November 2021 Fentem and Grumke (2021) reported that a judge in Cole County, Missouri, said that the Missouri state government did not have the authority to delegate decisions regarding mask mandates to state or local health departments, though elected officials could issue such mandates directly. St. Louis County government attorneys insist that this ruling does NOT apply to a masking order previously issued in the previous July by St. Louis County Executive Sam Page, because St. Louis County was not a party to the lawsuit.

[96] Becchetti and Salustri (2021).

1. Everyone should be required to purchase liability insurance for spreading contagious diseases to cover the losses from anyone who catches a contagious disease directly or indirectly from them.

    1.1 A simple formula might be to reduce the premium by a factor of (1-effectiveness) of a vaccine for those who are vaccinated. For example, the premium for a vaccine that is 95 percent effective might be 5 percent of the premium for someone who is not vaccinated. Similarly, the premium for a vaccine that is only 50 percent effective might be half that of the premium for someone who is not vaccinated. The premiums for both vaccinated and unvaccinated might be set to cover the cost of the burden of diseases and administering the insurance program.

    1.2 The insurance premium may also consider each individual's behavior patterns. For example, people may not have to buy the insurance unless they will be traveling to a place where the covered contagious disease may be more prevalent than it is where they currently reside and otherwise travel.

    1.3 For a disease that might plausibly be eradicated, some of the insurance premiums might be used to pay for increased contact tracing and ring vaccination as well as (a) research to facilitate understanding vaccine hesitancy, (b) appropriate action to challenge the official behaviors that contributed to vaccination hesitancy like the fake hepatitis B immunization campaign that the US CIA reportedly used to confirm the residence of Osama bin Laden prior to killing him,[97] and (c) public health campaign to make it easier to overcome vaccine hesitancy. After an eradication program has been declared successful, the insurance premium for that disease should drop to zero.

    1.4 This is similar to the liability insurance required to drive a car in many if not all countries in the world today. That insurance rate is higher for people in higher risk groups, consistent with what is proposed here.

2 Anyone with symptoms that could be due to a contagious disease should be legally required to consult a health care professional and enter quarantine if told to do so. The cost of the medical consultation, therapy and quarantine should be paid from the liability insurance for contagious diseases. This would include paying people for actual loss of income in quarantine by some formula that would be capped at some modest multiple of a prevailing minimum wage.

Requiring anyone with symptoms of a potentially contagious condition to seek medical attention and act according to the medical advice should reduce the transmission of disease by itself, thereby reducing the vaccination rate required to achieve herd immunity. It could also facilitate any eradication program.

Insurance payments for such a system could be based on actuarial calculations considering the evidence from research into how each disease spreads. Contact tracing could identify several individuals as most likely for the outbreak and could estimate the proportion of the total burden of the outbreak that was most likely due to each individual using Bayesian inference. If more than one insurance carrier was involved, these estimated proportions could be used to allocate the total burden to the different insurance companies with no need to declare any one person as most likely responsible

[97] Larson (2012). *BBC News Online* (2011).

for the outbreak.[98] If you are fully vaccinated, you may get the insurance for free, paid by increasing the rates on others who are not vaccinated.

An insurance mandate of this nature could be introduced using a "fee and dividend" system that is revenue neutral or slightly beneficial for the poor and middle class, similar to carbon fee and dividend systems designed to increase the market prices for fossil fuels in a way that does not generate massive protests as happened in the UK, Mexico, France, Zimbabwe, Haiti, and elsewhere.[99]

The main purpose of requiring liability insurance for contagious diseases is *not* to pay for the outbreaks but to help the public understand the following:

- Everyone benefits from others being vaccinated (and from others using other goods with positive externalities that can help control contagious diseases).
- You personally could become infected, be asymptomatic, and still be responsible for close family and associates getting sick and dying.
- Vaccines are never perfect.

This is similar to the malfunctioning forehead fever thermometer mentioned earlier: Part of the value (and in that case the only value) is to help people understand the potential impact of their actions on others.

Summary of policy implications

The following summarizes some of the most important implications of the discussion in this article:

1. To the extent that the international pharmaceutical industry operates a vaccine cartel as suggested above,[100] it should be broken. This could be abrupt using antitrust law. Or it could be more gradual using tax law or subsidies for (a) research whose results would explicitly be published in the public domain and (b) vaccine production facilities to make vaccines whose formulae are in the public domain.
2. Everyone should be required to purchase liability insurance for spreading contagious diseases with the rates adjusted based on their vaccination history, general health, location, and travel.
3. Everyone except the international pharmaceutical cartel would benefit from better preparations for future pandemics, including improved public health monitoring and improving systems for rapidly developing and deploying relatively inexpensive and more accurate tests for new problems along with new treatment modalities and vaccines.

[98] Laws making people liable for infectious diseases they might spread and mandating insurance for same could be structured so awards of liabilities and beneficiaries of the insurance would be entirely on an actuarial basis, thereby eliminating the transaction costs associated with bringing cases in a court of law.

[99] See Wikipedia on "Fuel protests in the United Kingdom", "2017 Mexican protests", "Yellow vests protests", "Zimbabwe fuel protests", "2018–2021 Haitian protests", and "Occupy Nigeria", accessed 19 September 2021.

[100] B. Baker (2021).

Changes like these will be difficult, because they will likely require challenging some powerful interests who benefit from political corruption built into the current political and economic systems that manage public health issues.[101] We hope that this discussion will contribute to developing a clearer vision of what needs to be done to improve the quality of public health policies available to the entirety of humanity, even to those whose social status might be threatened by the changes.

Appendix 1. Numbers and references behind Figure 1

Gallagher (2021) reported estimates of the basic reproduction number, R_0, for four different variants of COVID-19: the original Wuhan variant, Europe's first wave, and the Alpha and Delta variants. He gave a single number for Europe's first wave and ranges for the other three. Table 2 gives lower and upper limits and a point estimate for each of these variants plus the name of a Wikipedia article discussing that strain, the estimated date of a first case with, and the date that Wikipedia article was created. For computational convenience and to save space, these dates are expressed in ISO 8601 format: YYYY-MM-DD.

The numbers for the original Wuhan variant came from Billah, Miah, and Khan (2020). They reviewed 42 studies discussing the reproductive number of this ancestral coronavirus variant. They included 29 of those studies in a meta-analysis, which produced an estimate of 2.87 with a 95% confidence interval of 2.39–3.44. That estimate is the geometric mean of the limits they gave. That suggests that they essentially assumed a log-normal distribution for the estimate. We used that assumption to estimate the standard error of the logarithm of their estimate. We did not find confidence levels stated with the limits given for the Alpha and Delta variants. For convenience, we assumed they were also 95 percent confidence limits and used that to compute standard errors for the logarithms of their estimates. The largest of the standard errors computed was used as the standard error for Europe's first wave, which we used to compute limits for that.

The concept of herd immunity describes the aspect of a successful vaccination program as a public good.[102] If everyone with whom I interact is vaccinated, I'm not likely to get a disease, even if I have *not* been vaccinated. Other public health measures like diagnostic testing and masks carry similar positive externalities and may be public goods if adopted by a critical mass of the public. The Herd Immunity Threshold on the right margin of Figure 1 is the percent of the population that must be immune to establish endemic steady state,[103] i.e., where the number of new cases each day or month is neither growing nor declining. At that point the effective reproduction number,[104] being the average number of people in a partially immune population infected by an infected person, is 1.

[101] As outlined, e.g., in D. Baker (2016) and Stockman (2021).

[102] See Wikipedia, "Herd immunity" and references cited therein, accessed 15 September 2021.

[103] See the section on "Endemic steady state" in the Wikipedia article on "Mathematical modelling of infectious disease", accessed 19 September 2021.

[104] See the section on "Effective reproduction number" in the Wikipedia article on "Basic reproduction number", accessed 19 September 2021.

Table 2. Numbers for Figure 1

Variant	Lower limit	Estimate	Upper limit	Standard error of log (est.)	Est. date of first case	Creation date for Wikipedia	Wikipedia article
Wuhan[105]	2.39	2.87	3.44	.093	2019-12-01	2020-02-05	"Investigations into the origin of COVID-19" and "COVID-19"
Europe's first wave[106]	2.37	3	3.79	.12	2020-01-24	2020-02-22	COVID-19 pandemic in Europe
Alpha[107]	4	4.47	5	.057	2020-09-15	2020-11-15	SARS-CoV-2 Alpha variant
Delta[108]	5	6.32	8	.12	2020-10-05	2021-04-19	SARS-CoV-2 Delta variant
Omicron[109]	?	?	?	?	2021-11-24	2021-11-25	SARS-CoV-2 Omicron variant

The "basic reproduction number" concept tends to work on a societal level but not necessarily in a small group with high levels of contact like a household. If one member of such a group gets an airborne disease[110] like COVID-19, there is an elevated chance that all the other members of that group will also get that disease, though it may take longer for people who are vaccinated than for those who are not.

[105] The limits and estimates are from Billah, Miah, and Khan (2020). The date of the first case was inferred from the specified Wikipedia article, which said, "A phylogenetic analysis of [samples implied] that the first human infection occurred in November or December 2019." For specificity, we interpreted that as 2019-12-01. For "Creation date for Wikipedia", we used 2020-02-05, the creation date for the Wikipedia article on "COVID-19". See also Wikipedia "Investigations into the origin of COVID-19". Websites accessed 29 August 2021.

[106] The R_0 for Europe's first wave was taken from Gallagher (2021), as indicated in the introduction to this appendix. For the dates, we used the specified Wikipedia article which began, "The first case in Europe was confirmed in Bordeaux, France, on 24 January 2020." See Wikipedia, "COVID-19 pandemic in Europe", accessed 29 August 2021.

[107] The range for R_0 came from Gallagher (2021). For the dates, we used the specified Wikipedia article which said, "It was first detected in November 2020 from a sample taken in September". For convenience, we interpreted that as 2020-09-15. See Wikipedia, "SARS-CoV-2 Alpha variant", accessed 29 August 2021.

[108] As for Alpha, the range for R_0 came from Gallagher (2021). For the dates, we used the specified Wikipedia article, which said, "It was first detected in India in late 2020." That cited two sources, the second of which was Peacock (2021), who said, "The first B.1.617 genome in the global database (GISAID) dates back to 5 Oct 2020." We used that for the estimated date of the first case. See also Wikipedia, "SARS-CoV-2 Delta variant", accessed 29 August 2021.

[109] See Wikipedia, "SARS-CoV-2 Omicron variant", accessed 23 January 2022.

[110] Wikipedia, "Airborne transmission", accessed 19 September 2021.

Each person's susceptibility to an infectious disease is a random variable, whose distribution is impacted by their genetic makeup, personal history of exposure and vaccination, and their personal habits including but not limited to what masks they wear when, and ventilation in the shared living space.[111]

Appendix 2. How to price goods with positive externalities?

We consider the following in pricing:

1. P = Price to the consumer.
2. $V = V(P)$ = Volume of consumption at unit price P. V could be zero for sufficiently large P and could be unbounded for sufficiently negative P, i.e., when people are paid to consume the good. We expect V to be monotonically non-increasing in P.
3. $B = B(V) = B(V(P))$ = The total (gross) benefits that others derive from consumption of one additional unit at consumption volume V. This could be zero when V is 0. We expect $B(V)$ to increase to a maximum then decline as additional consumption is diverted to applications that do not carry positive externalities, e.g., with N95 face masks used to protect a person from breathing particles that are not contagious. If there is a maximum, it should be unique with the function non-decreasing prior to that maximum and non-increasing after the maximum.
4. F = Fixed costs required to develop the product and associated production processes. This in theory could increase with V as people spend more money to develop more efficient production processes justified by large volumes of demand, but we will suppress those effects in this notation to simplify the discussion.
5. $M = M(V)$ = The marginal cost of producing and distributing an additional unit at volume V. This should be non-increasing, on average declining with total production, as described in the literature on experience curve effects.
6. $T = F + \sum_{v=1}^{V(P)}[M(v) - B(v)]$= total cost to society at production volume V and price P.

We want to select P to minimize T. Equivalently, this would maximize the *net* benefits to others after subtracting fixed and total variable costs.

In many practical applications, it will be clear without a major empirical modelling effort that the benefits to society from someone consuming one additional unit, B, substantially exceeds the marginal cost of producing and distributing that unit, M. In such cases, the optimal price to the consumer, P, will be 0. This will not be true for goods like N95 respirators, which have uses that do not carry such positive externalities. For such products, it may be desirable to invest in more careful efforts to model B and M.

[111] The Wikipedia article on "Compartmental models in epidemiology" says that susceptibility (S) combined with exposure (E) sometimes leads to infection (I) and either death or recovery (R). Some people who recovered may be susceptible to a recurrence. However, their susceptibility after recovery or vaccination is usually less than without that experience. Wikipedia on "Airborne transmission" says, "Airborne transmission is complex, and hard to demonstrate unequivocally but the Wells-Riley model can be used to make simple estimates of infection probability." The Wells-Riley model essentially assumes exponential decay in the probability of remaining healthy as the number of disease particles inhaled increases. See also Wikipedia on the "Wells-Riley model". These Wikipedia articles were accessed 1 September 2021.

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