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Vision for a systems architecture to integrate and transform population health

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Entities involved in population health often share a common mission while acting independently of one another and perhaps redundantly. Population health is in everybody's interest, but nobody is really in charge of promoting it. Across governments, corporations, and frontline operations, lack of coordination, lack of resources, and lack of reliable, current information have often impeded the development of situation-awareness models and thus a broad operational integration for population health. These deficiencies may also affect the technical, organizational, policy, and legal arrangements for information sharing, a desired practice of high potential value in population health. In this article, we articulate a vision for a next-generation modeling effort to create a systems architecture for broadly integrating and visualizing strategies for advancing population health. This multipurpose systems architecture would enable different views, alerts, and scenarios to better prepare for and respond to potential degradations in population health. We draw inspiration from systems engineering and visualization tools currently in other uses, including monitoring the state of the economy (market performance), security (classified intelligence), energy (power generation), transportation (global air traffic control), environment (weather monitoring), jobs (labor market dynamics), manufacturing and supply chain (tracking of components, parts, subassemblies, and products), and democratic processes (election analytics). We envision the basic ingredients for a population health systems architecture and its visualization dashboards to eventually support proactive planning and joint action among constituents. We intend our ambitious vision to encourage the work needed for progress that the population deserves.

population health | systems engineering | systems architecture | analytics | visualization

Population health challenges span the full gamut of influences from sociology to technology and taxes and from politics and philosophy to finance and weather. Examples range from provision of clean water and waste disposal systems to highway maintenance, to grappling with the ethics of certain modes of treatment, editing genetic information, and revising and coordinating national or global plans for disease control. Planning for population health can extend to faith- and community-based organizations, scientific spillovers, economic growth, job creation, and dealing with the complexities of diabesity, substance abuse, cyberchondria, texting while driving, pricing of medicines and services, and other hidden layers of social influences. It extends to the fear of infectious microbes or cancer or dementia, issues of racism, firearm violence, inequality, and ultimately—perhaps most importantly—maintaining happiness and joy in life. All these systems, and their objectives and functions, require a basic degree of continuous integration, evaluation, and improvement in the service of keeping the population as healthy and productive as possible and assisting with the realities of being mortal.

Modeling and visualization of such complex phenomena can seem overwhelming, to say the least, setting aside their ultimate effectiveness, usefulness, and social acceptability in real use. Multiple dimensions and multiple states of population health are valued differently by different people. Ultimately, humans—not machines or machine learning—determine what creates value, progress, and success in population health. Thus, planning for population health relies on real people making choices and tradeoffs among options that have value in multiple dimensions.

Population Health Planning: Who Is Responsible?

The core issues in population health planning, often behavioral, financial, and involving joint operations, are exacerbated by barriers, some hierarchical (city, county, state, federal, international) and some jurisdictional (i.e., cross-organizational). Just within the US federal government system, population health goals are embedded not only in the functions of the Department of Health and Human Services (biomedical research, public health service, Medicare and Medicaid, regulation, disease control, health workforce planning, and others) but also in the Environmental Protection Agency (outdoor and indoor pollution) and the Departments of Labor (occupational safety), Commerce (intellectual property, trade tariffs, hurricane and weather forecasting), Agriculture (food supply and safety), State (immigration; aid, international treaty negotiations), Homeland Security (border security and terrorism), Justice (violence, addiction, prisons, regulatory enforcement), Transportation (motor vehicle safety, civil aviation, infrastructure maintenance), Energy (pollution, radiation, power), and Treasury (economic policy, insurance, taxes, and enforcement of firearms and alcohol laws). Other relevant federal departments include Veterans Affairs and Defense, which are responsible for the health and well-being of various defined populations, and the Social Security Administration, the Government Accountability Office, the Federal Reserve, and other counterparts both at state and international levels. Everybody has some responsibility for population health, but nobody is in charge.

A relevant illustration pertains to recent efforts regarding opioid abuse and deaths. One response was to control the

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amount and duration of opioid prescriptions, which in return led to increased overdoses and deaths from addicts switching to street drugs of highly variable potency and quality. Clearly, the "system" of substance abuse extends well beyond prescription-based medical care. The prohibition of prescriptions removes the blame from the medical system but does not resolve the epidemic.

Another example relates to how security personnel, ranging from private security officers in shopping complexes, corporate offices, factories, and universities to urban police and border security agents, focus on enforcing laws rather than on the broader impacts of their actions on population health. Indeed, laws and their enforcement, up to and including incarceration, are seldom formulated from the perspectives of population health. The United States spends less on social services than many other countries and spends much more on prisons in which inmates are often imprisoned for victimless crimes. The basic tradeoffs are not confronted.

The presence of numerous nongovernmental, private, and philanthropic participants as well as international partnerships, each with differing models for approaching population health issues, complicates integration, coordination, and consolidation in this system of systems. The plethora of plans, planners, and planning activities for various diseases are representative of the complexity. Examples exist in which strategic plans for control of challenges such as obesity, diabetes, cancers, and neurodegenerative conditions have diffuse roles in many organizations but with no central responsibility or even any mention of budget authority to accomplish the stated task. The consequences of this modern Tower of Babel are enormous.

Comparative analyses have shown that excess deaths often result from human actions and behaviors such as tobacco and alcohol use, obesity and lack of exercise, sexual activities, drug use, and the use of firearms and motor vehicles (1, 2). Together these account for nearly half of all annual deaths, with quite stable (and well-recognized) trends from decade to decade. A comparison with recent NIH categorical research spending (3) shows that 10% of the agency resources are specifically devoted to these identifiable causes of death, the largest being tobacco use (18.1% of deaths, 0.9% of the total NIH budget) and obesity (16.6% of deaths, 3% of the NIH budget). Next in number of deaths comes alcohol abuse (3.5% of deaths, 1.5% of the NIH budget). Drug abuse accounts for the largest actual spending on these behavioral issues (3.2% of the NIH budget), a figure very likely to rise as future efforts respond to the current opioid crisis.

Using 2000 as a reference year, drug-related deaths have increased from 17,000 to 72,000, the largest increase by far due to overdoses of synthetic opioids (fentanyl and related drugs), which now represent ~3% of all deaths (4). Thus, NIH-identified spending on drug-related deaths approximately matches (in percent) the proportion of deaths due to drug overdose, but for tobacco use the deaths-to-spending ratio is 20:1, for obesity the ratio is 11:2, and for alcohol abuse the ratio is 7:3. In 2017, 73,000 people suffered nonfatal injuries from firearms, and 33,000 died from firearms injuries, but NIH research on firearm deaths is under $0.5 million, below their reporting threshold (3).

Complex human actions and behaviors emerge from many sources, including cultural patterns, economic forces (such as taxation), direct corporate marketing and advertising, and, in many cases, underlying genetic predispositions and also perhaps (social) media, all of which contribute their influences. We believe that a well-integrated systems approach to understanding the actual drivers of these behaviors and actions and their cumulative effects on population health is essential for improvements in resource planning and allocation in support of desired health outcomes.

The State of the System

In this perspective, we offer a vision for a systems-level portrait of current and anticipated states of population health. We gain inspiration from systems engineering platforms developed and successfully applied for comprehensive analytics, visualization, and planning in other areas of the economy, including market and labor performance, supply chain logistics, Internet service provision, utilities management, crime tracking, weather monitoring, aviation traffic, classified intelligence, national security, defense planning, power generation, and sports as well as election analytics.

The primary value of a systems architecture is to illuminate the basic relationships and influences and a pathway for practical integration among the entities and the participants. The component models provide a quantitative and qualitative profile of the systems architecture. The dashboard visuals provide shifting views of the system and a dynamic interface for interaction. Understanding the state of the system and its numerous risk states is a precondition for successful formulation and adaptation of strategic plans. This observation simply reflects a well-known dictum in engineering practice that one cannot control something without measuring its presence and intensity.

The systems architecture for population health could feasibly materialize through the alliance of current capacities in systems engineering, computing, network and complexity science, information processing and storage, interactive gaming, and predictive analytics (now indeed common in utilities, finance, sports, weather, entertainment, and politics). As a next-generation challenge, we propose that the modeling and visualization communities could develop a situational-awareness platform that could provide live operational snapshots of programs, real-time functional portraits, and dynamic flows and foreseeable trends in matters of population health.

Some might view the concept and prototyping of a systems architecture for population health as formidable and grand(iose), even utopian and unattainable. At every level of population aggregation (from a city block to a county to a state to a country or a collection of regional countries), understanding the current status of—let alone forecasting vulnerabilities for—population health could be daunting. Immediate responses to threats and the proposed long-run solutions may often have nothing in common. The public anxiety emanating from a viral outbreak might need to be confronted in conjunction with related news and updates "going viral" at the speed of light. The long-term prospects may include a preventive or therapeutic vaccine and further knowledge about the biological and cultural bases of the underlying disease, neither of which may be available in the short run. Further, the benefits and costs of immediate responses fall primarily on the current generation, whereas responses such as immunity, cures, eradication, or complications can have multigenerational and multinational effects.

Despite these complexities, an effort to gain a visual sense of the state of population health, such as understanding the flow of risks and resources, the dynamics of various interventions in reducing and mitigating those risks, and the relevant failure modes at multiple levels, seems to be an essential starting point. Currently, there are no common approaches across population health for diagnosing and dealing with even common failure modes—be they the transmission of pathogens, the consequences of hurricanes, or the weakening of public works capabilities. A systems architecture could better organize these approaches and orient us to respond to specific events.

Basic Architecture

The proposed population health systems architecture could be abstracted in a basic form as shown in Fig. 1. This abstraction builds from a class of complex systems architectures for characterizing physical, human, economic, and social phenomena (5). The lowest level in Fig. 1 includes the interactions of individual agents who provide and consume services. These agents includes clinicians and patients, teachers and students, social workers, police officers, fire fighters and citizens as well as digital assistants that affect some elements of population health.

These interactions (the next level in Fig. 1) draw upon service capabilities and information provided by operational processes and controls. This level includes physical and organizational capabilities and information ranging from policies and procedures to capability-specific information. Interactions yield service outcomes such as health treatments, educational attainments, referrals to family services, utilities, and housing. Information is generated in the process through means such as health records, school transcripts, social security claims, and general records of transactions.

Moving to the third level in Fig. 1, the availability of process capabilities and information systems depends on investments by organizations, driven by their business aspirations and fiduciary responsibilities in the context of society's policies, regulations, and incentives. Such investments are intended to yield results in terms of performance, costs, and economic returns. Without these investments, population health-related capabilities would decline, affecting individual access to associated services.

Finally, society's policies, regulations, and incentives influence aggregate productivity as well as economic and other returns. The (well-recognized) fragmented nature of the US health and medical system hinders addressing obvious tradeoffs across the levels of the systems architecture. For example, Medicare typically does not consider costs of specific treatments while making national coverage determinations, thus contributing to increases in the costs of all medical care beyond what might be achieved. This could impose further tax burden on workers financing Medicare and affect their choices of employment, recreation, food, housing, and other choices. Similarly, society has only recently begun to pay attention to returns on higher education and to discuss the impacts of steadily increasing tuition costs, but these returns not only arise with employment and lifetime earnings (and hence tax or philanthropic contributions) but also potentially with wise health-related choices and actions (6).

The basic architecture in Fig. 1 could enable the creation of system dashboards (an example is envisioned in Fig. 2) by the various participants in the system—medical care, education, social services, national security, environmental protection, and law enforcement, among others. These dynamic, interactive dashboards would necessarily present different views to enable the various players to access the information and controls they each need to fulfill their responsibilities. While these views may be very different in their levels of abstraction and aggregation, their consistency and compatibility would be essential.

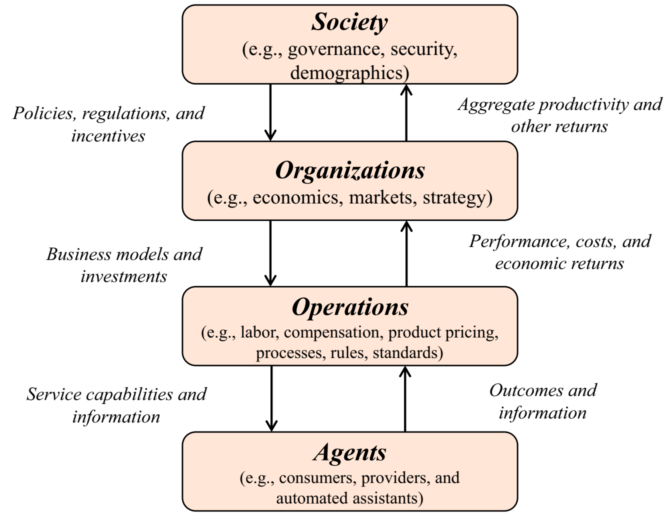

Fig. 1. A multilevel abstraction of a population health systems architecture relating to the flow and compatibility of information from society to individual agents, and vice versa. Additional arrows showing flows of influences across layers have been omitted for visual clarity.

Some Operational Features

A key structural feature for the systems architecture would be modularity and flexibility. Just as individual computer users can specify what appears on their "home page," a systems architecture and its dashboards will have broad flexibility coupled with strong modularity. This can enable the development of an ensemble of linked models and applications, a design strategy that underpins much of mobile platforms and smartphone apps, to understand patterns and linkages across population health trends. We do not seek to specify the exact contents or to instantiate the desirable systems architecture, since they will vary with setting and across time.

The first block from the left in Fig. 2 lists representative contextual priorities. These are highly variable factors, but as a package they convey what matters most, to whom, from whose perspective, and perhaps why. Choosing what matters (and how much) in this setting involves group decision making that also must be improved to achieve desired goals (7). If the development of a new vaccine or a combination therapy were in question, representative attributes could include health considerations ranging from premature deaths and incident cases averted to operational matters such as cold-chain fit and delivery mechanisms. The vaccine-related attributes could also range from national priorities such as defense and foreign policy to more technical ones such as new production platforms and product thermal stability. Every attribute comes with a different set of data structure and demands. Traditionally, only a limited range of information has been applied to support these attributes, but a systems architecture could enable joint analysis of numerous data feeds (the second block from the left in Fig. 2). These wide-ranging data feeds, from standard life tables to live status updates and spatiotemporal information obtained through satellites, can be integrated and hosted on cloud-based repositories that offer instant historical comparisons and trend analysis.

Data on smaller population units (e.g., states) can be assembled upward into larger ones (e.g., nations), creating possible economies of scale for the systems architecture. This obviously leads to the point that the systems architecture would benefit from up-to-date information on the relevant population, including size, racial and ethnic distribution, educational attainment, income distribution, housing (including homelessness rates), employment, transportation patterns, voting participation, taxation of all types (income, sales, gasoline, tobacco and alcohol, property, and other taxes), costs of living by important categories (housing, food, medical care, and so forth), as well as weather forecasting and environmental emissions.

The systems architecture would necessarily have access to additional information, beginning with age-specific morbidity and mortality rates, preferably by important subclasses of the population (such as income strata, educational attainment, and ethnicity). Stratification of population groups is essential to determine the affordability of interventions, be they prevention, screening, treatment, or educational campaigns. As the architectural design evolves, it would be valuable to add cause-specific measures of morbidity and mortality. For example, recent health concerns highlight the importance, of understanding trends in cause-specific mortality from various infectious diseases, sexually transmitted diseases, opioid and other drug abuse, alcohol abuse,

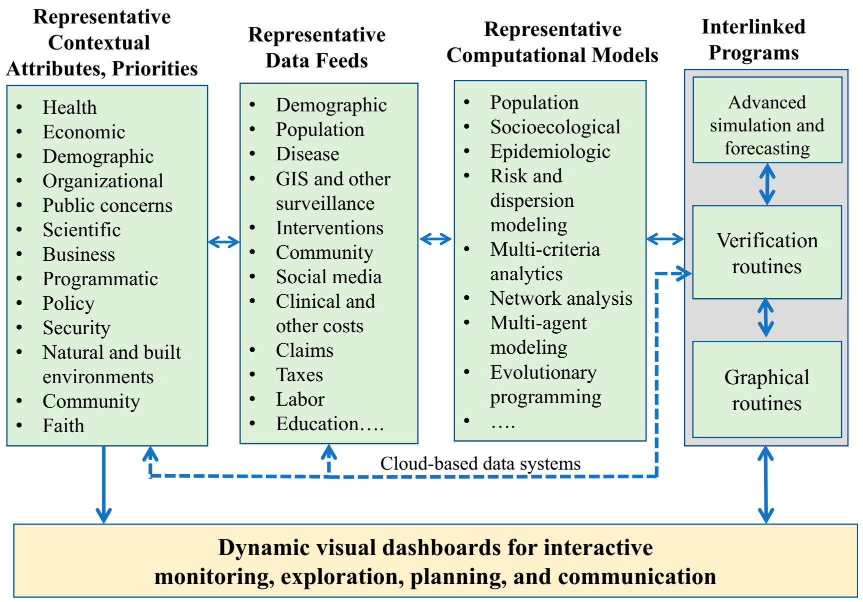

Fig. 2. Envisioned basic components of a systems architecture.

suicide, homicide, and toxic chemical exposure and from more traditionally labeled causes of death such as cardiovascular diseases and cancers that are known to be linked to human behaviors and actions (1, 2).

The use of emergency and urgent care facilities may be an important leading indicator, but integrated measures of medical care utilization from insurance claims data can also inform these issues. Arrest and incarceration data may provide important clues about adverse trends in population health, although these must be interpreted with caution, since they can change through shifts in behavior or through law enforcement efforts. The data feeds would desirably include direct measures of people's self-perceived health status, including such measures as mobility, freedom from pain, and measures of mental health and happiness.

Projection of the value of investments in population health would require both "income statements" and "balance sheets" to trade off near-term expenditures and long-term returns (8). Determining the value of investments by focusing only on the individuals in the population health system is insufficient and needs to extend to the governance and leadership of corporations that provide the many types of services (medical care, education, food supply, vehicle safety, and many others) that affect health and well-being. The incentives confronted by chief executive officers and their C-suite leaders can affect how they lead corporations, which in turn can affect the health of their workers, their customers, and ultimately those along the supply chain. Of course, the rewards and incentives for workers in governmental organizations at all levels can affect their performance of their work and hence affect population health.

The practical notion of incentives and behavior modification expands to interorganizational (and international) arrangements. It is now widely understood that payment mechanisms for medical care often create perverse incentives that increase costs and degrade health outcomes (6). Recent efforts have emerged to test new payment models to counteract perverse incentives through such mechanisms as profit-sharing between insurers and care providers while assuring improved quality of care, primarily through the newly envisioned accountable care organizations. We can be assured that perverse incentives abound in the world of medical care and insurance (6) and are plausibly found with comparable frequency in other markets that affect or monetize population health. All these data or estimates would be useful in fueling various computational, predictive, and multilevel models for population health (the third block from the left in Fig. 2).

Next come the integrative programs (linked to the far-right block in Fig. 2) to combine, test, and retest these types of data for a rich graphical narrative showing improvements or deteriorations of key indicators. These visual sequences could be fed to displays along with input priorities and attributes for an array of planning scenarios. Each user will have a different view (or perception) of the population health situation. Therefore, a vital role of the visual platform and the architecture in general is to assure data consistency and standards across multiple feeds while supporting discussions leading toward compatibility and convergence.

Changes in levels or trends of various direct measures of health status can trigger specialized modeling of causation or responses. For example, if the dashboard shows an increase in emergency room admissions and hospitalization for opioid use, this could rapidly trigger a modeling effort to understand the causes and suggest interventions at the earliest possible date. These models and visuals can beneficially combine the prowess of tools based on operations research, epidemiology, survey design, behavioral sciences, and for example, statistical, econometric, process control, social network, and multiagent modeling as currently used in widely disparate circumstances. As a key design element, the results from these models would appear in a readily interpretable and interactive visual form that can synchronize immediately with other architectural elements on display to participants. The rapid integration of these visuals at multiple levels has been demonstrated to facilitate group decision making on complex matters (9).

Information Complexity

On matters of population health, the nature and quality of information must contend with the so-called "V6-D3-I3" challenge (10). Information comes in different volumes, velocities, and varieties and involves different degrees of veracity, virtualization, and value (V6). Information is also distributed and dynamic and needs to be processed and packaged for useful decision support (D3). Finally, information requires infrastructure, intelligent assistance (or assistants) to process data, and investments to maintain its quality (I3). Given this dynamic, how could one assemble reliable evidence to assess the effects of various interventions, including policies and programs, on population health?

Information to support the dashboards will have differing degrees of availability, reliability, and verifiability. At the top of the ladder of quality could be results from experiments that are carefully controlled, allowing scientific purity but often limiting the applicability of those results in real scenarios or populations. Meta-analyses of such data add further confidence to the conclusions drawn from such data. Among the various efforts underway to expand and curate data for better health and medical decisions is a major international activity with over 2,000 researchers seeking to visualize and "quantify the magnitude of health loss from all major diseases, injuries, and risk factors by age, sex and population" (11) involving significant investments from the Bill and Melinda Gates Foundation (11–13). Other useful data may come from insurance claims and reimbursement or from such sources as police, fire, and emergency medical technician incident reports as well as from randomized clinical trial data or syndromic and geospatial surveillance. Data feeds and status updates from social media might lead to better understanding, e.g., of sources of food contamination risks, pest and rodent activity risks, or even potential risks of homicide, suicide, or other high-stakes situations.

Some of the data combinations envisioned are likely to challenge not only computational and algorithmic power but also legal and ethical standards. Two obvious areas with these issues are (*i*) gathering and combining multiomics information and (*ii*) merging public health and clinical information across individuals in ways that are not currently envisioned. For example, the use of electronic health records across US medical care providers is expanding, but there is almost no meaningful interoperability among them that would, if available, both improve care quality and reduce costs and would, when integrated across the supply chain, increase our understanding of which health and medical interventions worked well, and for what types of people (6).

Structure and Management

Is a Systems Architecture for Population Health Realistically Feasible? The simple answer is, "Yes." Numerous working examples of continuous monitoring of complex adaptive systems exist that offer real-time understanding of actions and forecasts. An important example is the monitoring of air traffic by multiple agencies around the world, augmented by numerous private monitoring systems (each major airline has its own monitoring and forecasting model), to understand potential delays, bottlenecks, consequences of mechanical failure of aircraft, or weather. Similarly, the Nuclear Regulatory Commission maintains a vigilant system to monitor and manage nuclear power facilities, as does the Department of Energy for the overall status of and risks to the electrical grid. The Federal Reserve (along with ad hoc systems of the banks themselves) monitors the health of the banking system. The military has an ongoing system to measure and counteract threat from potential foes. The Department of Homeland Security and members of the intelligence community monitor potential threats (for example, from terrorism) using data feeds ranging from travel bookings and semantic analyses of social media to communication intercepts and drone-captured videos.

Another example of a successful systems architecture is the development by IBM (not a typical construction or civil engineering firm) of continuous optimization models to manage traffic congestion, a challenge afflicting major cities and their population health worldwide (14). As some might note, people are not in traffic, people are the traffic. Uncontrollable traffic jams had widespread effects, including pollution, public frustration, and ultimately workforce productivity. IBM's systems analytic effort across Stockholm and other major cities to understand the traffic patterns and disruptions of the city involved successive data collection through transponders, cameras, and public feedback. The resulting recommendation that cities should not build more bridges or roads but instead should charge consumers for travel during high-demand hours was initially counterintuitive. Results included changes in public behavior (carpooling, use of public transportation) and positive environmental impacts. This goes with recognition, however, that any policy choice—such as peak load pricing for traffic control—has limits of effectiveness that must be balanced against the public and political acceptability, factors prominent in issues of population health.

Systems architectural thinking has been successful in other public sectors as well. The US federal highway system (conceived during the times of President Roosevelt and implemented during the term of President Eisenhower) was well planned to provide an integrated transportation infrastructure for defense as well as public use. Subsequent highway engineering and automotive product design efforts for population health have involved influential changes such as rumble strips, horizontal curve safety, lane markers, center and edge lines, crash barriers, signage, speed limits, seat belts, and airbag requirements, fuel economy standards, and, as noted earlier, congestion pricing (14).

In private-sector manufacturing, specifically aviation, Boeing completely rethought the production of the 787 Dreamliner after facing numerous delays due to fragmented supply chains. For example, Boeing did not know who their suppliers were beyond the first tier and thus could not directly diagnose and manage delays (15). Airbus similarly faced assembly issues—cables that were too short because there were no integrated design processes across suppliers or because the first-tier suppliers used incompatible computer-aided design packages (16). Both firms recognized the need for expanding and capitalizing on systems integration as articulated in this perspective.

We acknowledge that our envisioned systems architecture embodies far greater operational complexity than many of these existing technological and civic systems, since population health is affected by factors ranging from anthropology to zoology. As noted earlier, almost every cabinet-level federal agency directs activities that affect population health to some degree. The integration of these many viewpoints and responsibilities may be the most challenging aspect of our envisioned system, which takes us to the next key question.

Who Would Manage the Systems Architecture? Among the many options for managing the envisioned systems architecture, we may need a new type of independent oversight and coordination at the national level (linked to state and local levels), including relevant budget authority to achieve desired outcomes. A proposal from the Blue Ridge Academic Health Group focuses on the need for a national health board charged with monitoring, forecasting, long-term planning, and decision making modeled after the responsibilities of the Federal Reserve (17). We see an analog for this concept in the way the Federal Aviation Administration plans for, monitors, and conducts its operations. To help develop the initial prototypes of the systems architecture, a firm or a coalition of partners with core competencies in systems engineering, analytics, human factors, and stakeholder engagement would be important. Numerous qualified groups exist in the private technology sector and in the domain of the federally funded research and development centers.

How Should the Various Dashboards Be Customized? A rigid and overly complex central architecture loses its value. Each state and federal agency and branch of government (setting aside private, nongovernmental, and philanthropic participants) might choose to have its own customizable architectural version, and our envisioned coordinating body also would have has its own set of constituent models within its version. Each architecture should be able to drill down into more detail, but the principal systems architecture, which is not intended as a construction blueprint, would ideally focus on monitoring, planning, and analysis of alternatives and adjacencies.

Dynamic multicriteria models can help with realistic analyses of alternatives on the selected dimensions of population health and prioritize their placement within the systems architecture that can vary with time, purpose, and context (18–20). Examples might include such attributes as overall mortality rates, emergency care use, mental health indexes, or equity and fairness among subpopulations of interest (as shown in Fig. 2). In the next level of planning, multicriteria comparisons can aid the trade-off and choice analyses among highly differing health and other interventions for a particular purpose. As an example, in controlling obesity, multicriteria models could, in concept, compare interventions such as urban design, weight-loss medications, low-cost exercise facilities, employer-provided free gym memberships, laws regulating particular food types (e.g., sugary products), availability of play areas for children, and others. Any such use of multicriteria models in group settings also requires a selection (voting) mechanism that leads to priority weighting. The subject of the voting methods and associated rules ventures into the domain of social choice that offers key insights for decision support (7).

The dashboards would also support temporal as well as spatial forecasting models. A central issue with forecasting (and financing) the level of proposed integration is who pays, who gains, and over what time periods. When the payer is different from the party gaining returns, the payers simply see the investments as costs that they try to minimize, even within the same government or a corporate entity, as is common with population health and policies (21). In line with our earlier discussion, within the realm of US health insurance, the separation of coverage for prescription drugs from other types of medical care disconnects the financial incentives in adverse ways. Prescription drug plan managers seek to minimize the drug-related costs even if doing so undesirably affects the total costs of medical care. Thus, a drug that actually reduces total medical expenditures may be eliminated from coverage because of its effect on drug insurance premiums (6).

A particular challenge with population health forecasts is that investments happen upstream while cost savings or other gains due to a healthy population often accrue downstream. Standard cash-flow analysis employs a discount rate to assess net present values of investments, considering projected inflation. Ideally, the value of such investments would appear on organizational balance sheets, but government units, such as the US Congress and federal as well as state and local agencies, tend to be run by income statements, without balance sheets. Consequently, longer-term gains may often be dismissed as irrelevant to the priorities of organizations or political considerations.

Ultimately, enterprise-level transformation of population health, as envisioned here, typically embodies fundamental shifts that challenge the current mode of operations (22). The dashboards of the architecture can be used to explore what changes the various participants would be asked to support, keeping in mind that every dollar saved is currently somebody's income. This would help in framing key tradeoffs and thinking through the adjacent effects or other consequences that are not merely unintended but also are uninformed or uncoordinated.

Use Case Concept

As an example, consider how approaches to controlling and eventually eliminating malaria might develop using a systems architecture. With over 200 million active malaria cases globally—the great majority in Africa—more than 1,000 children under the age of 5 years die every day from this disease, and the total number of malaria-related deaths is 450,000 per year. Although the need for malaria control is well understood, neither prevention nor cure has been attainable, despite billions of dollars expended on the effort. One of the main methods for reducing the disease burden is the use of simple, cheap mosquito netting around beds to prevent bites. Later, chemical coatings on the netting were introduced to increase effectiveness. Since mosquitos breed in standing water, simple measures to reduce its availability have some efficacy, as does insecticide spraying. Such sanitation methods have succeeded in eradicating malaria in many European and other advanced countries in the 20th century (23, 24).

The five malaria-causing parasite species have a common life cycle, circling among infected humans through transmission of bites from female mosquitos. This provides several likely pathways for interrupting the cycle and for the potential final eradication of the disease, since the parasites require human hosts during their life cycle. A complication also arises, given that the parasitic disease source has evolved to create some resistance to the most common drug (chloroquine) in use for decades, and newer drugs are unaffordable for the low-income nations (25). Potential efforts to interrupt the parasitic life cycle and hence reduce, if not eliminate, malaria now include various treatment options, vaccination, and genetic modification of mosquitos to interrupt their breeding cycle. Some of these approaches have potential scientific spillovers to other diseases, most notably other mosquito-borne diseases such as Zika virus disease (for which the first mosquito-gene modification tests took place), yellow fever, dengue fever, chikungunya, and West Nile virus disease.

If a particular intervention (such as genetic modification of mosquitos) has even partial success, the value of other interventions (such as vaccines and drug treatments) for that condition may decline. Thus, the same intervention may offer both a promise for reducing the disease burden and a potential threat to business and product-development opportunities. As experience in eradicating poliomyelitis around the world has demonstrated, the international coordination required to contain and eliminate the underlying source pathogen can take decades.

All these couplings show why an overall systems architecture for integrating various approaches and participants would be even more crucial for progress. The biological and programmatic complexities aside, the potential for failure is magnified by the intense interactions along every dimension of the problem—financial, technological, political, cultural, and behavioral. Consider also the geopolitical dimension: Although some travelers from Europe contract malaria, by far the greatest concern for the European Union has been the large and growing influx of emigres from malaria-endemic regions that may strain social services, medical care, education, housing, and other important resources in the recipient nations (26). This reemphasizes the international consequences of this disease.

In this intricately multifactorial and multiobjective scenario, a systems architecture can guide both an investment portfolio and an implementation portfolio for malaria, which are achievable, in concept, through the schematic shown in Fig. 2. These two portfolios require an aggregation model that transcends the traditional notions of doing an option-by-option analysis and then adding up those options and that enables a multiplex comparison of numerous interventions that deal with differing severities of malaria. This would require characterizing, with common language and structure, the costs, safety, effectiveness, and coverage of the various interventions. Similarly, one could compare bed nets, vaccines, therapeutic drugs, sanitation, and even gene-based alterations of mosquito reproduction. The same comparison, by extension, could consider treatment or prevention of dengue fever, Zika virus disease, Ebola hemorrhagic fever, chikungunya, and yellow fever.

In this use case, a systems architecture would support an in silico laboratory to evaluate the elements in prevention, planning, and first-response interventions (as appropriate, say in residential communities). Requiring in-depth discussions and design tests with various user groups around the world, the systems architecture could provide valuable pathways not only for thinking about the basic influencers of the decision but also for valuing the different ranges, dimensions, and futures of outcomes (as opposed to a single static metric), and for converging on an agreement based on evolving figures of merit. Examples of attributes in this case, in addition to cure rates, could include the probability of species eradication; adherence to interventions; alternative counteractive approaches such as mosquito nets as well as clean water supply and sanitation that would have productive value beyond malaria control; the dosage and storage profile of drugs (e.g., longevity, renewal frequency, number of doses; biological profile); effects on international migration; antimicrobial resistance (and other environmental factors); cultural factors; environmental and climatic factors (also linked to immigration); and additional goals such as milestone targets for product development and launch.

Computing and visualizing these interactions and tradeoffs would require the blending of software routines including risk models (of both financial risks and infectious disease features), disease propagation models, population processes, and immigration data models and would require extensive parametric testing (especially for technology demand forecasting). In addition to these computational features, the testing of the systems architecture and the various visualization dashboards would involve scientific and policy decision makers to determine what types of attributes are critical and in what contexts. Methods to guide collective decisions would also need to be tested as part of the package development. A full-fledged systems architecture to consider and analyze the options and futures in such a complex system will not evolve spontaneously, nor need it do so. Component parts can be built up, tested, linked, and expanded through modular prototyping, with necessary estimates and real data support.

Challenges for Higher Education and Research

Universities and research institutes have important roles to play at all levels of the systems architecture for population health. However, the competencies needed to address these issues are often currently taught and researched in relative isolation, without a sense of the need for integration across subjects, departments, and schools. Academia's penchant for increasing hyperspecialization is obstructive and counterproductive to the multidisciplinary systems perspectives needed to advance population health. As the late systems theorist Russell Ackoff once stated, "We must stop acting as though nature were organized into disciplines in the same way that universities are" (ref. 27, p. 6). In particular, traditional promotion and tenure paradigms have been recognized as working against both the concept and the conduct of the team-based crossover research efforts needed to address the challenges stemming from population health complexities, although tenure seems to be giving way to contingent workforces (28).

The funding and publication processes associated with current research are being subjected to increasing economic pressures (29). The number of proposals and articles submitted is steadily growing, while competitive research funds and publication chances in major journals are diminishing. New approaches for conducting research are needed for population health, especially when discovery science is still dominantly viewed as the mechanism to gain tenure and fame. Among the many ideas in this realm, a recent proposal argues for combining applied and basic research to yield both synergies and a broader base of funding (30), and another perspective argues that the distinctions between applied and basic research are outmoded and possibly irrelevant (31). These are critical organizational issues to be dealt with if improvements in population health are serious goals of universities and research institutions.

The concept of approaching healthy living as a life-course strategy is largely missing across all levels of schooling and public literacy and, vitally, across all the health professions. Promulgating this kind of awareness would require an introduction to systems design and maintenance (both key aspects of engineering), with an emphasis on how health interacts with and is influenced by education, built and natural environments, social services, cultural practices, and both financial and social capital.

A central element of a systems architecture involves shifting from fault finding to fully streamlining and fixing the system (32). In other words, just "staying in one's swim lane" protects organizations and their vested interests but is inadequate for addressing the needs of population health. A systems architecture can highlight or stimulate new competencies at the junction of health, engineering, nursing, behavioral sciences, industrial design, business, policy, sociology, anthropology, civic studies and organization, rural and urban planning, public works maintenance, marketing, computing, game design, communication, and cultural evolution. Understanding and improving population health is a systems problem and not a narrow concern of surgery, nursing, precision medicine, or other healing arts, let alone genetics, bioethics, and insurance. This broader frame potentially motivates a substantial review and revision of our current funding and investment priorities, how we conduct research, and for what purpose.

Prospects

No single entity currently has a broad integrated overview of the state of population health. It is everybody's responsibility and in everyone's interest, but nobody is held accountable for promoting population health in the most productive and harmonious manner. The late modernist architect Walter Gropius said, "Good architecture should be a projection of life itself and that implies an intimate knowledge of biological, social, technical and artistic problems. But then—even that is not enough. To make a unity out of all these different branches of human activity, a strong character is required . . . ." (ref. 33, p. 11). In that spirit, as we have envisioned and articulated here, a common systems architecture seems essential to integrate and ultimately transform population health.

With the effects of digital Darwinism—technological developments surpassing organizational capabilities to adapt to change—being felt across all levels of population health, we see an important opportunity for advancing proactive monitoring, forecasting, and tradeoff analyses in this most consequential area of society. The kind of multilevel systems engineering we envision has been applied and expanded constructively in numerous other areas over many years, with routine refinements, well-organized modularity and flexibility, and upward compatibility from the smallest to the largest units of population or market analysis.

We fully appreciate that our vision deals with a system more complex than is commonly understood, since it involves all the facets of human aging, actions, and behavior, economic and technical uncertainties, and clashes in public (and private) interests. Nevertheless, we must confront the real complexity of the problem to make significant progress. Assuming away the complexity does not make it vanish. We realize that we are putting forward a bold, admittedly ambitious, vision statement, but we hope to provoke discussion and debate with the intent of advancing population health.

A system as complex, adaptive, emergent, and expansive as population health is best served by adopting ambitious stretch goals rather than being satisfied with easily achievable incremental or even lesser goals. One source of our optimism is that the envisioned systems architecture and integration does not have to be complete or perfect. Indeed, we may never achieve that. However, unlike getting halfway to the moon, reaching halfway to fulfilling a vision for transforming population health has tremendous value.

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