6 Information Infrastructure to Support Public Health

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Learning Objectives

1. Explain how infrastructure and information architectures support the work of public health organizations.
2. List and describe the three components of the public health infrastructure.
3. Identify and describe seven components of a generalized health information architecture.
4. Compare and contrast the concept of infrastructure with that of information architecture.
5. Define the role an informatician serves within a public health organization.
6. Distinguish between the informatics competencies required of various public health roles.
7. Identify trends affecting the public health infrastructure.

Introduction

Every nation, state, and local community faces threats to its health from disease, environmental, and human (e.g., war, bioterrorism) agents. To monitor and protect the community, societies create public health infrastructures. A public health infrastructure can be envisioned as a framework composed of three interconnected systems:

1. Organizations—Governmental and non-governmental entities with interrelationships that create and enforce policies to protect, monitor, and improve population health
2. People—The public health workforce, which contains both personal and professional interrelationships within and between organizations
3. Information and communications technologies (ICT)—Hardware, software, and devices that capture, store, manage, exchange, and create data and information used by public health organizations and its workforce

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A capable, prepared public health infrastructure consists of a skilled public health workforce, robust ICT, and effective organizations [1]. Working together, people across several public health organizations can leverage ICT to support health and well-being for a community, state, nation, or region. Such collaboration is necessary to address the core functions of public health while protecting populations from disease and injury.

Evolution of the Public Health Infrastructure

Infrastructures evolve over time as organizations, people, and technologies advance. Much of the evolution in public health infrastructures result from a response to disease outbreak when challenges with or gaps in the existing infrastructure are noted. For example, anthrax attacks in the United States identified a gap in the ability to detect outbreaks caused by biological agents [2], which manifest disease in populations quite differently from infectious diseases and injuries. As a result, the United States invested in its public health infrastructure to increase capacity for syndromic surveillance, which is the detection of initial manifestations of disease before diagnoses are established [3–5]. More on syndromic surveillance is available elsewhere in the book (see Chap. 16).

While global threats of infectious diseases, demonstrated by outbreaks of H1N1, Middle East respiratory syndrome, and Zika virus, have continued to increase investment in the public health infrastructure, a strict focus on infectious disease surveillance has diverted attention away from other areas of population health, including the rising epidemic of chronic illness as well as the impact of social determinants on health. Going forward, public health agencies are challenged to evolve infrastructures to be flexible, with capacity for addressing outbreaks due to terrorism, the food supply chain, migration, social determinants, and chronic illness. Major shifts in health care financing, the growth of electronic health record (EHR) systems in health care delivery, and a widening array of population health data sources necessitate further investment in and upgrades to the public health infrastructure.

The Affordable Care Act of 2010 in the United States authorized a number of payment reforms to clinical health, including the creation of accountable care organizations (ACOs) in which providers are charged with managing defined populations [6]. ACOs are further required to conduct community health assessments and report population level metrics to payers, including the US Centers for Medicare and Medicaid Services (CMS). Such changes in the health system challenge traditional roles for public health agencies. Armed with sophisticated electronic information systems, ACOs and payers seek to collect, manage, analyze, and report data on chronic diseases, the communities where their populations reside, and the health of their respective populations. Public health agencies must in turn evolve from being the only entities capable of assessing and monitoring population health to become strategic and enabling partners involved in population health practice. Internationally, the focus on universal health coverage similarly challenges ministries of health to collaborate with both public and private health care delivery systems to impact population health.

Health care information management is also experiencing rapid transformation from paper-based to electronic records. The adoption and use of ICT to capture, store, and analyze health information began in earnest in the late 1990s. However, the Health Information Technology for Economic and Clinical Health (HITECH) provisions of the American Recovery and Reinvestment Act of 2009 accelerated adoption in the United States by providing incentives to hospitals and physicians to become meaningful users of electronic health record (EHR) systems [7]. To qualify for incentives, hospitals and providers must comply with a set of administrative rules from CMS [8]. These rules include a set of public health reporting objectives, including the submission of electronic laboratory reports to public health departments for notifiable conditions, submission of information for syndromic surveillance programs, and increased exchange of information with public health registries [9]. More information on the regulatory environment and its impact on public health informatics can be found elsewhere (see Chap. 4).

In other nations, similar initiatives to implement eHealth strategies have resulted in new ICT systems at district, province, and national levels. Given increased electronic methods for data reporting, public health organizations have been challenged to redesign or upgrade ICT as well as work processes [10, 11].

The increase in electronic reporting of information ushered in a new era in public health, dubbed the "Neolithic Informatics Revolution" by author Brian Dixon, where agencies are increasingly moving from "hunter-gatherers" of data silos to "agrarian cultivators" of shared information farms. Historically, public health workers wandered into the field to collect data directly from a variety of sources including but not limited to patients, nurses, physicians, allied health professionals. The rise of EHR systems, health information exchange networks, and mobile health applications has resulted in more data and information being electronically reported from health care providers to public health agencies [12]. In addition, electronic surveying and crowdsourcing technologies enable public health agencies to capture increasing amounts of information on health behaviors directly from consumers [13, 14].

Current trends suggest that, in the future, public health agencies will spend less time gathering the data they need to monitor the health of populations. Public health workers will instead focus their time and energy on analysis and application of the information received (e.g., rapid analysis of electronic population data to identify emerging threats to the public's health). The exploding use of ICT in other health-related organizations has also increased the number of potential sources of data for use in public health processes. The shift from hunter-gatherer to data agrarian will also mean that public health agencies will no longer control the entire information chain, becoming collaborators and secondary users of data collected for other, typically clinical, purposes.

Introduction to the Chapter

This chapter describes the key elements for a successful, robust public health infrastructure. The chapter begins by defining the concept of an information architecture and describing core technologies necessary to support existing and evolving needs of public health organizations. Next the chapter discusses the role of public health organizations in designing and managing the public health infrastructure. Finally, the chapter examines the critical role that people play in supporting and evolving the public health infrastructure. The chapter concludes with an example of a real-world infrastructure that supports public health functions.

A Robust Information Architecture for Public Health

Historically, public health agencies have created and maintained information silos that served individual divisions aligned with specific business and regulatory processes (e.g., HIV/AIDS, immunization registry, environmental monitoring). Such a model makes it difficult for program areas to share information with one another, and it requires agencies to gather and store the same data in multiple places. Furthermore, multiple silos increase health agency costs for hardware and software licenses, as well as for personnel costs required to manage multiple systems. Given a changing ICT landscape in which data are cheap, there exists an increasingly ubiquitous cloud for processing and storage, and agencies need to integrate data and information from a growing list of electronic sources, thought leaders in public health informatics recommend standardized approaches to collecting data once and using it for multiple business processes across ICT systems within a public health organizations [15, 16]. Achieving this vision requires a robust information architecture for public health.

Information Architecture

The term *information architecture* (IA) refers to the logical configuration of various elements including hardware, software, information flow, and technical standards necessary to support the information needs of users (e.g., employees, customers). Typically an IA consists of a blueprint or model of the information systems used by the organization to support specific business processes. For example, in Fig. 6.1, an IA for a clinical dashboard depicts how information about a type 2 diabetes patient is integrated from various source ICT systems (e.g., electronic health record, personal health record) for display to a clinician. Databases are depicted as cylinders, software applications are depicted as desktop computers, and the dashboard is depicted as a monitor. The IA represents how each ICT component fits together to form an information system that supports a specific business process—retrieving information about a type 2 diabetes patient including his or her diabetes-related prescriptions, recent diabetes-related laboratory measurements, and adherence to taking his or her medications.

The term IA is related to similar terms used in the information and computer sciences. For example, the term *data architecture* refers to the approach used by the organization to collect, store, manage, integrate, and use data in support of a given business process. A data architecture

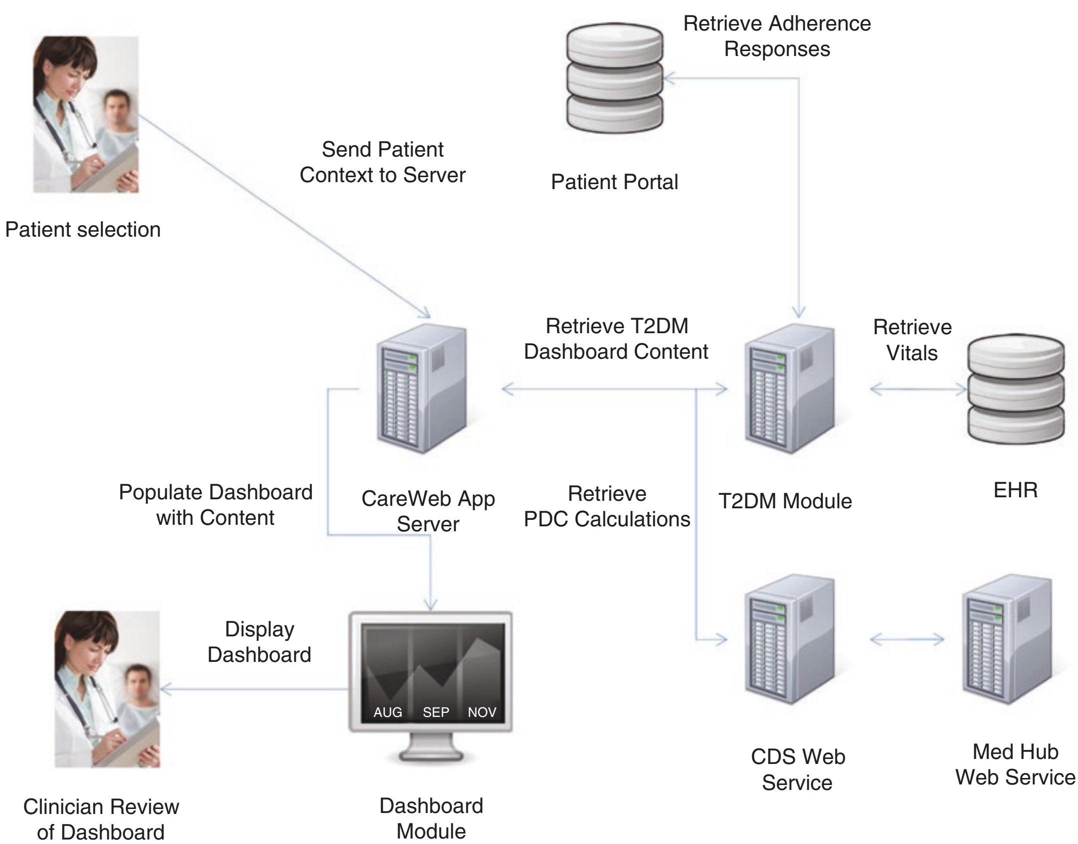

Fig. 6.1 Information architecture for a clinical dashboard that integrates and displays information for a patient with type 2 diabetes from multiple sources, including laboratory, medication, and patient entered information. This figure first published in the *Journal of Medical Internet Research (JMIR) Medical Informatics* [17]. *EHR* electronic health record; *CDS* clinical decision support; *T2DM* type 2 diabetes mellitus; *PDC* proportion of days covered (by a medication)

will specify the data standards to be used by the ICT to ensure the data can be interpreted and shared by the organization with partners. Such detail is not necessarily included in an information architecture.

Given that public health organizations increasingly collect, store, manage, and use an ever growing array of data and information to support complex business processes, the term *enterprise architecture* is often used to describe the approach used at the higher levels of the agency to organize data, information and ICT systems. The difference between an IA and an EA (enterprise architecture) is the scale to which the information system is used within the organization. Whereas an IA might provide the blueprint for an immunization information system used within a single division of the health department, the EA will provide a blueprint for how various ICT systems, such as the laboratory, syndromic, and case-based surveillance systems, connect or interoperate to support the tracking of infectious disease outbreaks across the agency.

An Information Architecture Unlocks Potential for Public Health Organizations

A robust IA for public health (PH) can enable organizations to more comprehensively assess, manage, and improve population health. For example, a robust IA would not only allow PH organizations to better connect the information systems already in use within PH, but also to connect to external information systems. Public health organizations may wish to connect to information systems operated by health care organizations, other governmental agencies (e.g., police, housing, environmental), or social service organizations who provide housing or other services to individuals in a community. Consider the following scenarios and how an IA would support public health functions in a community.

Surveillance of Chronic Diseases

While many jurisdictions have laws that require the reporting of communicable or infectious diseases, such as measles, tuberculosis, and gonorrhea, few jurisdictions have access to information on the rates of heart disease, diabetes, or other non-communicable or chronic diseases. In the US, the CDC uses the Behavioral Risk Factor Surveillance System (BRFSS) to collect data on individuals who may have received a chronic disease diagnosis from a healthcare provider. While data on prevalence are available at state and county levels, local health departments remain challenged to examine disease data in detail within their county or city. Integrating electronic health records from hospitals or physician practices with the data from the BRFSS could enable local health departments to better track disease rates over time as well as assess whether individuals diagnosed are receiving health services [18]. A robust IA might depict how the PH organization could interface with EHR systems or other PH information systems to better capture information on chronic disease rates and services. A robust IA for public health can enable better tracking of chronic disease and evaluation of PH interventions that could potential reduce chronic disease burden in a community.

Responding to Community Needs

In 2017, the US Department of Health and Human Services (HHS) declared a public health emergency in the United States to address an epidemic of opioid-related overdoses, many of which resulted in death. Data from the CDC [19] identified the following trends with respect to overdose-related deaths:

- From 1999 to 2017, more than 700,000 people died from a drug overdose. The number of overdose deaths in 2017 was 6 times higher than in 1999.
- Around 68% of the more than 70,200 drug overdose deaths in 2017 involved an opioid.
- An estimated 130 Americans were dying each day from an opioid overdose.

In response to the opioid epidemic, many local health departments have begun to explore ways to connect their infrastructures to information sources outside their organization. For example, poison control centers capture data on individuals who call following an opioid poisoning event. Emergency medical services (EMS) organizations collect data on individuals who overdose on opioids and need medical intervention. A robust IA for public health might depict how information systems at EMS organizations and poison control centers might be connected with available PH information systems to more comprehensively capture, manage, and analyze data on opioid-related events [20]. When developed, a robust IA could enable health departments to better assess and intervene to reduce opioid-related incidents.

A Model Information Architecture for Public Health

A robust IA for public health must standardize data and information across four fundamental dimensions:

1. Who received public and/or private health services?

   A PH infrastructure must capture information about individual(s) who have diseases, experience injuries, receive vaccinations, and/or are exposed to environmental hazards.
2. Who provided the health services?

   A PH infrastructure must capture information regarding provider(s) who diagnose a person with a disease/condition/exposure and/or provide treatment to an individual. This includes clinical providers, PH nurses, as well as disease investigation specialists (DIS officers).
3. Where were health services received?

   In a fragmented health care delivery system, individuals receive treatment or preventative services at numerous locations. The PH infrastructure must capture information describing the location where vaccines were delivered, treatment was performed, and/or the individual was exposed.
4. What specific care was provided?

   The PH infrastructure must capture information on what happened during an encounter. What vaccine was given? What was the laboratory result that confirmed a suspected diagnosis? How was the environmental exposure identified?

The architecture in Fig. 6.2 depicts several technical components that enable a public health organization to capture, store, manage, and share information across the four key dimensions. The architecture is based on the *service-oriented architecture (SOA)* concept in which discrete, interoperable services function together as an information system. Each component of the architecture can be a different software application or Web-based service. While each component plays a critical role, the sum of the system is greater than its individual parts.

Components of the model information architecture:

1. A *client registry* (CR) manages the unique identity of people receiving health services or diagnosed with disease—"For whom"
2. A *health worker registry* (HWR) is the central authority for maintaining the unique identities of health providers—"By whom"
3. A *facility registry* (FR) serves as a central authority to uniquely identify all places where health services are administered—"Where?"
4. A *terminology service* (TS) serves as a central authority to uniquely identify the clinical activities that occur within the care delivery process by maintaining a terminology set mapped to international standards—"What?"
5. A *shared health record (SHR)* is a repository containing the normalized version of content created within the community, after being validated against each of the previous registries. It is a collection of person-centric records for patients with information captured by the health agency.
6. A *health management information system (HMIS)* stores aggregate health care data, such as disease incidence rates as well as quality indicators like the proportion of individuals screened for Hepatitis C. These indicators are routinely collected measures defined by PH organizations, including medical societies, CDC, or payers.

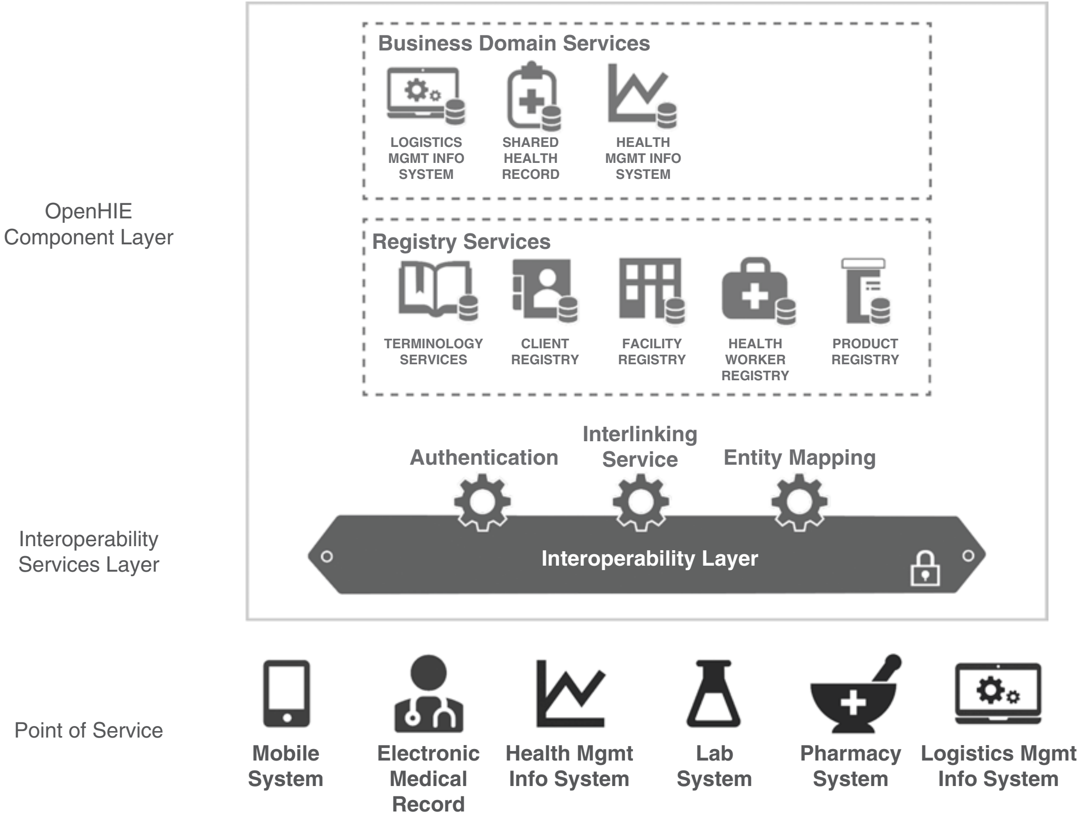

Fig. 6.2 Example of a generic information architecture that depicts how various information systems deployed in a health system could interoperate with common components deployed within a ministry or state health department. Original image, used with permission, is available at ohie.org. Reproduced with permission from OpenHIE, *Architecture Framework*, OpenHIE: an Open Health Information Exchange Community, Copyright © 2019 OpenHIE. Available from https://wiki.ohie.org/display/documents/OpenHIE+Architecture

7. An *interoperability services layer* receives all communications from point of service applications within a specified population, and orchestrates message processing among the point of service application and the hosted infrastructure elements. This component handles security and authentication from trusted external systems. Other industries refer to this as an enterprise systems bus (ESB).
8. An *interlinking service* is an application that links health workers to facilities where they are credentialed or assigned by the ministry.
9. *Entity mapping* links duplicate records. This could match entities to determine if there are potential matches within a single list or across two lists. This function can be used with any entity, but has been most often used with patient demographic records to link an individual patient's records from disparate systems or to match facility records across different systems.
10. *Point of service systems*, such as an electronic health record (EHR), laboratory information systems, and mHealth applications, are used by clinicians and by other PH workers to access and update person-centric shared health information and record healthcare transactions.

Furthermore, this SOA-based architecture offers flexibility, allowing health departments to add other, trusted external applications, such as a syndromic surveillance system, or a different kind of data store, such as a de-identified repository of survey data, to the architecture. The SOA approach enables many kinds of applications, services, and repositories to co-exist, provided they are integrated in a manner that allows them to leverage and be leveraged by the rest of the architecture. A health department may have use for multiple kinds of repositories for various legacy (e.g., vital records system) and new (e.g., social media) data types. As long as the repositories are exposed through the interoperability layer to apps and services, an infinite number of options are available for deployment.

Technical Approaches to Supporting the Infrastructure

There exist multiple technical solutions for supporting the IA for a PH organization. Historical approaches relied primarily on large mainframe computers, centralized computing machines that were only accessed by a few people within the organization. As technology evolved, organizations deployed multiple physical servers (fast computers that were much smaller than a mainframe) to meet the different needs of the divisions within a health department (e.g., HIV server, STD server, immunization server). Employees would connect their desktop computers to various servers to access information or input data into a particular server-based application. Software was also installed "locally" on the machine used by the PH professional. Many PH organizations continue to use servers as well as desktop machines that run local software.

An important trend in the computing industry is virtualization. *Virtualization* refers to the creation of a virtual representation of a physical machine or "local" software application. Whereas software would typically be loaded onto the machine used by a PH professional, a virtualized application operates remotely—usually this application is running in a virtual "machine" or operating system that sits on top of a powerful server. Thus a PH organization can invest in a small number of physical servers that can run many virtual machines and applications. The technology for virtualization has existed since 2008, yet many organizations are just now replacing their legacy infrastructure with virtualized environments and applications, including PH organizations.

While many virtual machines (VMs) are created and run on top of physical servers that are purchased and operated by the PH organization, VMs can also operate in the cloud. Cloud computing is also a decade-old technology that scales up the concept of virtualization. Much like a cloud in the sky is composed of millions of water molecules that together form what appears to be a singular object to the human eye, a computing *cloud* is a collection of computers operating remotely, via the Internet, that appear to be a singular system. The computers share resources (e.g., CPU cycles, memory) with one another so a VM or virtual application can run smoothly even though it might be operating off computers on the other side of the country or world. PH organizations now have the opportunity to install software applications and run VMs in the cloud just as easily as they can off physical servers in their computer room.

There are multiple options for a PH organization to use the cloud to virtually support all or some of its technical infrastructure. These options exist along a continuum from no use of the cloud to complete virtualization using the cloud. The options are depicted below in Fig. 6.3, which distinguishes whether a specific component of the IA in a PH organization would be locally hosted on hardware (e.g., servers, physical machines) or virtualized in the cloud therefore hosted by a third party (e.g., vendor, another PH organization like CDC). The options are now briefly introduced and described:

- Locally Hosted: In this scenario, the PH organization would not use the cloud at all. Instead, the organization would use internal hardware (e.g., servers) to host an application (e.g., cancer registry) and its associated data. Any virtualization would occur on hardware owned and managed by the PH organization.
- Infrastructure as a Service (IaaS): In this scenario, the PH organization employs the cloud to

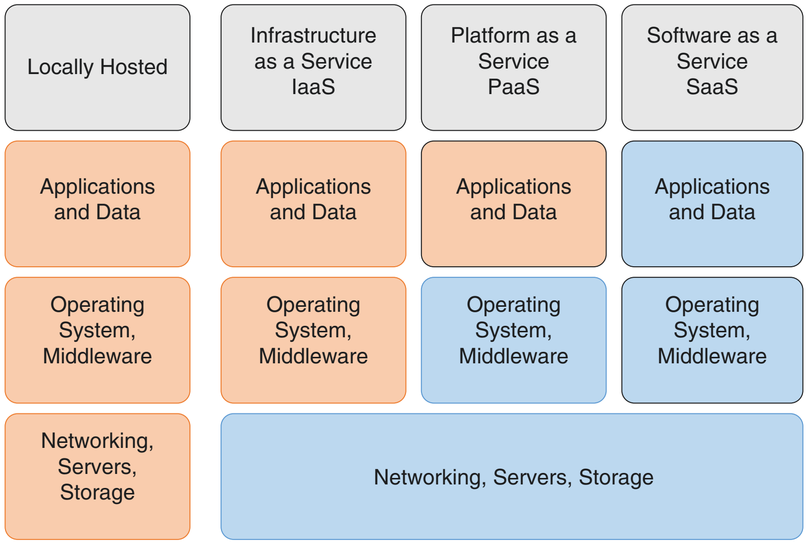

Fig. 6.3 Comparison of cloud-based service options for a PH organization to consider for its technical infrastructure. The components of a system highlighted in orange correspond to those locally hosted on hardware or virtual machines managed by the PH organization. The components highlighted in blue correspond to those hosted virtually in the cloud by a third-party vendor or organization

virtualize some aspects of the infrastructure for a system. A virtual data center is deployed to allow the PH organization to manage remote servers and storage. The PH organization manages the operating systems that run on VMs, the data on the remote storage, and the applications that run on the VM operating systems. An example of IaaS is Amazon Web Services or AWS.

- Platform as a Service (PaaS): In this scenario, the PH organization uses more cloud-based services to virtualize its technical environment. In addition to a virtual data center, the PH organization uses third-party organizations to manage the operating systems and other "middleware" components of its infrastructure. The only aspects of its environment managed by the PH organization are the software applications that run in the virtual environment as well as the data captured, stored, and used by the organization. An example of PaaS is Windows Azure.
- Software as a Service (SaaS): In this scenario, the PH organization uses the cloud for every aspect of a system or service. In addition to virtual servers and operating systems, the applications and their data are managed remotely in the cloud. This kind of service could be used for a specific use case in public health (e.g., immunizations, electronic lab reporting), or it could be used for an entire division within the organization. Examples of SaaS include Dropbox, Zoom, and Google Apps (e.g., Google Docs).

The "right" option for an organization to use in a given use case will vary based on its needs and its comfort with virtualization. For example, smaller organizations may lack the ability to procure expensive hardware and experienced staff who can manage complex systems. Yet cloud-based solutions might also be overkill for many things a small health department may need to do. Many states and the CDC are using a variety of cloud-based solutions for various aspects of their infrastructure. For example, the CDC is using AWS to virtualize national syndromic surveillance efforts so that state and local health departments can remotely manage their syndromic data and the CDC can scale the computing power needed to meet the demands placed on the system as more jurisdictions join the network.

Important to the selection of whether some or all of an organization's infrastructure should be virtualized is security, as many PH information systems contain protected health information. More information on security and privacy can be found in Chaps. 9 and 10.

Illustrations of Robust Public Health Information Architectures

Consider the following scenarios involving a robust IA for public health in which PH information systems connect and exchange data with other PH information systems or external information systems that add value in support of PH functions in the community.

Immunization Records

An immunization information system (IIS, also known as immunization registry) is a classic example of a public health informatics application. An IIS maintains a longitudinal, person-centric record of immunizations given to an individual over his or her lifetime and supports providers in delivering age-appropriate immunizations, leading to improved vaccination coverage. The main functions of IISs are to:

- Consolidate immunization data from disparate sources;
- Provide patient-specific vaccine forecasting/decision support based on known immunization history and patient age;
- Support the creation of reminder and recall notices;
- Support proper vaccine inventory management; and
- Generate vaccination coverage assessments.

IISs exist in most states, and, as of 2011, 84% of US children aged <6 had two or more immunizations recorded in an IIS [21]. IISs are adept at receiving both batch and real-time information from clinical information systems in a variety of formats, but less frequently provide two-way, real-time information exchange and synchronization between EHRs and the IIS [22]. For example, clinicians often access IISs through standalone applications, independent of their EHR systems, in order to view patient immunization histories and vaccine forecasts. Stage 3 Meaningful Use regulations issued in 2017 from CMS require EHR systems to enable information exchange with an IIS, promoting interoperability across the health ICT ecosystem.

Bidirectional exchange requires that the public health technical infrastructure be capable of receiving and sending messages with clinical and other health information systems. When a message arrives at the health department, it must pass through the interoperability services layer (recall Fig. 6.2) and match to a patient record in the shared health record. This is facilitated by a call to the client registry, which attempts to link the incoming message to an existing patient. If no match is found, then a new patient record can be created. Next, the interlinking service within the interoperability layer matches information in the immunization message to records in the health worker and facility registries, respectively. Here the system seeks to ensure that the provider administering the immunization and the facility where the immunization was given match valid providers and facilities in the jurisdiction. Finally, the system calls the terminology service to match the information about which immunization(s) were administered to the patient or the reason(s) for refusal. Standardized vaccine data, such as CVX codes developed and maintained by the CDC, provide the name of the vaccine along with the manufacturer name and lot number [23]. Once the various parts of the incoming message have been matched to client, provider, facility, and terminology data, the information in the message can be stored in the shared health record. The infrastructure now supports storing millions of immunization events in the shared health record, along with other existing information about the individuals—such as birth certificate records.

The other function of an IIS is to provide decision support to providers, informing nurses and physicians when a patient is overdue for certain immunizations (e.g., pneumovax for adults over 65). A shared public health infrastructure can support this through an interface with the IIS [24]. A physician can use the IIS to query the infrastructure to receive an immunization history and recommendations on overdue items. The IIS calls the health interoperability layer, which uses the client registry to locate all immunization records in the shared health record for the selected patient. The raw immunization records are then passed back to the IIS, which can deliver them to the requesting physician, along with recommendations derived from the shared health record. The IIS and infrastructure work together to manage person-centric immunization data.

Electronic Laboratory Reporting

Electronic laboratory reporting (ELR) involves the transmission of laboratory data, following the confirmation of a reportable disease, to a public health agency. ELR has been used successfully in a number of cities, states, and nations to improve public health surveillance [25, 26]. Public health agencies that have implemented and used ELR report a number of benefits. First, notifiable disease reports that arrive electronically arrive faster than the previously used paper-based reports [25–27]. Second, ELR has been shown to improve reporting rates, or the proportion of disease cases that are reported to public health [25–28]. Thus ELR can address the problem of underreporting of disease cases [29, 30].

Most states in the US have some capacity to receive electronic reports from laboratories [31]. Given variable adoption rates, routine ELR was made a requirement in the regulations for both Stages 2 and 3 of the CMS Meaningful Use Program as well as the 2018 Promoting Interoperability Program. Laboratory information systems are required to electronically submit laboratory results to EHR systems for delivery to clinicians, and hospitals are encouraged to electronically report laboratory results for notifiable disease cases to public health departments using their EHR system.

ELR can leverage a common public health infrastructure by connecting lab information systems to the health interoperability layer. As lab messages arrive, the patient, provider, and facility information can be matched to respective records in the client, provider, and facility registries. The vocabulary service interprets the Logical Observation Identifiers Names and Codes (LOINC®) codes, which identify the test performed by the laboratory [32], and the Systematized Nomenclature of Medicine-Clinical Terms (SNOMED CT®) codes, which identify organisms, substances, diseases, and other findings from the lab test [33]. Data from the ELR messages could then be stored in the shared health record, linking multiple tests performed on the same individual to aid in case investigation procedures. The shared health record would also link ELR information to immunization history and other clinical observations known by the health department about an individual. Other information systems in the health department could query or extract data from the shared health record to aggregate counts of reported disease or examine relationships between immunization history and diagnoses for vaccine-preventable disease.

Electronic Case Reporting

Electronic case reporting (eCR) is another electronic method for reporting a case of infectious disease to a public health authority. Whereas ELR messages are sent from the laboratory, eCR messages are sent from physician practices or hospitals. These messages include details beyond what can be sent in an ELR message, such as the patient's disposition at the time of clinical diagnosis. An eCR message might also contain details about the patient's vaccination history, social determinants, and symptoms. These details can be used by DIS officers at the health department to identify suspected or probable cases prior to laboratory reporting.

In Stage 3 of the CMS Meaningful Use Program as well as the 2019 Promoting Interoperability Program, CMS promoted eCR as a valid public measure for hospitals. The requirement nudges hospitals to move "towards sending 'production data'" to public health authorities in their jurisdiction.

To advance the transition towards eCR, the *Digital Bridge* initiative, a broader effort aimed at improving the PH infrastructure in the United States [34], facilitated a series of pilot programs across the US [35, 36]. In each pilot, public health authorities received 'production data' from hospitals via automated electronic messages sent from EHR systems. Major EHR vendors partnered with the Digital Bridge consortia to implement standards-based exchange of data on notifiable disease cases with local and state public health authorities. A more experimental demonstration project involving the CDC, Georgia Tech Research Institute, and the Regenstrief Institute, leveraged the emerging standard FHIR (Fast Health Interoperable Resources, detailed in Chap. 18) to query eCR data elements from an EHR following the receipt of an ELR message from a physician practice [37].

A robust IA for public health could include a case management system (e.g., the CDC's NBS) that receives eCR messages from hospitals, physician practices, and other public health jurisdictions. The IA might include a system that receives the external communications and performs routine linkage or de-duplication with internal systems before adding new cases to the case management system, involving the client registry, facility registry, and terminology service.

Bidirectional Communication

Public health has a responsibility to both monitor disease and inform the community on events involving disease spread and management. Thus, the public health infrastructure requires the capacity to both receive data from health care information systems and deliver information to clinical systems. In other words, the public health infrastructure needs to support bidirectional communication with EHR and other health information systems. Informing front line clinical staff about population health outcomes and events using a common infrastructure is form of public health decision support, described and detailed further in Chap. 20.

Health departments often communicate community-level information or statistics to physician offices and hospitals using postal mail or electronic newsletters [38]. As the public health infrastructure becomes more interoperable, bidirectional communication from public to clinical health information systems is likely to increase [39]. The common infrastructure we describe supports bi-directional communication in a variety of scenarios, such as:

1. *Public health alerts*, used to raise a clinician's index of suspicion for known or as of yet unidentified disease or condition emerging in the community. For example, one study utilized a common clinical infrastructure outside the EHR to deliver guidance and information on vaccine supply management to primary care clinicians during the H1N1 outbreak [40]. Other studies have examined methods for pushing alerts directly into EHR systems based on increased reports of shigellosis or another reportable disease [41, 42].
2. *Routine population health statistics* to support healthcare organizations and their increasing responsibilities for patient population health management. By making health statistics and research results more readily available to support clinical decision-making, both the clinician and the patient are enabled to make better-informed decisions about a course of treatment.
3. *Person-specific case management* or other information to support coordinated care management between clinical and public health.

A common infrastructure in public health can support knowledge repositories and applications that push alerts and information out to providers using the health interoperability layer. Provider and facility registries can contain electronic addresses for providers that enable routing of messages both to and from clinical information systems.

Role of Organizations: Managing the Public Health Infrastructure

Public health organizations manage the public health infrastructure. They carry out their duties in three ways:

1. By *creating and enforcing policies*, public health organizations define the scope of the public health infrastructure.
2. By *organizing work*, public health organizations define the business processes that drive the public health infrastructure.
3. By *managing people*, public health organizations define how and when the workforce can access and use public health data and information.

The work performed by public health agencies is diverse and expansive in nature. The Institute of Medicine [43] defines three core functions of public health: (1) assessment and monitoring of the health of communities and populations at risk to identify health problems and priorities; (2) formation of public policies to solve identified local and national health problems and priorities; and (3) assurance that all populations have access to appropriate and cost-effective care, including health promotion and disease prevention services, and evaluation of the effectiveness of that care.

The nature of public health is shifting in the twenty-first century. Whereas public health activities have in the past largely focused on monitoring and intervening in the spread of communicable diseases (e.g., polio, tuberculosis, HIV/AIDS), chronic and environmental threats are increasing in prevalence. Therefore, while agencies must continue to record data on the spread of infection and fight emerging diseases that spread quickly, efforts at many public health organizations are expanding into community-based interventions to improve self-management of chronic illness and complex physical/social/behavioral interventions to prevent environmental and chronic disease in healthy populations. Furthermore, the Patient Protection and Affordable Care Act (PPACA) of 2010 requires private ACOs to conduct annual population health assessments, blurring the traditional line between private and public health organizations.

Therefore, the technical infrastructure described here is a suggested core designed to support a wide range of public health functions. However, unique laws, regulations, and requirements of a given public health organization may necessitate amendments or additions. As new policies are enacted that change the nature of public health work, the infrastructure that supports public health will need to be amended.

This point is illustrated in the National Institute of Standards and Technology's Enterprise Architecture Model, which emphasizes that an organization's business processes should drive its infrastructure [44]. Effective management of the public health infrastructure will require organizations to understand its business processes and the needs of public health workers. Otherwise, health departments will suffer the same fate as the one in New Jersey, where the introduction of ELR led to a significant increase in the completeness of disease reports, but it "exceeded local investigative capacity" [45].

Business Process Analysis and Redesign

A business process describes a set of activities and tasks that logically group together to accomplish a goal or produce something of value for the benefit of the organization, a stakeholder, or a customer [46]. In the context of public health, a business process is intended to support the needs of the health agency, community, or a target population. Because information technology and services facilitate business processes, a clear understanding of these processes is needed to ensure that public health informatics strategies will result in maximally effective and efficient support of public health needs.

Documenting business processes and redesigning them to meet the challenges associated with (a) the shift from acute to chronic disease surveillance and (b) increasing electronic data flows from clinical health, can be achieved using business process analysis (BPA). BPA gathers information from stakeholders about existing processes with an eye towards redesigning the processes to improve efficiency or enhance the value they produce. This technique has been utilized by the Public Health Informatics Institute (PHII) to redesign and enhance multiple business processes in the context of public health. For example, PHII has defined functional requirements for immunization information systems [47] and public health surveillance [48]. BPA is further recognized and recommended as a best practice for achieving the Public Health Informatics agenda [15].

User-Centered Approach

In addition to analyzing and redesigning business processes, public health organizations need to understand end users' (public health workers') information needs [49]. Asking and involving users in the design, development, and implementation of the infrastructure will maximize the likelihood that ICT in agencies meets not only the business needs but also the context of use.

User-centered approaches require early and frequent involvement of frontline public health workers. When designing a system or process, workers should be asked about their needs. Low fidelity prototypes or wireframes (e.g., hand drawn illustrations or simple computer mock ups) can be used to elicit and identify user needs before any system engineering work has been done [50], reducing cost to make changes after implementation. If purchasing a commercial system, users can review screenshots, process diagrams, and interact with demo systems to provide feedback to the group in the organization making purchasing decisions. Usability testing can also be performed where end users attempt to complete certain tasks using an information system [51]. Vendors can be asked to make a test or demo system available to the organization for such testing during the evaluation process if specified in request for proposal documentation.

The Role of the Public Health Workforce

People are the third component of the public health infrastructure. Managing the PH infrastructure requires a knowledgeable and capable workforce of individuals who can effectively use the information resources in a PH organization and individuals who implement, support and enhance ICT systems for the PH organization. Multiple roles across the public health workforce require competencies in informatics [52]. Organizations must train and prepare four types of PH workers:

1. Executives—State health officers, county health officers, branch chiefs, and others who *lead a PH organization or division*. Leaders in PH organizations must understand what informatics is and how it contributes to the functions of public health. Leaders must further establish a vision for informatics within their organization, outlining how they see their organizations achieving transformation through the implementation and use of a robust information infrastructure.
2. Managers—Individuals who *direct or coordinate a PH program*. Managers in PH organizations must select and implement information systems that will support their program area. While managers might receive assistance from an informatician in these decisions, all managers should have some foundational informatics competencies that support them making strategic decisions about which information systems and functions are implemented. Managers must also facilitate conversations with their employees to determine information needs of the group.
3. End users—Epidemiologists, communicable disease nurses, food safety inspectors, and others on the front lines of public health who *interact with information systems*. These workers need training on the systems they use to conduct the business of public health. They further require support from managers and informaticians who can facilitate their information needs.
4. Informaticians are specialists who support PH organizations in the *design, management, and evaluation of information systems and work processes*. They often interact with others in the PH workforce to select, implement, and use ICT systems. More on these specialists follows.

Public Health Informaticians

The role of a public health informatician (sometimes called an 'informaticist') is defined by consensus-based competencies [53, 54] from the CDC, Association of Schools of Public Health

(ASPH), and American Medical Informatics Association (AMIA). These specialists in informatics provide critical services, such as the development of an IA for their organization, implementation of new ICT systems that meet end user needs, and collaborative work with partners to realize interoperable, robust PH ICT systems.

Public health organizations must hire or train informaticians to meet their informatics needs. An increasingly popular role within PH organizations is a Chief Public Health Informatics Officer. This senior leadership position bridges the gap between public health program areas, the ICT department (which might be an external, central division of government), and the senior health officer. This individual has the responsibility to set an informatics vision for the organization, which often aligns the overall mission and vision of the organization with the data and information needs of the organization. An informatics officer usually provides oversight of key ICT systems to ensure they are meeting end users information needs, and she may also direct the selection of new ICT systems to improve PH operations (in collaboration with the appropriate division chief or program manager).

Currently just one percent (1%) of the US public health workforce includes individuals who self-report they serve in an informatics role [55, 56]. The most recent fielding of the Public Health Workforce Interests and Needs Survey (PH WINS) [55] identified the prevalence of informaticians within the broader US-based PH workforce. At the state level, 1.1% of PH employees identified themselves as working in an informatics role. At the local level, just 0.3% of PH employees self-identified as an informatician. Furthermore, fewer than one-third of informaticians reported working in an informatics program area. Respondents who did not work in an informatics area reported working in other common program areas, including epidemiology and surveillance, vital records, and administrative support.

Given the findings from the PH WINS, there is a need to train and mentor additional PH workers into informatician roles. The CDC, Council for State and Territorial Epidemiologists (CSTE), and some academic organizations are preparing epidemiologists and others to become informaticians through MPH as well as post-doctoral training programs. For example, the Fairbanks School of Public Health, part of Indiana University, features an MPH program where students complete courses on informatics, analytics, and data management on top of their core training in leadership, communication, epidemiology, and other core PH disciplines [57]. Internships and other applied experiences part of the academic program focus on managing informatics within a PH organization rather than a specific program area or PH function. The individuals who complete such a program would serve as informaticians within a PH organization.

For the foreseeable future the US will require additional training and mentoring programs to meet the growing demand in jurisdictions for informaticians. Furthermore, model job descriptions are needed to ensure consistency in the role of public health informatician across jurisdictions as few PH organizations have a defined informatics program area.

Public Health End Users

The growing need for public health informatics competencies will further require schools of public health to produce available candidates for positions that will work to modernize information systems and strategically align information needs with work processes. Faculty in public health schools will either need to create informatics concentrations or specializations within epidemiology degree programs, or they may collaborate with schools of information, computing, or informatics to offer joint majors or minors in public health informatics. These programs will provide modern competencies to public health professionals, which can be leveraged by departments to train existing personnel. While some universities have such programs, additional programs are needed to ensure future public health workers have the right set of informatics competencies [58].

Public health professionals across the infrastructure will need some understanding of informatics, ICT, and how information is central to work processes. Specifically, as identified via the PH WINS [55], non-informatics specialists identified significant gaps in their ability to "identify appropriate sources of data and information to assess the health of a community" and "collect valid data for use in decision making." Such core knowledge as a component of training in public health will help the workforce collaboratively work towards improving public health systems and population outcomes.

The Indiana Network for Patient Care: A Real-World Instantiation of a Robust Information Infrastructure Supporting Public Health Processes

The Indiana Network for Patient Care (INPC) is the nation's longest-tenured and most comprehensive health information exchange (HIE) network. Researchers at the Regenstrief Institute created the INPC in 1995 with the goal of providing clinical information at the point of care for the treatment of patients [59, 60]. The architecture of the INPC inspired the IA described in this chapter, and the INPC remains an active technology laboratory influencing the evolution of the public health infrastructure given the examples below where the HIE is used to support a wide range of public health functions.

The primary use of the INPC is to improve communication and decision-making in the context of individual patient care. However, because the INPC standardizes incoming clinical and administrative data, the HIE network enables a wide range of secondary uses, including public health reporting and syndromic surveillance [59, 61]. For example, clinical laboratory test results are mapped to a set of common test codes (e.g., LOINC®) with standard units of measure for use in the following scenarios:

- Patient care—displaying all blood lead level measurements chronologically in a table or chart for clinician review;
- Public health—identifying elevated blood lead levels in pediatric patients reportable to public health; and
- Research—extracting address data for patients with elevated lead levels and integrating such information with the geographical locations from environmental studies identifying elevated soil lead levels.

These are similar activities to those in health departments around the world, and the INPC often partners with local and state health departments to facilitate access to data they need to support the core functions of public health.

The INPC Supports Public Health Use Cases

Since 1998, the Regenstrief Institute has maintained an operational, automated ELR system called the Notifiable Condition Detector (NCD) as a service provided by the INPC [62]. The NCD identifies clinical results that are positive for reportable conditions and automatically reports them to both local and state health departments in near real-time. Data sources (hospital, state health, and referral laboratories) transmit results to the INPC in electronic format. The NCD processes incoming ELR messages using LOINC® codes, ICD-based diagnoses, and natural language processing to determine if a test is potentially reportable, and the NCD uses the CDC reportable condition mapping table [63] to verify reportable conditions. Final results are shared with health agencies in a variety of formats including Health Level 7 (HL7®) and comma delimited files (CSV), based on the jurisdiction's technical capacity.

The INPC has further supported efforts to increase infection preventionists' (IP) awareness of patients' MRSA infection history and reduce the spread of healthcare acquired infections (HAIs) in INPC facilities. Over the course of one year, researchers found that 286 unique patients generated 587 admissions accounting for 4335 inpatient days where the receiving hospital was not aware of the prior history of methicillin-resistant *Staphylococcus aureus* (MRSA) [64]. These patients accounted for an additional 10% of MRSA admissions received by study hospitals over one year and over 3600 inpatient days without contact isolation. To improve physician and IP awareness of patients who should be in contact isolation given a history with MRSA or vancomycin-resistant *enterococcus* (VRE), Regenstrief first developed and implemented a clinical reminder to alert physicians when a patient on the contact isolation list did not have a standing order for contact isolation [65]. Then, Regenstrief scientists expanded this innovation to the INPC, alerting IPs when patients who had a history of MRSA or VRE were admitted to their facilities [66, 67]. In the first year, the INPC delivered 2698 admission alerts for patients with a history of MRSA, one-fifth of which (19%) were based on data from a different institution.

The Indiana Network for Population Health

While the INPC facilitates many use cases in public health, health departments in Indiana desire access to information beyond clinical health organizations. For example, health departments seek data on the social determinants of health as well as environmental exposures. Therefore, building upon the success of the INPC, the Regenstrief Institute is partnering with multiple public health and community organizations to develop the Indiana Network for Population Health (INPH).

The INPH links clinical data available in the INPC with information systems in local and state public health organizations as well as environmental sensors, EMS systems, and other governmental data resources. For example, a local health department might wish to track environmental exposures of individuals who were born in a certain geographic region during a 3–5 year time period in comparison to a sharp rise in skin cancer diagnoses among young men. Another epidemiologist at a state health department might be interested in a potential linkage between social determinants, such as the proportion of individuals who lack a college education, and vaccination rates among young children across several counties in an urban area.

The INPH is an initiative in its early stages at the time of publication. The network and use cases will develop and expand in the coming years as public health departments gain experience working with a robust IA to enhance their ability to capture, analyze, and share population health information.

The Indiana Addictions Data Commons

One of the first use cases to illustrate the concept of the INPH is the Indiana Addictions Data Commons (IADC). The IADC was initiated by the Regenstrief Institute in response to Indiana University's "Addictions Grand Challenge." The program challenged researchers to focus on addressing the opioid epidemic through multidisciplinary, multi-sector research projects [68]. Each project, 32 in total, involved a different set of partners from the community working to examine needle exchange programs, neonatal abstinence syndrome, overdose risk factors, etc. The projects all had information needs, yet there existed no central resource to support accessing the data necessary to conduct research that spans medical, behavioral, social service, and governmental sectors.

The IADC was created to support the information needs of the groups examining opioid use disorder, opioid overdose events, etc. The IADC provides a more streamlined mechanism for those interested in obtaining both clinical and non-clinical data, which have largely remained in the "silos" of various organizations. The IADC will facilitate better understanding of the breadth and depth of information available and enable easier, more standardized access for research as well as routine public health practice.

Summary

The public health infrastructure requires a skilled public health workforce, robust ICT, and effective organizations. This chapter reviewed a model ICT architecture, examples where information systems are supporting effective public health practice, key informatics factors for managing organizations, and important informatics aspects of the workforce. These dimensions of the public health infrastructure are complex and evolving. One thing that is clear is the public health infrastructure will change as health reform is implemented and additional information systems are adopted in both clinical and public health. The principles and lessons in this chapter, however, should help guide informaticians seeking to design, implement, evaluate and evolve ICT across the public health infrastructure.

Future Directions

The public health infrastructure of the future will consist of a robust IA that interconnects ICT systems within a PH organization as well as ICT systems from health care and social service organizations that support achievement of the vision outlined in Public Health 3.0 [69]. This vision, outlined by the US Department of Health and Human Services, seeks to have PH organizations form vibrant, structured, cross-sector partnerships in which they leverage timely, actionable data and metrics to guide population decision-making. Achieving this vision requires the broader PH ecosystem to focus on the following:

- Intelligent Public Health Systems
- Interoperability
- Infrastructure Investment

Intelligent Public Health Systems

While many PH organizations are currently in the process of implementing Public Health 2.0 (e.g., the Neolithic Revolution described earlier), in which manual, paper-based processes are replaced with ICT systems, it is time for PH organizations to move towards the development, implementation, and use of artificial intelligence for core public health functions. Health care organizations, as well as other sectors (e.g., retail, transportation), are embracing a growing number of applications in which "Big Data" are rapidly analyzed to inform and improve operations. Artificial intelligence applications, such as machine/deep learning, could be used by PH organizations to discover emerging infectious diseases or assess the impact of a community-based program to connect new mothers to prenatal care.

Intelligent systems that facilitate "learning public health systems" towards the vision of Public Health 3.0 will require significant changes to the current PH infrastructure. Traditional client-server systems and analysis tools installed on individual workstations will need to be replaced with cloud-based and software-as-a-service models. Computing power will need to come from the larger, collective ICT community rather than expense servers purchased by PH organizations. File systems and relational databases will likely need to be used in combination with NoSQL data stores, as well as application programming interfaces (APIs). These newer models of data management and information architectures will facilitate innovation in how PH organizations get their work done, yet they are dramatic changes from how PH organizations have collected, stored, managed, and used data in the distant and recent past. The transition will require strategic thinking and planning from skilled informaticians working in partnership with PH leaders and non-PH organizations.

More information on "Big Data" and analytics is available in Chap. 12.

Interoperability

While some PH organizations currently participate in HIE networks (such as the INPC) or interconnect their vital records systems with their surveillance systems, achieving the vision of Public Health 3.0 will require a strategic effort to embrace the concept of interoperability and deploy interoperable ICT systems that interconnect not only within health departments but with health care organizations, social service organizations, other governmental agencies, and private-sector organizations. Currently the US Office of the National Coordinator for Health Information Technology (ONC) is focused on interoperability of ICT systems used by health care delivery organizations. This kind of focus is needed in public health which arguably requires more interconnectivity with partners as well as the other levels of the public health system (e.g., local, state, federal).

Interoperability will require PH organizations to strategically invest in ICT systems that can be connected to other ICT systems. Moreover, an interoperability strategy will require PH organizations to implement newer technologies, such as APIs, that will enable partners access to PH data in near real-time. Reciprocally PH organizations will need to stream data from external APIs to drive analysis and decision-making with respect to population health. Furthermore, interoperability will require stronger governance of shared data assets across the enterprise and the development of a culture of sharing when it comes to public health data and information.

More on interoperability and HIE can be found in Chap. 18.

Infrastructure Investment

Achieving the vision of Public Health 3.0 will require significant investments in modernizing the public health infrastructure. New ICT systems, cloud-based IA models to enable intelligence, and an emphasis on interoperability will require significant funding from federal, state, and local sources. A typical organization spends 5–10% of its budget on ICT infrastructure each year, which includes the desktops used by end users, enterprise servers, and the individuals who support the ICT environment. Public health organizations will need to increase their investment in ICT to complete the Neolithic revolution and begin the transition to an intelligent Public Health 3.0 environment.

Funding for public health has been historically weak. Furthermore, recent trends have been downward with PH budgets cut at the local, state, and federal levels. This is true even for PH informatics. For example, the CDC previously offered an extramural, interprofessional education program (referred to as SHINE), which included training in place for public health agency staff as well as fellowship positions throughout the country. However, SHINE lost funding in 2017. Similarly, we have observed cuts in funding to informatics programs in the large, national PH associations that have greatly reduced their activities to build and support the existing network of informaticians in PH. In response, several professional organizations have begun lobbying the US Congress to invest $100 million in new funding for CDC to modernize the PH infrastructure [70]. This campaign, dubbed "Data: Elemental to Health," seeks to garner support for an investment in CDC to facilitate upgrades in the PH infrastructure that align with the many concepts described in this book: syndromic surveillance, eCR, laboratory information systems, workforce, and vital records. An investment of this magnitude would be required to initiate a transformation towards Public Health 3.0. However, it is likely that the US would need to invest further, and strategically partner with health care and private organizations, to achieve a full transformation of the PH infrastructure.

Review Questions

1. Describe the three components of the public health infrastructure. How do they work together to support public health practice?
2. What challenges does the public health infrastructure face, and how can public health organizations respond to these challenges?
3. How can public health agencies leverage interoperable, health information exchange networks to support their mission of population health monitoring and improvement?

4. What is an information architecture? How can an IA drive change within a public health organization?
5. What does the information architecture of your public health organization look like? What two changes would you make to the IA to enhance the public health infrastructure in your organization?
6. What are the roles of a public health informatician in building and enhancing the public health infrastructure?

References

1. Centers for Disease Control and Prevention. Public health's infrastructure: a status report. Atlanta: Department of Health and Human Services; 2001.
2. Medicine Io. The future of the public's health in the 21st century. Washington, DC: The National Academies Press; 2003.
3. Buehler JW, Whitney EA, Smith D, Prietula MJ, Stanton SH, Isakov AP. Situational uses of syndromic surveillance. Biosecur Bioterror. 2009;7(2):165–77. https://doi.org/10.1089/bsp.2009.0013.
4. Lober WB, Karras BT, Wagner MM, Overhage JM, Davidson AJ, Fraser H, et al. Roundtable on bioterrorism detection: information system-based surveillance. J Am Med Inform Assoc. 2002;9(2):105–15.
5. Lazarus R, Kleinman KP, Dashevsky I, DeMaria A, Platt R. Using automated medical records for rapid identification of illness syndromes (syndromic surveillance): the example of lower respiratory infection. BMC Public Health. 2001;1:9.
6. Devore S, Champion RW. Driving population health through accountable care organizations. Health Aff. 2011;30(1):41–50. https://doi.org/10.1377/hlthaff.2010.0935.
7. The American Recovery and Reinvestment Act of 2009, House of Representatives, 111th Congress Sess. 2009.
8. Medicare and Medicaid Programs. Electronic health record incentive program--stage 3 and modifications to meaningful use in 2015–2017. Final rules with comment period. Fed Regist. 2015;80(200):62761–955.
9. Lenert L, Sundwall DN. Public health surveillance and meaningful use regulations: a crisis of opportunity. Am J Public Health. 2012;102(3):e1–7. https://doi.org/10.2105/AJPH.2011.300542.
10. Foldy S, Grannis S, Ross D, Smith T. A ride in the time machine: information management capabilities health departments will need. Am J Public Health. 2014;104(9):1592–600. https://doi.org/10.2105/ajph.2014.301956.
11. Dixon BE, Gibson PJ, Grannis SJ. Estimating increased electronic laboratory reporting volumes for meaningful use: implications for the public health workforce. Online J Public Health Inf. 2014;5(3):225. https://doi.org/10.5210/ojphi.v5i3.4939.
12. Williams KS, Shah GH. Electronic health records and meaningful use in local health departments: updates from the 2015 NACCHO informatics assessment survey. J Public Health Manag Pract. 2016;22(Suppl 6):S27–33. https://doi.org/10.1097/PHH.0000000000000460.
13. Olson D, Lamb M, Lopez MR, Colborn K, Paniagua-Avila A, Zacarias A, et al. Performance of a mobile phone app-based participatory syndromic surveillance system for acute febrile illness and acute gastroenteritis in rural guatemala. J Med Internet Res. 2017;19(11):e368. https://doi.org/10.2196/jmir.8041.
14. Whiteside U, Richards J, Huh D, Hidalgo R, Nordhauser R, Wong AJ, et al. Development and evaluation of a web-based resource for suicidal thoughts: NowMattersNow.org. J Med Internet Res. 2019;21(5):e13183.
15. Massoudi BL, Goodman KW, Gotham IJ, Holmes JH, Lang L, Miner K, et al. An informatics agenda for public health: summarized recommendations from the 2011 AMIA PHI conference. J Am Med Inform Assoc. 2012;19(5):688–95. https://doi.org/10.1136/amiajnl-2011-000507.
16. Yasnoff WA, Overhage JM, Humphreys BL, LaVenture M, Goodman KW, Gatewood L, et al. A national agenda for public health informatics. J Public Health Manag Pract. 2001;7(6):1–21.
17. Dixon BE, Alzeer AH, Phillips EO, Marrero DG. Integration of provider, pharmacy, and patient-reported data to improve medication adherence for type 2 diabetes: a controlled before-after pilot study. JMIR Med Inform. 2016;4(1):e4. https://doi.org/10.2196/medinform.4739.
18. Dixon BE, Zou J, Comer KF, Rosenman M, Craig JL, Gibson PJ. Using electronic health record data to improve community health assessment. Front Public Health Serv Syst Res. 2016;5(5):50–6.
19. Centers for Disease Control and Prevention US. Understanding the epidemic. Department of Health and Human Services, US, Atlanta, GA. 2018. https://www.cdc.gov/drugoverdose/epidemic/index.html. Accessed 17 Sept 2019.
20. Del Fiol G, Crouch BI, Cummins MR. Data standards to support health information exchange between poison control centers and emergency departments. J Am Med Inform Assoc. 2015;22(3):519–28. https://doi.org/10.1136/amiajnl-2014-003127.
21. Centers for Disease Control and Prevention. Progress in immunization information systems--United States, 2011. MMWR Morb Mortal Wkly Rep. 2013;62(3):48–51.

22. Grannis S, Dixon BE, Brand B. Leveraging immunization data in the e-health era: exploring the value, tradeoffs, and future directions of immunization data exchange. Atlanta: Public Health Informatics Institute; 2010.
23. Savage R. HL7 version 2.5.1 Implementation guide for immunization messaging. Atlanta: Centers For Disease Control and Prevention; 2012.
24. Centers for Disease Control and Prevention (CDC). Progress in immunization information systems - United States, 2012. MMWR Morb Mortal Wkly Rep. 2013;62(49):1005–8.
25. Effler P, Ching-Lee M, Bogard A, Ieong MC, Nekomoto T, Jernigan D. Statewide system of electronic notifiable disease reporting from clinical laboratories: comparing automated reporting with conventional methods. JAMA. 1999;282(19):1845–50.
26. Overhage JM, Grannis S, McDonald CJ. A comparison of the completeness and timeliness of automated electronic laboratory reporting and spontaneous reporting of notifiable conditions. Am J Public Health. 2008;98(2):344–50.
27. Panackal AA, M'Ikanatha NM, Tsui FC, McMahon J, Wagner MM, Dixon BW, et al. Automatic electronic laboratory-based reporting of notifiable infectious diseases at a large health system. Emerg Infect Dis. 2002;8(7):685–91.
28. Nguyen TQ, Thorpe L, Makki HA, Mostashari F. Benefits and barriers to electronic laboratory results reporting for notifiable diseases: the New York City Department of Health and Mental Hygiene experience. Am J Public Health. 2007;97(Suppl 1):S142–5.
29. Lombardo JS, Buckeridge DL, editors. Disease surveillance: a public health informatics approach. Hoboken: Wiley; 2007.
30. Doyle TJ, Glynn MK, Groseclose SL. Completeness of notifiable infectious disease reporting in the United States: an analytical literature review. Am J Epidemiol. 2002;155(9):866–74.
31. Turner K, Ferland L. State electronic disease surveillance systems --- United States, 2007 and 2010. MMWR Morb Mortal Wkly Rep. 2011;60(41):1421–3.
32. McDonald CJ, Huff SM, Suico JG, Hill G, Leavelle D, Aller R, et al. LOINC, a universal standard for identifying laboratory observations: a 5-year update. Clin Chem. 2003;49(4):624–33.
33. Value Proposition for SNOMED CT. International Health Terminology Standards Organization. http://www.ihtsdo.org/snomed-ct/value-proposition-for-snomed-ct/. Accessed 28 Nov 2011.
34. Public Health Informatics Institute. Digital bridge. 2017. http://www.digitalbridge.us/. Accessed 24 Feb 2017.
35. Digital Bridge. Implementation overview. 2019. https://digitalbridge.us/infoex/implementation/. Accessed 1 Jul 2019.
36. Black J, Hulkower R, Suarez W, Patel S, Elliott B. Public health surveillance: electronic reporting as a point of reference. J Law Med Ethics. 2019;47(2_suppl):19–22.
37. Dixon BE, Taylor D, Duke JD. Integration of FHIR to facilitate electronic case reporting: results from a pilot study. Stud Health Technol Inform. 2019;264:940–4.
38. Dixon BE. The perceived and real value of health information exchange in public health surveillance. Indianapolis: Indiana University; 2011.
39. Dixon BE, Gamache RE, Grannis SJ. Towards public health decision support: a systematic review of bidirectional communication approaches. J Am Med Inform Assoc. 2013;20(3):577–83. https://doi.org/10.1136/amiajnl-2012-001514.
40. Gamache R, Stevens KC, Merriwether R, Dixon BE, Grannis S. Development and assessment of a public health alert delivered through a community health information exchange. Online J Public Health Inf. 2010;2(2):3214.
41. Lurio J, Morrison FP, Pichardo M, Berg R, Buck MD, Wu W, et al. Using electronic health record alerts to provide public health situational awareness to clinicians. J Am Med Inform Assoc. 2010;17(2):217–9.
42. Lombardo JS, Garrett N, Loschen W, Seagraves R, Nichols B, Babin S. An informatics solution for informing care delivery of immediate public health risks to their patients. Online J Public Health Inf. 2009;1(1):1–15.
43. IOM. The future of public health. Washington: National Academy Press; 1988.
44. Chen D, Doumeingts G, Vernadat F. Architectures for enterprise integration and interoperability: past, present and future. Comput Ind. 2008;59(7):647–59. https://doi.org/10.1016/j.compind.2007.12.016.
45. McHugh LA, Sorhage FE, Tan CG, Langer AJ. Effect of electronic laboratory reporting on the burden of lyme disease surveillance--New Jersey, 2001-2006. MMWR Morb Mortal Wkly Rep. 2008;57(2):42–5.
46. Public Health Informatics Institute. Taking care of business: a collaboration to define local health department business processes. Decatur: Public Health Informatics Institute; 2008.
47. Public Health Informatics Institute. Defining functional requirements for immunization information systems. Decatur: Public Health Informatics Institute; 2012.
48. Public Health Informatics Institute. Redesigning public health surveillance in an eHealth world. Decatur: Public Health Informatics Institute; 2012.
49. Dixon BE, Grannis SJ. Why "what data are necessary for this project?" and other basic questions are important to address in public health informatics practice and research. Online J Public Health Inf. 2011;3(3):3792.
50. Russ AL, Weiner M, Russell SA, Baker DA, Fahner WJ, Saleem JJ. Design and implementation of a hospital-based usability laboratory: insights from a department of veterans affairs laboratory for health information technology. Jt Comm J Qual Patient Saf. 2012;38(12):531–40.

51. Dixon BE. Enhancing the informatics evaluation toolkit with remote usability testing. AMIA Annu Symp Proc. 2009;2009:147–51.
52. LaVenture M, Brand B, Baker EL. Developing an informatics-savvy health department: from discrete projects to a coordinating program part II: creating a skilled workforce. J Public Health Manag Pract. 2017;23(6):638–40. https://doi.org/10.1097/phh.0000000000000658.
53. Kulikowski CA, Shortliffe EH, Currie LM, Elkin PL, Hunter LE, Johnson TR, et al. AMIA board white paper: definition of biomedical informatics and specification of core competencies for graduate education in the discipline. J Am Med Inform Assoc. 2012;19(6):931–8. https://doi.org/10.1136/amiajnl-2012-001053.
54. Centers for Disease Control and Prevention. Competencies for public health informaticians. Atlanta: CDC; 2009.
55. McFarlane TD, Dixon BE, Grannis SJ, Gibson PJ. Public health informatics in local and state health agencies: an update from the public health workforce interests and needs survey. J Public Health Manag Pract. 2019;25(Suppl 2):S67–77. https://doi.org/10.1097/PHH.0000000000000918.
56. Dixon BE, McFarlane TD, Dearth S, Grannis SJ, Gibson PJ. Characterizing informatics roles and needs of public health workers: results from the public health workforce interests and needs survey. J Public Health Manag Pract. 2015;21(Suppl 6):S130–S40. https://doi.org/10.1097/phh.0000000000000304.
57. Trustees of Indiana University. MPH – public health informatics. Fairbanks School of Public Health, Indianapolis. 2018. https://fsph.iupui.edu/academics/masters/mph/informatics/index.html. Accessed 2 Jul 2019.
58. Joshi A. Population health informatics workforce, competencies, and training programs. In: Joshi A, Thorpe L, Waldron L, editors. Population health informatics: driving evidence-based solutions into practice. Burlington: Jones & Bartlett Learning; 2017. p. 31–62.
59. Biondich PG, Grannis SJ. The Indiana network for patient care: an integrated clinical information system informed by over thirty years of experience. J Public Health Manag Pract. 2004;Suppl:S81–6.
60. Overhage JM. The Indiana health information exchange. In: Dixon BE, editor. Health information exchange: navigating and managing a network of health information systems. 1st ed. Waltham: Academic Press; 2016. p. 267–79.
61. Grannis SJ, Stevens KC, Merriwether R. Leveraging health information exchange to support public health situational awareness: the indiana experience. Online J Public Health Inf. 2010;2(2):3213. https://doi.org/10.5210/ojphi.v2i2.3213.
62. Fidahussein M, Friedlin J, Grannis S. Practical challenges in the secondary use of real-world data: the notifiable condition detector. AMIA Annu Symp Proc. 2011;2011:402–8.
63. Gamache RE, Dixon BE, Grannis S, Vreeman DJ. Impact of selective mapping strategies on automated laboratory result notification to public health authorities. AMIA Annu Symp Proc. 2012;2012:228–36.
64. Kho AN, Lemmon L, Commiskey M, Wilson SJ, McDonald CJ. Use of a regional health information exchange to detect crossover of patients with MRSA between urban hospitals. J Am Med Inform Assoc. 2008;15(2):212–6. https://doi.org/10.1197/jamia.M2577.
65. Kho AN, Dexter PR, Warvel JS, Belsito AW, Commiskey M, Wilson SJ, et al. An effective computerized reminder for contact isolation of patients colonized or infected with resistant organisms. Int J Med Inform. 2008;77(3):194–8. https://doi.org/10.1016/j.ijmedinf.2007.02.005.
66. Kho A, Lemmon L, Dexter P, Doebbeling B. An operational citywide electronic infection control network: results from the first year. AMIA Annu Symp Proc. 2008;6:1222.
67. Kho AN, Dexter P, Lemmon L, Carey D, Woodward-Hagg H, Hare S, et al. Connecting the dots: creation of an electronic regional infection control network. Stud Health Technol Inform. 2007;129(Pt 1):213–7.
68. Indiana University. Responding to the addictions crisis. Trustees of Indiana University, Bloomington, Indiana. 2018. https://addictions.iu.edu/. Accessed 17 Sept 2019.
69. DeSalvo KB, O'Carroll PW, Koo D, Auerbach JM, Monroe JA. Public health 3.0: time for an upgrade. Am J Public Health. 2016;106(4):621–2. https://doi.org/10.2105/AJPH.2016.303063.
70. Healthcare Information and Management Systems Society. HIMSS co-leads effort to secure $100 million in house appropriations bill for CDC Public Health Infrastructure Modernization. HIMSS News, Chicago. 2019. https://www.himss.org/news/himss-co-leads-effort-secure-100-million-house-appropriations-bill-cdc-public-health-infrastructure. Accessed 2 Jul 2019.