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Exploring Health Information Exchange Through a System of Systems Framework

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ABSTRACT

Clinical decisions require timely availability of holistic patient health information including clinical, demographic, behavioral, and socioeconomic risk factors. Health information exchanges (HIEs) help bridge the technical and organizational divides between disparate Electronic health records (EHR) systems and facilitate the sharing of health information between providers and between patients and providers through collaborative governance, secure protocols, and interoperable standards. HIEs come in many varieties and can be highly complex, both technically and organizationally. This conceptual paper adopts a system of systems (SoS) framework from the systems engineering discipline to analyze and break down the complexity of HIEs. The mnemonic nature of the five characteristics of the Boardman and Sauser SoS Model (A for Autonomy, B for Belonging, C for Connectivity, D for Diversity, and E for Emergence) makes it easier to understand the intricacy of HIEs and helps remove the barriers to effective use of HIEs for care coordination, patient safety, and patient-centered care quality.

KEYWORDS

Collaboration, Collaborative Framework, DirectTrust, Electronic Health Records, Health Information Exchange, Health IT, Patient-Centered Healthcare, System of Systems, Systems Engineering

1. INTRODUCTION

Healthcare is a complex adaptive system consisting of organizations, people, and technologies that are both independent and interdependent. As a complex adaptive system, it exhibits non-linear, dynamic, and indeterministic behaviors that are unpredictable and difficult to manage and control (Rouse, 2008). Figure 1 shows the many stakeholders and how each of them plays a different role in a complex relationship to deliver healthcare. Quality healthcare requires the collaboration and concerted efforts of all stakeholders through information sharing and coordination.

Clinical care decisions require complete and longitudinal patient health information at the right time and right place. Timely and unobstructed sharing of patient records between healthcare plans, organizations, and providers are critical for efficient and effective delivery of patient-centered care. A 2010 survey reported that the average U.S. patient sees 18.7 different doctors during their lives and for patients over 65 years of age, the average increases to 28.4 individual doctors, including primary care, specialists, hospital and urgent care providers (PR Newswire, 2010). Before comprehensive and

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Figure 1. Stakeholders and interests in health care. Source: Healthcare as a complex adaptive system (Rouse, 2008, p. 19).

Stakeholder	Risk Management	Prevention	Detection	Treatment
Public	e.g., buy insurance	e.g., stop smoking	e.g., get screened	
Delivery System			Clinicians ^a	Clinicians and providers ^b
Government	Medicare, Medicaid, Congress	NIH, Government CDC, DoD, et al.	NIH, Government CDC, DoD, et al.	NIH, Government CDC, DoD, et al.
Non-Profits		American Cancer Society, American Heart Association, et al.	American Cancer Society, American Heart Association, et al.	American Cancer Society, American Heart Association, et al.
Academia	Business schools	Basic science disciplines	Technology and medical schools	Medical schools
Business	Employers, insurance companies, HMOs		Guidant, Medtronic, et al.	Lilly, Merck, Pfizer, et al.

^aThe category of clinicians includes physicians, nurses, and other health care professionals.

^bThe category of providers includes hospitals, clinics, nursing homes, and many other types of testing and treatment facilities.

longitudinal health records controlled by patients and accessible to all healthcare providers become a reality, the healthcare industry must rely on Health Information Exchanges (HIE) to enable trusted, secure, interoperable, and timely sharing of health information among disparate Electronic Health Record (EHR) systems.

HIEs come in a variety of forms and functions. Technically, a HIE can use push-based, query-based, or consumer-mediated communication technology. Geographically, a HIE can be operated locally, state-wide, regionally, or nationally. Organizationally, a HIE can be convened and governed by an EHR vendor, a community of healthcare organizations, or a single healthcare system. Architecturally, a HIE can be centralized, federated, or a hybrid of both. The variety and diversity in the organizational structure and technical architecture of HIEs make it difficult for practitioners and researchers to understand the intricate operations of a HIE and can be a barrier to effective adoption and utilization.

This paper aims to break down the complexity of HIE by using the System of Systems (SoS) framework to analyze and summarize the common characteristics. The SoS framework has been used in Systems Engineering discipline to guide the design and development of complex systems consisting of multiple independently owned and operated sociotechnical systems, typically seen in the defense and transportation industry. The SoS framework aligns well with various collaborative frameworks commonly practiced in business management and healthcare industry. The SoS model by Boardman and Sauser (2006) is particularly useful in exploring HIE. This model specifies five characteristics of an SoS using five mnemonics: A for Autonomy, B for Belonging, C for Connectivity, D for Diversity, and E for Emergence. These easy-to-remember mnemonics reflect the principle of user-centered design (UCD) and help create a shared mental model for practitioners and researchers in their effort to deliver and improve patient-centered healthcare through the effective adoption and use of EHRs and HIEs. To illustrate the five characteristics, this paper uses DirectTrust, a push-based secure messaging HIE, as a case study.

2. HEALTH INFORMATION EXCHANGE

2.1. EMR vs EHR vs PHR

There are many terms and acronyms used in Health IT, some of which are similar and related which may cause confusion. Three terms relevant to the discussion are described below.

Electronic Medical Record (EMR) and Electronic Health Record (EHR) both refer to a computerized information system that stores and manages patient records. EMR is the precursor to EHR and was traditionally limited to patients' medical or clinical information. Over time, EMR went beyond medical or clinical information to include any type of information that is relevant to a patient's health including socioeconomic and behavioral risk factors (race, ethnicity, education level, smoking and alcohol usage, fitness, etc.). Hence, the narrower "M" for medical is replaced with the broader "H" for "Health". For this reason, EHR is used consistently through this paper. In some context, EHR may refer to the health records themselves instead of the computer system that manages them. For this reason, sometimes, the term EHR system is used to distinguish the system from the records it manages.

A Patient Health Record (PHR) is defined as "an electronic application through which patients can maintain and manage their health information (and that of others for whom they are authorized) in a private, secure, and confidential environment" (HealthIT.gov, n.d.-a). The difference between an EHR and a PHR is that EHR is used primarily by healthcare providers and administrative staff while a PHR is used by patients and their representatives. For example, a web portal or mobile app provided by a healthcare organization to allow its patients to securely access their health records is considered a PHR.

2.2. Forms and Functions of HIE

The word "exchange" in HIE can be either a verb or a noun (HiMMS, n.d.):

- As a verb, HIE is defined as "the sharing action between any two or more organizations with an executed business/legal arrangement that have deployed commonly agreed-upon technology with applied standards for the purpose of electronically exchanging health-related data between the organizations;"
- As a noun, HIE is defined as "a catch-all phrase for all health information exchange, including regional health information organizations (RHIOs), quality information organizations (QIOs), Agency for Healthcare Research and Quality (AHRQ)-funded communities and private exchanges."

Over the past decade since the enactment of the Health Information Technology for Economic and Clinical Health (HITECH) Act of 2009, which provides federal funding for the adoption of health IT along with the mandate of meaningful use, there have been widespread implementations of EHRs and HIEs that connect EHRs to facilitate trusted, secure, and interoperable sharing of patient health information. EHRs and HIEs help the healthcare industry move from the traditionally inefficient paper-based health records management and mail/fax-based information exchanges to the modernized and more efficient electronic health records and electronic exchanges.

Technologically, HIEs use a variety of communication techniques for information exchange (HealthIT.gov, n.d.-b):

- **Directed (push):** Ability to send and receive secure information electronically between care providers to support coordinated care;
- **Query-based (pull) exchange:** Ability for providers to find and/or request information on a patient from other providers, often used for unplanned care;
- **Consumer-mediated exchange:** Ability for patients to aggregate and control the use of their health information among providers.

Architecturally, there are three types of HIE:

- **Centralized:** Patient data is collected and stored in a centralized repository, data warehouse or other database. The HIE has full control over the data, including the ability to authenticate, authorize and record transactions among participants;
- **Federated (Decentralized):** Interconnected but independent databases allow for data sharing and exchange, and user access to the information is granted only when needed;
- **Hybrid:** Incorporates variations of federated and centralized architectures to harness the advantages of both. These are becoming common as various combinations of available services are implemented.

Geographically a HIE can be local such as county-wide, state-wide, regional covering multiple states, or national; Organizationally, a HIE can be sponsored by government agencies, community-based not-for-profit organizations, or EHR vendors.

3. SYSTEMS OF SYSTEMS

3.1. System vs System of Systems

The discipline of Systems Engineering deals with the definition, design, development, and deployment of engineered systems ranging from mechanical, electrical, electronic systems, or any hybrid of the three. The father of General Systems Theory, von Bertalanffy (1968), defined a system as “a set of elements in interaction.” Boardman and Sauser (2008) believed ‘togetherness’ is the essence of a system because it draws “together of various parts and the relationships they form in order to produce a new whole”. Here the term “element” and “part” are used. Another commonly used term is “component.” In general, a system consists of closely coupled interconnecting components. An individual component is typically not functional and useful in and of itself. Components are dependent on each other and rely on the encompassing system to provide the necessary structure to function.

While a system is a tightly coupled set of components and its operations are typically under the control of a single organizational entity, many of the larger and complex sociotechnical systems consist of loosely coupled and independently managed and operated subsystems without a central command and control mechanism. This type of system is defined as a system-of-systems (SoS). A SoS is a special system that exhibits characteristics beyond the general characteristics of a system; the operations of a SoS require a more specialized system thinking approach called the System-of-Systems thinking. Jamshidi (2008, p. 5) defined systems of systems as “large-scale integrated systems which are heterogeneous and independently operable on their own but are networked together for a common goal.”

A system is considered an SoS only if it exhibits the following five characteristics (Maier, 1998):

- **Operational Independence:** Constituent systems are independent and able to operate without dependency on other constituent systems or the existence of the encompassing SoS;
- **Managerial Independence:** Constituent systems are governed by their own rules rather than by external ones when they are participating in an SoS;
- **Geographical Distribution:** Constituent systems are dispersed geographically or virtually; hence, they rely on some form or facility of communication to share their operations results with each other;
- **Evolutionary Development:** An SoS can be under constant change due to evolution in its purpose and mission. For example, market conditions can change business strategies, resulting in changes of missions. Each constituent system can also undergo its own developmental process;
- **Emergent Behaviour:** The behaviors of an SoS emerge as a result of the synergistic collaboration of its constituent systems.

The behavior and performance of a healthcare system reflect the characteristics of a SoS. Each stakeholder is managerially and operationally independent of each other. They are typically geographically dispersed, and each is going through its own developmental process and life cycle. They collaborate, communicate, and cooperate to provide quality care for patients. As a result of collaboration, innovations in clinical diagnosis, disease presentation and treatment, and care delivery and management emerge to improve health and wellness.

3.2. Boardman and Sauser Model of SoS

Built on Maier (1998) and several others' work, Boardman and Sauser (2006) summarized the characteristics of a SoS using five mnemonics that are easy to understand and remember: A for Autonomy, B for Belonging, C for Connectivity, D for Diversity, and E for Emergence:

- **Autonomy:** Each constituent system is autonomous in the process of fulfilling the purpose and mission of the SoS. This covers Maier's first two characteristics: operational and managerial independence;
- **Belonging:** Each constituent system chooses to belong on a cost/benefit basis; each aims to advance its own causes at the same time benefit the larger mission of the SoS. The Maier model does not explicitly include this characteristic;
- **Connectivity:** Constituent systems communicate, coordinate, and cooperate with each other to share information and knowledge in order to advance their own goals and the goals of the SoS. The Maier model does not explicitly include this characteristic;
- **Diversity:** Each constituent system is unique and has unique capabilities to augment each other and contribute to the SoS. This covers Maier's Geographical Distribution but goes beyond to include any type of diversity such as virtual, organizational, service, etc.;
- **Emergence:** New and novel capabilities and behaviors emerge through the released autonomy, committed belonging, open connectivity, and collaborative diversity. This covers Maier's Emergent Behaviour.

For its comprehensiveness and simplicity, this paper adopts the Boardman and Sauser SoS model to explore HIE.

3.3. The Alignment Between SoS Model and Collaborative Frameworks

Collaboration has been researched intensively in management and social science and applied widely in many practices. In healthcare, multiple professionals including physicians, nurses, pharmacists, dieticians, and social workers must collaborate to deliver quality care for patients. In addition, multiple organizations including governments, health insurance plans, care providers, communities, and families must collaborate to ensure healthcare is insured, scheduled, coordinated, and paid for throughout the entire process of care delivery. Heath, Appan, & Gudigantala (2017) used the collaborative framework to explore HIEs and guide their development as healthcare leaders face various challenges in building a collaborative environment for patient information sharing.

Thomson and Perry (2006) identified five major dimensions that help understand the process of collaboration: Governance, Administration, Mutuality, Reciprocity & Trust, and Autonomy. These five dimensions can be mapped to the SoS model as shown in Table 1 which shows *Diversity* and *Emergence* from SoS framework were not present in this collaboration framework.

Another collaborative framework (The Collaborative, 2016) consists of eight principles as shown in Figure 2.

Table 2 maps the eight principles of the Collaborative Framework to the five characteristics of SoS. The table shows that there is greater alignment between SoS framework and this collaborative framework.

Table 1. Mapping between the five characteristics of SoS and the five dimensions of collaboration

Five Characteristics of a SoS (Boardman & Sauser, 2006)	Five Dimensions of Collaboration (Thomson & Perry, 2006)
<i>Autonomy</i>	<ul style="list-style-type: none"> • Autonomy
<i>Belonging</i>	<ul style="list-style-type: none"> • Governance • Administration
<i>Connectivity</i>	<ul style="list-style-type: none"> • Mutuality • Reciprocity & Trust
<i>Diversity</i>	
<i>Emergence</i>	

Figure 2. Collaborative framework 2016 – 2020. Source: The Collaborative Framework 2016 – 2019 (The Collaborative, 2016).



Table 2. Mapping between the five characteristics of SoS and the eight principles of collaboration

Five Characteristics of SoS (Boardman & Sauser, 2006)	Eight Principles of Collaboration (The Collaborative, 2016)
<i>Autonomy</i>	Independence
<i>Belonging</i>	Commitment and Participation Equal standing and responsibility
<i>Connectivity</i>	Positive Working Relationship Transparency Joint Learning
<i>Diversity</i>	Complementarity
<i>Emergence</i>	Outcome-focused

4. EXPLORING HIE THROUGH SOS FRAMEWORK

4.1. HIE as a SoS

Among many participants in a HIE, EHR systems, healthcare organizations, and healthcare providers are the most active participants. They represent three major actors: Technologies, Organizations, and People. They form a loosely coupled collaborative community with a shared vision of caring for patients and common goal of sharing information to coordinate workflow, ensure patient safety, and improve care quality. Their behaviours are bound by a mutually agreed-upon trust framework rather than a central command and control management authority; the secure exchange of information is facilitated through interoperable standards and protocols. Innovations emerge through the ongoing interactions of the diverse participants. Table 3 summarizes the analysis of HIE using the lenses of the SoS framework.

4.2. An Illustrative Case - DirectTrust

Direct messaging protocol was first unveiled as a new vehicle for health information exchange in 2011 and is now a key enabler to meet the meaningful use requirements for Centers for Medicare

Table 3. Expectation and behavior of participants in a HIE

Characteristics of SoS	Applicability in a HIE
Autonomy	Each participant operates as an independent entity with its own mission and goal and participates in the HIE on a voluntary basis.
Belonging	A trust framework is established to define the shared mission and common goal; Governing processes and interoperability standards are established to facilitate secure exchange of health information to deliver quality healthcare.
Connectivity	Participants actively exchange patient health information via a common standard and a shared infrastructure.
Diversity	Each participant has its unique roles, responsibilities, and goals. Each brings unique capability, value, and perspective to the exchange community to achieve the benefit of multidisciplinary collaboration.
Emergence	The exchange of health information leads to the availability of richer information about patients, better insights of patient health, and improved care coordination, patient safety, and care quality. Innovative use of information in clinical care and population health management emerge to benefits all participants and ultimately patients.

and Medicaid Services (CMS). The secure, scalable, email-like messaging protocol was created to replace the traditional inefficient way of exchanging health records using paper-based postal mails or fax machines. This effort was described as an “example of how the public and private sectors can come together in a collaborative, entrepreneurial explosion of mojo to improve and advance healthcare in America” (Miliard, 2011).

DirectTrust is a collaborative nonprofit association of over 100 health IT and health care provider organizations to support secure, interoperable health information exchange via the Direct messaging protocols. DirectTrust has created a “trust framework” that extends the use of Direct exchange to over 100,000 health care organizations and nearly two million Direct addresses. This trust framework supports both provider-to-provider Direct exchange and exchange between consumers/patients and their providers.

DirectTrust’s trust framework makes it easy for health care professionals, health IT vendors and their patients/customers to communicate securely, with identity proofing and regardless of end-user application. Over 300 EHR and PHR vendors’ products, and over 50 other types of HIEs, participate in the DirectTrust network, ensuring interoperability and security for exchange of health information to more than half the professionals in the U.S. health care system (DirectTrust, n.d.-a).

4.2.1. Autonomy

The DirectTrust membership is voluntary and the participation in message exchange is also voluntary. Each participating system, organization, and provider operate and evolve in its own unique way and at its own pace. This autonomy gives all stakeholders the maximum control and independence to mind their own business without undue interference.

4.2.2. Belonging

DirectTrust created the governance policy and trust framework to achieve a common goal and a shared mission which binds all participants together in a collaborative and supportive network. “This Framework comprises technical, legal, and business standards that members of the DirectTrust community agree to follow, uphold, and enforce” (DirectTrust, n.d.-a).

The common goal is to “establish and maintain a national, transparent Security and Trust Framework upon which trust relationships for exchange technology can be scaled and federated nationally” (DirectTrust, n.d.-a).

The shared mission is to “support health information exchange that is secure, interoperable, affordable, ubiquitous and usable by diverse end-users” (DirectTrust, n.d.-a).

4.2.3. Connectivity

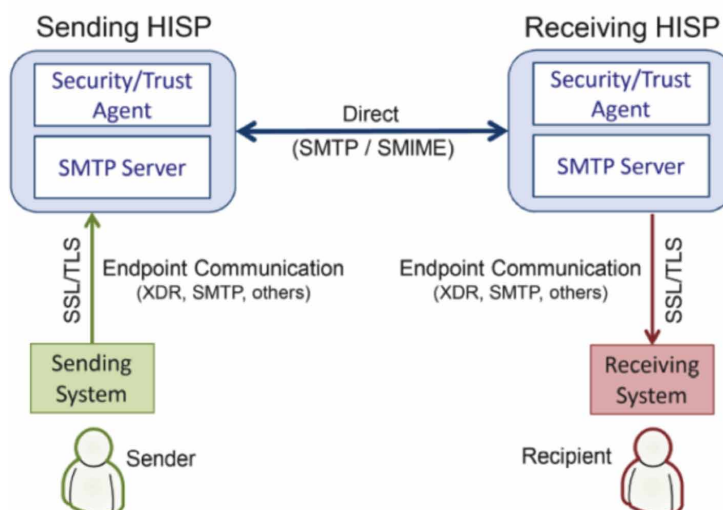
DirectTrust relies on over fifty Health Information Service Providers (HISP) to provide technical infrastructure for participating systems, organizations, and individuals to securely exchange messages. As shown in Figure 3.

A HISP can be considered as a virtual post office where senders and recipients exchange electronic health information. All HISPs communicate and collaborate with each other to ensure trusted and secure exchanges on behalf of the senders and recipients.

4.2.4. Diversity

The diverse participants of DirectTrust include government entities, care organizations, care professionals, health plans, hospitals, pharmacies, clinical labs, and patients. DirectTrust standards development seeks to be inclusive and represent all stakeholders and aims for balance and a lack of dominance of each Standards Workgroup. DirectTrust established various Interest Categories and ensures that a single Interest Category may not dominate the rest. The interest workgroups include diverse organizations from various categories including regulatory agencies, care organizations, care professionals, health IT vendors, consumers and patients.

Figure 3. How Direct messages are exchanged through HISPs (DirectTrust 101 n.d.b)



4.2.5. Emergence

There have been many innovative and successful use cases of DirectTrust (DirectTrust, n.d.-d). Table 4 shows a few examples.

Over the past five years, DirectTrust also enjoyed steady growth as shown in Figure 4.

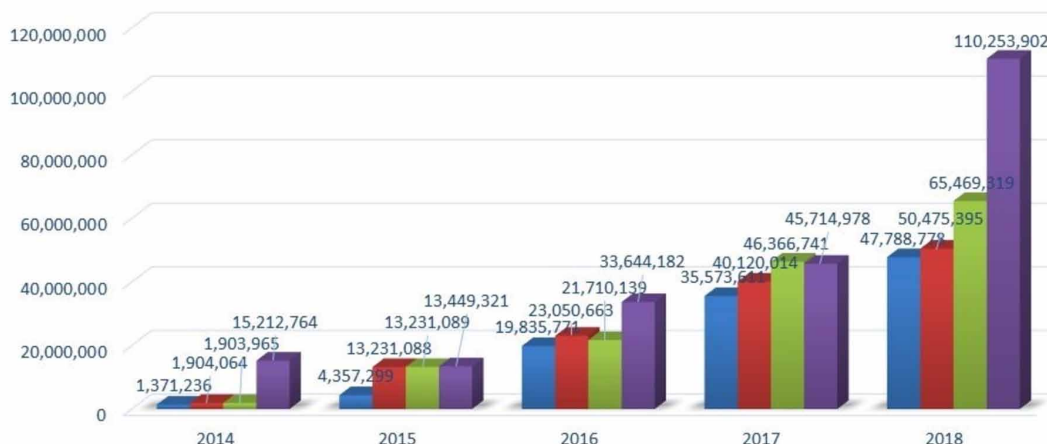
4.2.6. Summary

The following summarizes observations from the illustrative case of DirectTrust: Autonomy and Belonging go hand-in-hand. Without Belonging, there will be no common mission and goals and no opportunities to achieve a higher purpose. Without Autonomy, there will be little motivation and

Table 4. Sample use cases and success stories of DirectTrust

Use Case	Success Story
Bi-directional referrals through Direct messaging	Sutter Health created bi-directional closed loop referral workflows to send referrals and receive information back from consultants via Direct, resulting in more efficient workflows, quicker referral turnaround times, and improved patient and staff satisfaction.
Admit-Discharge-Transfer (ADT) notifications to patient's Primary Care Physician's (PCP) EHR via Direct messaging	Circle Health/Lowell General Hospital EHR sends real-time ADT notifications using Direct messaging to PCP' EHRs (Cerner) to help better coordinate care for patients. Upon receipt of the ADT notification the PCP sends the patient's latest progress note via Direct to the Hospital. This arrives in a hospital pool and is attached to the patient's chart for the patient's hospital caregivers to review.
Closed loop referrals between Veteran Affairs (VA) hospitals and community specialists via Direct messaging	In Ohio, the VA uses Direct Messaging with three large Ohio health systems for closed loop referrals. This has resulted in significant savings of time and staff resources for information exchange. Direct Messaging has improved care coordination for Veterans. A VA user in Ohio says with VA Direct Messaging, "that we get [health information] immediately from community providers- plus we can converse electronically if there is an issue with the medical records!"

Figure 4. Number of Direct messages exchanged each quarter from 2014 to 2018 (DirectTrust, n.d.c)



impetus for creativity and innovation. Diversity and Emergence also go hand-in-hand. Diversity is a necessary condition to achieve emergence of unexpected innovations. Emergence is the outcome of the joined forces of Autonomy, Belonging, Connectivity, and Diversity.

5. CONCLUSION

The system of systems (SoS) framework established in the Systems Engineering discipline deals with the definition, design, development, and deployment of multiple independently managed and operated systems in a collaborative manner to achieve common missions and goals. This framework shares the spirit of the collaborative framework prevalent in management and social science. Healthcare is a complex system that involves independent actors with diverse and often conflicting interests and multiple disciplines including life science, engineering, information technology, and socioeconomics. SoS is a useful and powerful framework for analysing and understanding healthcare and the interactions between organizations, people, and technologies with the healthcare system.

A key challenge facing healthcare and its adoption of health IT is the interoperability of disparate Electronic Health Records (EHRs) to share patient information. Health Information Exchanges (HIEs) serve as information hubs to facilitate the secure and trusted exchanges of patient information. HIEs come in many shapes and forms and their intricate structures and operations can be difficult to grasp. This conceptual paper explores HIEs through the lens of the SoS framework to help researchers and practitioners understand their intricate operations. The Boardman and Sauser model of SoS provides a comprehensive yet easy to understand framework for the analysis of a SoS. It defines five characteristics of a SoS using five mnemonics: A for Autonomy, B for Belonging, C for Connectivity, D for Diversity, and E for Emergence. This paper uses DirectTrust as an illustrative case study and analyses it from these five dimensions to gain clear understanding of its operations.

Patient-centred healthcare demands the timely availability of comprehensive and longitudinal patient health information including clinical, administrative, socioeconomic, and behavioral information at the point of care for better care coordination, patient safety, and care quality. HIEs are the key enablers and increased understanding of their structures and operations helps achieve meaningful use of health IT in patient-centred healthcare.

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