Bridging Healthcare's Data Divide with API-First Architecture

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Abstract

Healthcare’s growing dependency on the secure and timely sharing of medical information across disparate systems has exposed the inherent limitations of existing healthcare information exchange (HIE) solutions. The challenge of achieving healthcare interoperability at scale has seen significant investments of time, money, and expertise from stakeholders throughout the health information ecosystem. Nonetheless, evidence shows that demand for a robust, reliable, and efficient infrastructure for health information exchange remains unabated. APIs are the next logical step in providing this connectivity. Yet APIs must be treated as strategic artifacts in their own right. API-First Design, where APIs are treated as design artifacts and all decisions made as part of design are made with APIs in mind, provides the foundations for realizing the full potential of APIs in HIE.

API-First Design provides a road map for healthcare organizations looking to enable interoperability in an evidence-based manner. The design and development of the APIs that form the cornerstone of interoperability within an organization strongly influence the organization’s ability to realize the benefits of interoperability, and these APIs represent significant investments that warrant dedicated governance and oversight throughout the API lifecycle. Organizations that make the effort to establish a clear understanding of the API requirements shared by their stakeholders and to apply best practices in the design, build, and management of their APIs stand a much better chance of reaping the benefits of interoperability than those that fail to do so.

keywords: API-first architecture,Healthcare interoperability,HL7 FHIR standards,Electronic health records (EHR) integration,Health information exchange (HIE),RESTful APIs in healthcare,Digital health ecosystems,Clinical data interoperability,Healthcare IT infrastructure,Secure health data sharing.

1. Introduction

Improving interoperability across systems, services, and stakeholders is paramount for the evolution of healthcare, particularly with respect to health information exchange (HIE). APIs are universally acknowledged as key enablers and investments in the development and deployment of these artifacts should be managed accordingly. API-First Design, which takes the API as the primary design and implementation artifact, enhances the likelihood that APIs will provide the desired outcomes. API-First Design encompasses several concepts: treating APIs as first-class, business-aligned assets; establishing a roadmap for API design and deployment; following a design-to-contract approach; establishing API design and development standards; embracing API maturity models; and adopting oversight and governance processes for API design and deployment.

Interoperability is a necessary condition for health information exchange and improving these exchanges will yield value over time. Investments in interoperability are easily quantified, but quantifying the value of improved exchange is far more difficult. Nevertheless, evidence points to an unfulfilled potential from HIE, with studies showing that health systems realize no value or even suffer a loss from exchanges with many trading partners.

1.1. Background and Significance

Efforts to achieve interoperability remain one of the most pressing issues for the health information technology community. Becker[Becker20177] states that APIs must be treated as strategic assets and recommends API First Design as a strategy to enhance progress. Nevertheless, the results on the impact of API First Design are mixed. Becker and Whinter[Becker20177, Becker2017] note that the API ecosystem has matured rapidly; however, companies applying API designing API consulting tools, resources, and API strategies have not provided conclusive evidence of superior outcomes. Becker and Whinter question whether organizations adopting an API-First approach realize sufficient improvements to justify the costs of reorientation.

The American Institute of Architects (AIA) asserts that good design requires collaboration between multiple disciplines—architecture, civil engineering, structural engineering, mechanical engineering, electrical engineering, plumbing engineering, and interior design—working together and using methods such as BIM. The API ecosystem requires a similar approach to API design, development, deployment, operation, and maintenance in support of achieving data interoperability. Successful health information exchange requires the participation of patients, health providers, payers, laboratories, commercial entities, and trading partners. The Open Data Center Alliance stipulates the need for a global community effort to reverse the trend of IT capital expenditures and operation expenditures without sufficient return on investment. Nevertheless downed systems and unrecoverable sensitive medical records such as electronic health records remain common.

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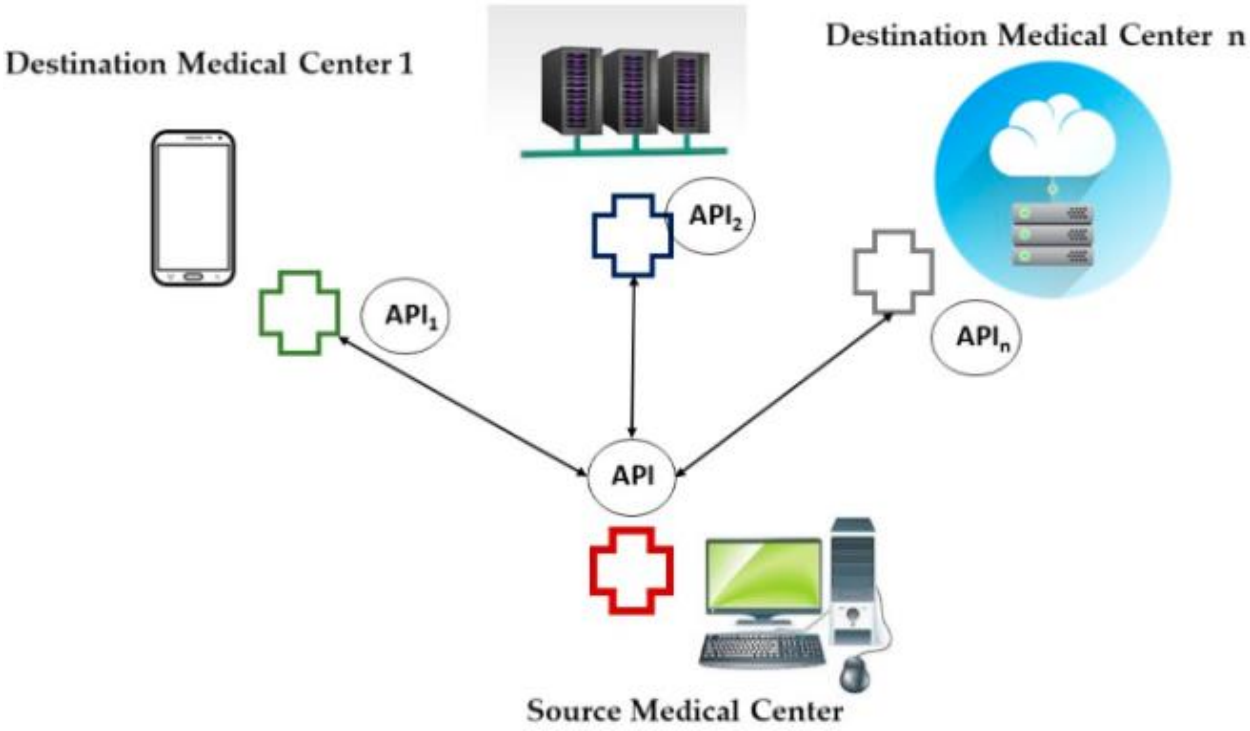

Fig 1: API Design for Interoperability of Medical Information Systems

1.2. Research design

The aim is to demonstrate that the API-First approach can help overcome the prevailing impediments to healthcare system interoperability. Interoperability is thus viewed in its broadest sense—not merely the capability to exchange data, but also the capability to interpret the data exchanged at the level of the receiver. Given that APIs interconnect systems, the focus is on the relationships between the API and data exchange stakeholders (e.g., data producers and consumers) and the API Governance decisions that impact the ability to exchange data. API-First is subsequently examined more closely to show how its mature practice enables standardized design patterns, tests, and certification criteria that conveniently document the API's capabilities. The work then calls attention to the requisite full-side support for accelerating API adoption.

Evidence is drawn largely from the healthcare domain, although many conclusions apply in different sectors. Healthcare is brimming with APIs—thousands are available on public APIs directories—but for data exchange, the volumes remain small and often monitored by transaction fees. Yet investment in back-end systems necessary for supporting API publish-subscribe capabilities is often substantial and organizations seek to justify this expenditure. Examining the market economics, it becomes

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evident that APIs must be delimited. Interoperability investments cannot be left solely in the vendors' hands, nor should customers continue to be incidental beneficiaries of API technology.Management (Wang et al. 2020) and mature API economy (Bahr, V. und R. Müller, 2018) research is rich with frameworks, supported more by empirical evidence than by case studies. Hence questions for the healthcare domain are: "What are the maturity and governance models for API capabilities from a data exchange perspective?" and "What are the API architectural patterns for healthcare data exchange?"

Equation 1: Interoperability as a function of syntax, semantics, security, and availability

$$I = f(S_x, S_m, Q, G, A)$$

where

- I= interoperability level
- S_x= syntactic interoperability
- S_m= semantic interoperability
- Q= API quality
- G= governance/compliance quality
- A= operational availability

A simple weighted linear form is:

$$I = w_1 S_x + w_2 S_m + w_3 Q + w_4 G + w_5 A$$

subject to

$$\sum_{i=1}^{5} w_i = 1, w_i \geq 0$$

Derivation

Step 1: The paper says interoperability depends on more than exchange alone.
So interoperability must depend on several factors, not a single variable.

Step 2: Let each factor be normalized to $[0, 1]$. Then total interoperability should also lie in $[0, 1]$.

Step 3: The simplest aggregation of several normalized factors is a weighted sum.

Step 4: To keep I normalized, require the weights to sum to 1.

So the derived equation is:

$$I = \sum_{i=1}^{5} w_i \, x_i$$

2. Conceptual Foundations of API-First Design

API-First Design is defined as creating and documenting an API before the implementation of the API or the service. This definition highlights two important elements of API-First Design. First, it stresses the idea that an API is not an afterthought incidentally developed during the implementation of a service but rather a strategic artifact that must be explicitly designed. Second, it frames the API documentation as an important deliverable of the design effort. API-First Design encompasses several core principles that offer strategic and tactical guidance for exploiting APIs. First, it emphasizes a design-to-contract mindset centered on modeling resource interfaces. API-First implies identifying all exchange actors and modeling their interactions. Furthermore, because APIs are designed contracts, the design-time design process considers how the API may be used throughout its operating life cycle and how to keep its usage understandable.

The resource-oriented perspective of REST proposes modeling data exchange as the manipulation of *resources*, that is, distinct pieces of information with a well-defined lifecycle. RESTful APIs expose resources through a uniform interface that (1) enables a small set of standard and how-to operations that can be applied to all resources (CRUD); (2) structures API responses as directed state machines, thus providing a discovery mechanism that minimizes external API documentation (HATEOAS); and (3) promotes the orderly definition and redefinition of resource structures within an API ecosystem, allowing added or modified resources to be reused by all ecosystem participants. This resource modeling can be applied at three different levels of abstraction: the level of domain resources, of APIs, and of API ecosystems.

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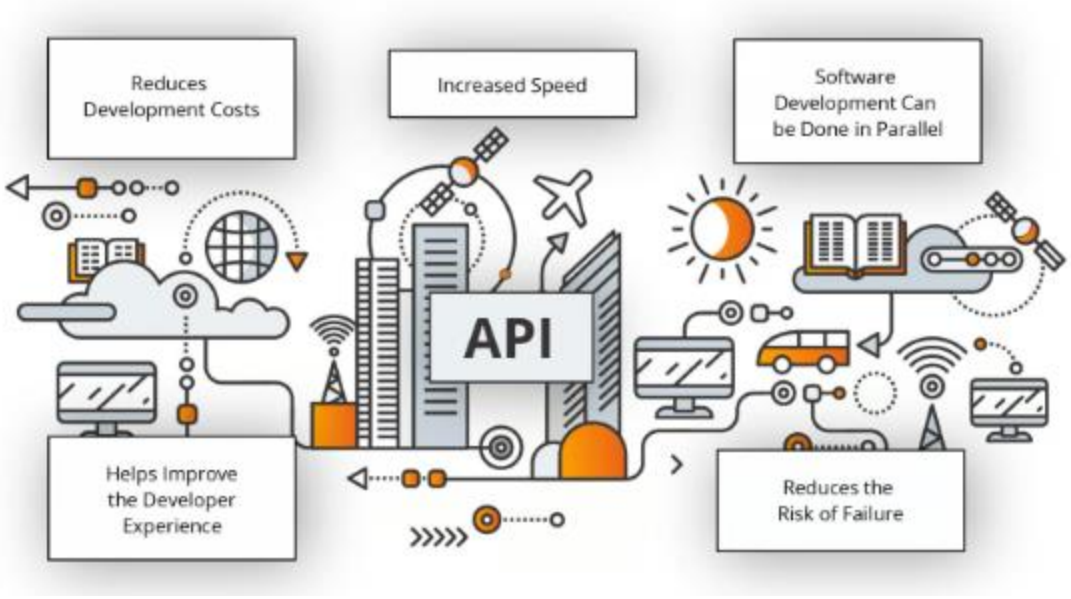

Fig 2: API-first design

2.1. Definitions and core principles

API-First Design denotes a strategy that treats Application Programming Interfaces (APIs) as central, critical, and strategic artifacts in any enterprise architecture. Core principles include a design mentality centered on an API's consumers, a design process that is architecturally driven, and a strategy that emphasizes a design-to-contract approach. APIs are designed first and independently of their implementation; source code is generated from the API definitions.

The approach advocates that APIs should be treated as first-order citizens within both businesses and technology. Just as user interfaces represent the point of interaction between a company and its customers, APIs represent the conduit through which third-parties access the value (data, rules, and processes) contained in the enterprise systems. Increasing reusability demands and the expanding ecosystem of partners, vendors, and suppliers make self-service access via an API a paramount concern. APIs should therefore be managed across their full lifecycle like other assets of the organization, with clear rules governing their design and use.

API-First also suggests a shift of perspective. Successful consumer products are designed from the point of view of the end-user—what is important is not how pretty the interface looks but rather whether the user is able to find what they are looking for in just a few clicks. The same principle holds true for APIs: the objective is not to make the coolest-looking API, but rather to ensure that the consumers of the API can implement it quickly and without any problems. This mind-set enables the design of a robust and well-defined API that third-party developers want to use.

2.2. Interoperability goals in healthcare

API-First Design strives for extensive functional interoperability across all levels of a healthcare ecosystem according to Martin (2015). Functional interoperability means that when data are exchanged, there is a precise agreement about the syntax and semantics of the exchanged data— the meaning of such data is understood at the level of the information technology applications involved, although not necessarily by the end users. Data in a healthcare ecosystem must be exchanged with these properties. To achieve this, API-First Design embeds criteria that can be verified through the use of an Audit framework. API-First Design enables semantic alignment for human and machine-readable data by relying either on coding systems that are maintained by recognized authorities or on value sets obtained through the curation services of the ecosystem. These code systems and value sets are available during the execution of an exchange or the synchronization of the distributed state.

Data can have different meanings depending on their context; yet, in a healthy ecosystem, meaning and usage change naturally. Thus, for an ecosystem to realize its value, APIs must enable the expression and validation of data semantics. The synthesis of these semantic elements and the synchronization of the associated data makes it possible to go further and measure interoperability value by establishing mechanisms that track how the share of interoperable data is evolving over time and relates to the achievement of essential socioeconomic objectives, such as cost control, quality improvements, or population health management.

Principle	Description	Purpose
API as First-Class Artifact	APIs are designed before implementation	Ensures strategic alignment
Design-to-Contract	APIs defined via formal contracts before coding	Improves consistency and reuse
Consumer-Centric Design	Focus on API users (developers, systems)	Enhances usability
Lifecycle Management	APIs governed across full lifecycle	Maintains quality and reliability
Documentation First	API documentation created early	Enables parallel development
Governance & Standards	Policies for API design and usage	Ensures interoperability

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Table 1: API-First Design Core Principles Table

3. Stakeholders and Maturity Models

State government and insurer policies strongly influence the healthcare interoperability ecosystem. Policymakers should envision a future state and articulate a plan to reach it by stimulating demand, building capacity, and ensuring that individual organizations contribute to system-level goals. Using an interoperability maturity model, stakeholders can better align their product roadmaps with policy objectives. Additionally, API publishers must prioritize which APIs to build first and whom to encourage to publish new APIs.

Supported by Integrated Healthcare Association's (IHA) Data Exchange Framework, a statewide blueprint for health information exchange, the maturity model recognizes four groups: the clinician, payer, lab, and patient communities that generate and consume data; the technology vendors that facilitate these exchanges; and the IHA itself, which supports all users across policy, governance, and funding tracks. Although the maturity model identifies community goals, no single entity can influence all to reach a higher level of capability.

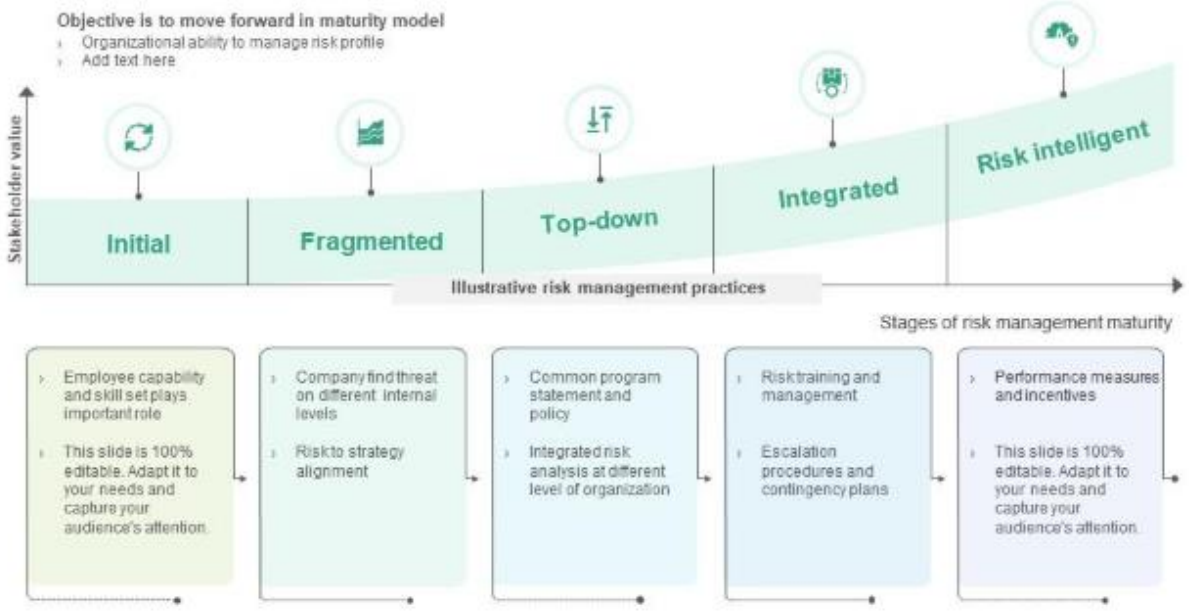

Fig 3: Maturity model with stakeholder value

3.1. Health information exchange participants

Healthcare interoperability enables timely and accurate access to health information. Achieving this goal requires solutions that providers, payers, laboratories, other stakeholders, and patients need and can use.

To realize the potential benefits of interoperability, the API-First strategy must engage an expanded range of stakeholders—beyond the technical communities designing APIs—to include those exploring the trade-offs and hidden costs of sharing health data with other parties. These stakeholders influence API design at different levels: (1) Business and Organizations—such as executive leadership, chief operating officers, and vendor professionals—guide policy documents and frameworks. (2) Business Use Cases—such as clinicians, payers, and involved organizations—focus on consent, reward systems, and de-identification. (3) Information Models—such as clinicians, information architects, and vendor professionals—address the information required for specific purposes. (4) Technical Use Cases—such as testers and implementers—test conforming implementations and authorization. (5) API Design and Governance—such as governance boards—ensure that the APIs created not only serve capital-intensive use cases but also provide affordable access for everyday clinical needs.

Equation 2: Syntactic interoperability score

$$S_x = \frac{N_c}{N_t}$$

where

- N_c= number of successfully conformant exchanges
- N_t= total exchanges tested

Derivation

Step 1: Syntactic interoperability means systems can exchange data in the required format.

Step 2: In testing terms, each transaction either conforms or does not conform.

Step 3: Therefore, the natural success ratio is

$$S_x = \frac{\text{conformant transactions}}{\text{all transactions}}$$

Hence:

$$S_x = \frac{N_c}{N_t}$$

If different message types matter differently, use weights:

$$S_x = \frac{\sum_{j=1}^{m} \alpha_j N_{c,j}}{\sum_{j=1}^{m} \alpha_j N_{t,j}}$$

3.2. API maturity and governance frameworks

API maturity models articulate increasing levels of API quality that contribute to business performance. While API producers and providers have the most to gain from improving the quality of their APIs, other stakeholders are also impacted—directly (such as API consumers and partners) or indirectly (API resellers, advisory and research firms, and even the market as a whole). API governance frameworks define the governance roles and decision rights for managing the APIs throughout their lifecycle. API governance models align the organization, its partnerships, and its objectives for the consumption of APIs when APIs are offered internal to the organization or partner APIs in a public-facing developer portal. An API maturity framework makes the investment case and business proposition clearer for investing in API development and quality enhancement either external to the organization (third-party APIs) or internal APIs.

API maturity models can guide the market into understanding the value and potential business benefits of APIs. For API producers and providers, models explain how to be more strategic and intentional about managing the full API lifecycle. Effective government at the API product management role enables stakeholders to focus on the business vital signs of the API and API program and alleviates the burden of governance by ensuring that the right analysts, VPs and decision-makers are engaged at the right moments in the discovery, design and development process. Through API catalogs, these stakeholders are made aware of any policies for consuming APIs across the organization, whether for internal use or third-party channels, and are given an avenue for providing templated input for enhancing the quality and business viability of those APIs. API governance roles align and specify appropriate levels of obsession with quality and investment in non-functional testing based on the business value of the API.

4. Architectural Patterns for Healthcare APIs

RESTful APIs are useful for re-implementing existing interfaces in an API-enabled manner or simplifying the integration effort for applications with well-defined data workflows. However, when fulfilling data flow requirements from multiple domains, an API architecture must encompass an adequate variety of data-delivery mechanisms. RESTful APIs are typically request–response-oriented, which may hinder performance due to latency in request response iteration or volume management. Event-driven APIs allow the creation and propagation of data events with publisher/subscriber distribution concerns, delivering real-time data to interested subscribers. Streaming APIs provide virtually continuous data flows as a (bidirectional) stream of events in a lightweight format (e.g. JSON lines) suitable for high-volume data flows, enabling scalability through policy-governed partitioning.

Health data flows have increased dramatically across the industry and are poised for even higher levels of activity through AI-related initiatives. FHIR supports RESTful data flows for the model resources but does not address other categories of data flow.

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However, it would be shortsighted to ignore these other potential API delivery mechanisms, as future applications may require them too. A broad-minded view would examine all possible data-delivery mechanisms—RESTful, event-driven, and streaming—and enable implementers to address them adequately whenever appropriate. Addressing these other API patterns may also open new business opportunities.

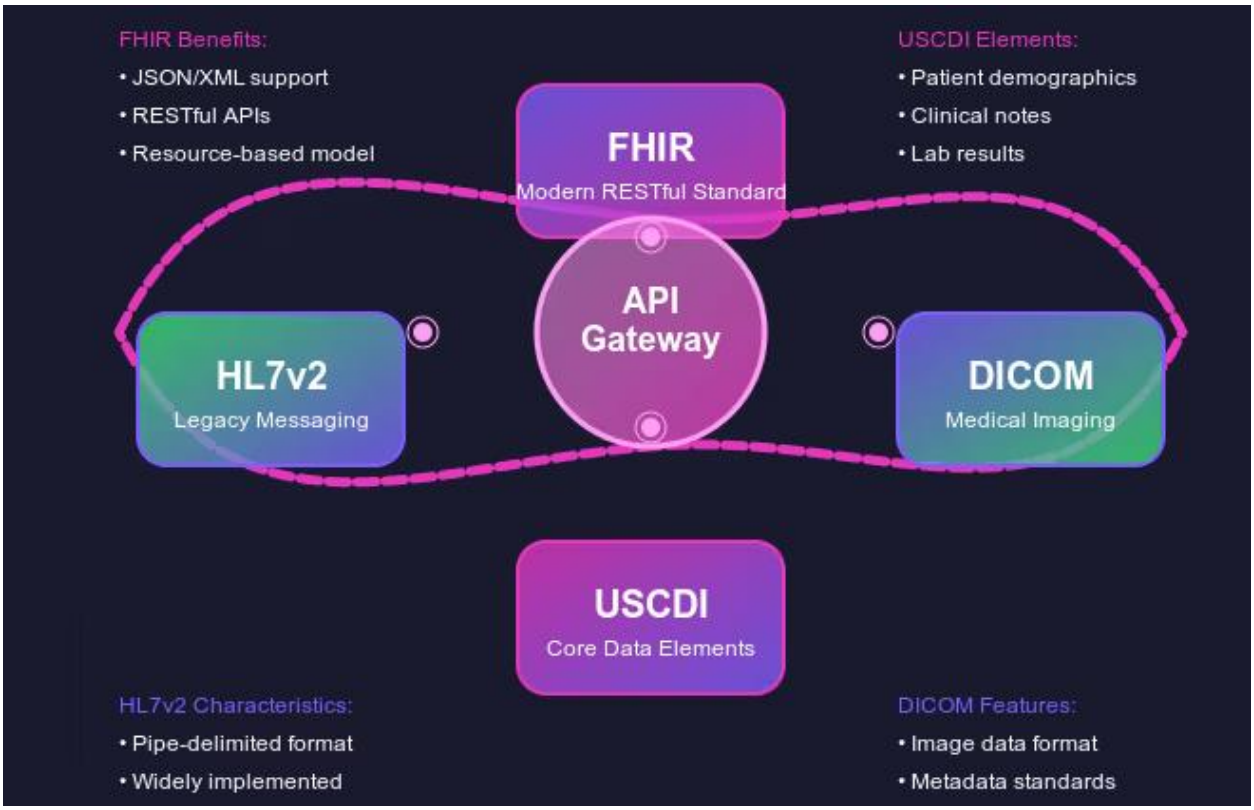

Fig 4: Architectural Patterns for Healthcare APIs

4.1. RESTful APIs and standardized resources

Most healthcare APIs should implement REST architectural constraints using resources consistently modeled according to Linked Data principles. CRUD operations on these resources should be expressed via the HTTP methods POST, GET, PUT, PATCH and DELETE; the state of a resource should control which operations are available; the consequences of operations should be discoverable by following hyperlinks in resource representations; and resource development should leverage existing work whenever possible. Implementing APIs in this manner improves their usability, enhances performance through caching, aids in API definition and client generation, and facilitates load balancing, geographic distribution and other scalability goals.

The four API patterns—RESTful CRUD, event-driven, provider-operated streaming, and client-operated streaming—have different latency and design tradeoffs that should be considered when making architectural choices. Many command or change-driven operations are best expressed through a resource state transition. However, some events or changes in state are more interesting or important than others and should therefore be published through an event-driven API, permitting interested parties to act on the event in an efficient and timely manner. For flows of real-time data, HATEOAS is not appropriate, but latency is paramount, governing the design decision of whether to create a streaming API on the healthcare provider side or on the consumer side.

Equation 3: Semantic interoperability score

$$S_m = \frac{N_v + N_m}{2N}$$

where

- N= total coded elements exchanged
- N_v= number correctly validated against the target value set
- N_m= number correctly mapped across coding systems

Derivation

Step 1: Semantic interoperability requires both:

- valid use of codes
- correct translation/mapping between coding systems

Step 2: Let

$$V = \frac{N_v}{N}, M = \frac{N_m}{N}$$

Step 3: Combine them equally:

$$S_m = \frac{V + M}{2}$$

Substitute:

$$S_m = \frac{1}{2}\left(\frac{N_v}{N} + \frac{N_m}{N}\right)$$

$$S_m = \frac{N_v + N_m}{2N}$$

4.2. FHIR and RESTful implementation strategies

The FHIR specification describes a set of Resource elements that can be assembled to describe virtually any health information. To realize the full potential of FHIR, these Resources must be delivered as RESTful HTTP-based APIs using the World Wide Web standards of HTTP, URIs, XML, and JSON. Each FHIR Resource has a common set of capabilities such as Create, Read, Update, Delete, and Search, with the provision of simple well-defined URLs enabling deep exploration of the web of health information. Each Resource must be formally defined for FHIR-based systems to be able to communicate to the fullest extent—including authorization—without further out-of-band agreement. Fulfillment of all these design requirements for any domain is, however, rarely possible in practice.

Two constraints on the use of FHIR for some healthcare domains are the desire for more stringent validation and the huge volumes of data. These are best treated with FHIR Profiles that define a constrained view of an FHIR Resource. A FHIR Profile specifically defines the conformity requirements for a set of resources, while FHIR Extensions provide mechanisms to augment existing Resources. Performance on an individual operation can be optimized under a profile by specifying slicing on collections of data in an FHIR Resource. Sensitivity can be expressed using the Provenance Resource. FHIR Profiles can also be used to indicate security labeling to support access control above the base CRUD capability. Such optimizations come at the cost of FHIR Resource reuse—so their application must be carefully considered and constrained.

4.3. event-driven and streaming APIs

APIs must be treated as strategic artifacts; evidence-based arguments, clarity, and formal structure support API-First Design as a strategy for healthcare interoperability.

Real-time data flows via event-driven and streaming APIs in public cloud services have the potential to improve patient outcomes through timely clinical intervention. Such flows require proactivity and engagement from the receiving party. Furthermore, processing data as they arrive can reduce compute spending compared to batch processing. Nevertheless, low latency comes at a cost. Queuing and stream processing services require additional management overhead; latency-sensitive processing adds complexity and can change the deployment architecture of dependent systems.

Event-driven and streaming APIs are designed for events and streams. An event is a notification that some occurrence has taken place. Generally, events are relatively small pieces of data that inform subscribers of a changed state that typically requires no immediate action. Event-driven system designs support such notifications by allowing anyone in the system to “publish” an event. Other participants can subscribe to these events, but the event publisher need not know what consumers exist or how many there are. Publish/subscribe is a well-known architectural pattern to handle event distribution and consumption. Streaming APIs operate on data streams that represent real-time flows from a data source. Unlike events, these flows are typically very large and require specialized handling, such as aggregation or windowing.

Unlike with standard API requests, data sensitivity and regulatory requirements are less easily enforced for event-driven data flows. For example, a patient may not want a clinical lab in another country receiving copies of their COVID-19 test results but may allow a government health authority to do so. Such authorizations are more complicated to handle than private or healthcare provider data-sharing consents.

Level	Description	Example in Healthcare
Domain Resources	Real-world entities	Patient, Doctor, Lab Result
API Level	Representation of resources in APIs	/patients/{id}
Ecosystem Level	Interaction across systems	Hospital ↔ Insurance ↔ Lab

Table 2: Levels of Resource Modeling in API-First Design

5. Standards, Compliance, and Data Semantics

Achieving interoperability in healthcare demands semantic data alignment so that exchanged information can be eciently processed and understood by the target system. This requires careful selection and proper linking of terminologies and value sets. Because sensitive health data is involved, stringent privacy and security controls must be in place. Data access must be authorized, and auditable consent management procedures implemented.

All data exchanges must be recorded. Audit logs should document what data were exchanged with which parties over what time frame, as well as how they have been accessed and used. Audit trails are also needed to support data provenance. These mechanisms help reinforce accountability in sensitive and trust-critical domains such as healthcare.

Support for standardized terminologies, privacy and security controls, auditing and consent management should be included in API APIs Standards and tooling implementations. These capabilities should be made easily accessible to all parties. They should also be prepared for testing with minimal configuration effort.

A set of well-defined coding systems is critical for enabling semantic interoperability across systems and applications. Such coding systems should incorporate standards-based value sets and mappings, and provide terminology services to allow linkages and translations across coding systems. Whenever important, the semantics of coding systems should be formally described in

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ontologies, thereby enabling use cases that require machine-based processing of data. Models for Privacy, Security, and Consent Management present mechanisms for online privacy and security protection and make use of distributed ledger technologies (DLT) to provide truly private and secure access to users' data. Such models enable users to impose fine-grained access control policies based on context for any kind of data. The control policies that govern access to the users' data can be enforced in a verifiable way using smart contracts and DLTs. Furthermore, consent management processes that guarantee the privacy of users can be followed without removing the incentive for data sharing.

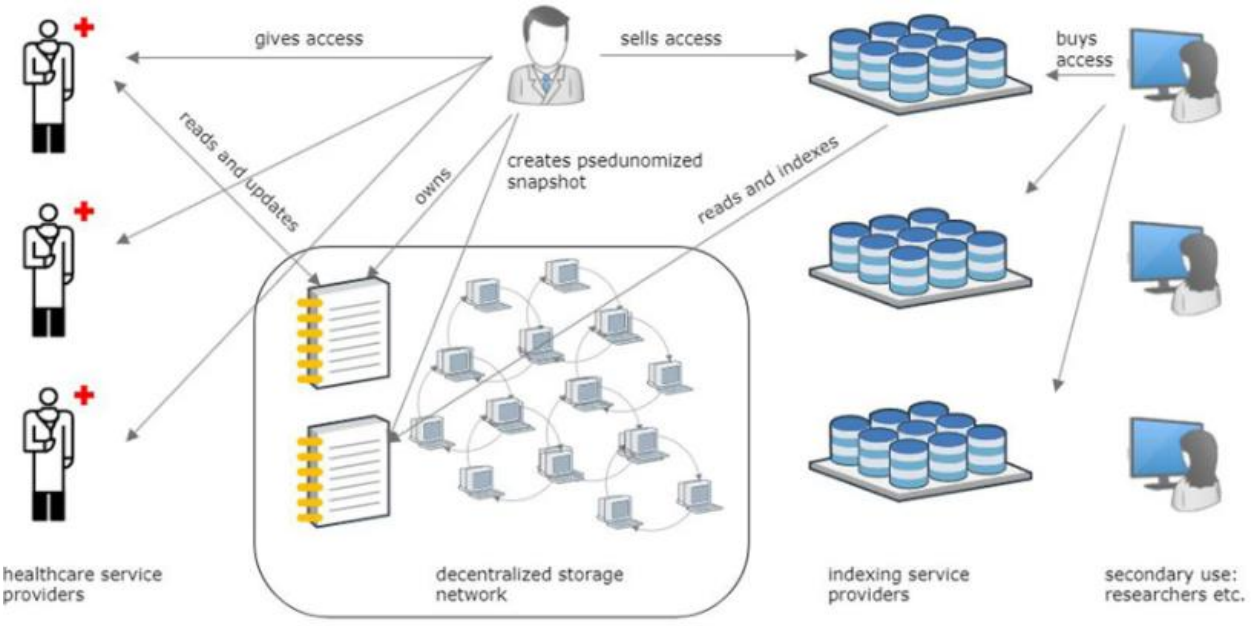

Fig 5: Standards, Compliance, and Data Semantics of Architectural Patterns

5.1. Terminologies and value sets

Successfully implementing an API-First design requires using appropriate terminology and the requisite semantic data coding. A coding system is a logical arrangement of codes for the representation of data values. Mapping is an active process of associating coding systems, or subsets of a coding system, with each other. It supports the maintenance of terminologies and value sets and their subsequent use in API calls.

A terminology service provides access to a terminology, a coding system, or a mapping, either for validation or for translation of codes. When used for validation, a terminology service supports semantic interoperability by checking that a code from a given coding system is being used correctly within the business semantics of the API, that is, that it is semantically allowed in the value

set assigned to the API parameter or data element. When used for translation, a terminology service enables mapping of the code supplied in the API call to any other coding system for coded data or value set defined in that other coding system.

To support these objectives, the availability of recent-value-set resources (the value set bindings) within the API call and the coding mappings at the time of the API call should always be guaranteed. In addition to general technical accessibility, appropriate levels of access control must be implemented for data sources hosting sensitive data whose presence in a terminologies or value set mapping service is essential for correct behavior in an OpenAPI-based HSTE ecosystem (for example, test results relating to drug abuse clearinghouse registries).

5.2. Privacy, security, and consent management

Access to personally identifiable user data must be limited only to authorized users. Policies governing data access are defined by laws, regulations, and business contracts. APIs should enforce these policies through Identity and Access Management (IAM) facilities, enabling organizations to determine who can do what, under which circumstances, and for which data. IAM includes authentication, which verifies identity via personal credentials such as passwords, security tokens, biometrics, and device context; authorization, which determines the access rights of each user or system; and access control, which defines how access rights are enforced. Unlike authorization, which is usually managed as a static list of roles and associated privileges, access control is applied to each unit of data and can vary from request to request.

End-to-end data protection requires data to be encrypted when it is stored, when it is being processed, and when it is being transmitted over the wire. APIs must ensure that data is encrypted for both storage and wire transmission and that any decryption of data is performed exclusively by authorized applications and users. For sensitive data, which is required to be encrypted at all times, APIs also need to provide protection mechanisms while data is being processed. Using special decryption keys that are only made available at runtime, sensitive data can be decrypted in-memory for processing without ever being stored in plaintext format at any time.

Equation 4: End-to-end API quality score

$$Q = \beta_1 R + \beta_2 P + \beta_3 Sec + \beta_4 Obs + \beta_5 B$$

where

- R= reliability
- P= performance
- Sec= security score
- Obs= observability score
- B= backward compatibility score

with

$$\sum_{k=1}^{5} \beta_k = 1, \beta_k \geq 0$$

Derivation

Step 1: The paper defines quality through multiple runtime and lifecycle attributes.

Step 2: Each attribute can be normalized to $[0, 1]$.

Step 3: Aggregate with weighted average.

Thus:

$$Q = \sum_{k=1}^{5} \beta_k \, q_k$$

5.3. Auditability and provenance

Auditability ensures accountability by enabling detection of misbehavior or rule violations. The entire system cannot be trusted by default; audit mechanisms provide the necessary checks and balances. Audit trails can include basic events, privacy violations, role or policy violations, integrity violations, and other incurred costs. They also answer questions about who has performed actions on sensitive data, ranging from data creation to data transfer to external parties.

Data provenance provides a complete history of the digital representation of a piece of data, usually referred to as a data product. It consists of the data source, data transformation steps, and data destination. A data product is said to have multiple lineage curves: in addition to the actual data product itself, it should include the historical traces of every modification that has happened to the data along the way. Data products should always be associated with their complete history, which is known as data lineage, in order to guarantee trustworthiness. A provenance-enabled platform monitors all data that is transferred within its area of responsibility and offers a provenance service that contains the complete history of that data.

Therefore, the audit and provenance capabilities should be present in every application using the data commons. The lines of all moves and modifications should automatically be acquired; otherwise, the systems cannot be trusted. Furthermore, the audit and provenance capabilities should not impose any operational or economic burden on their users. The data commons should generate those data tracking services and offer them as a commodity.

6. API Governance, Lifecycle, and Quality

The activities required to ensure adherence to API-First principles can be grouped into two main categories: governance of design-time decisions (when APIs are planned and created) and governance of runtime decisions (when APIs are consumed and

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managed). On the design side, API standards and software quality control systems are defined and enforced to minimize risk and maximize interoperability. On the runtime side, conformance with each API contract is assured, testing supports compliance with interoperability standards, and the impact of changes on dependent systems is assessed.

The API lifecycle encompasses all activities related to API provisioning, from design and production through deployment and consumption to retirement. In addition to design and engineering, it also includes documentation, discovery, testing, certification, operation, monitoring, maintenance, and deprecation. During initialization, an API testing suite is created. A mock testing environment is also established, allowing developers to test dependent systems well before the actual API implementation and its contract are available. Subsequently, the implemented API and associated contract are verified using the test suite. Deploying an API consumes resources and exposes operation costs, so careful monitoring is essential. Observability is thus crucial, enabling detection of anomalies that disrupt availability. APIs also have a limited lifetime: eventual deprecation must therefore be planned, and any effect on dependent systems assessed.

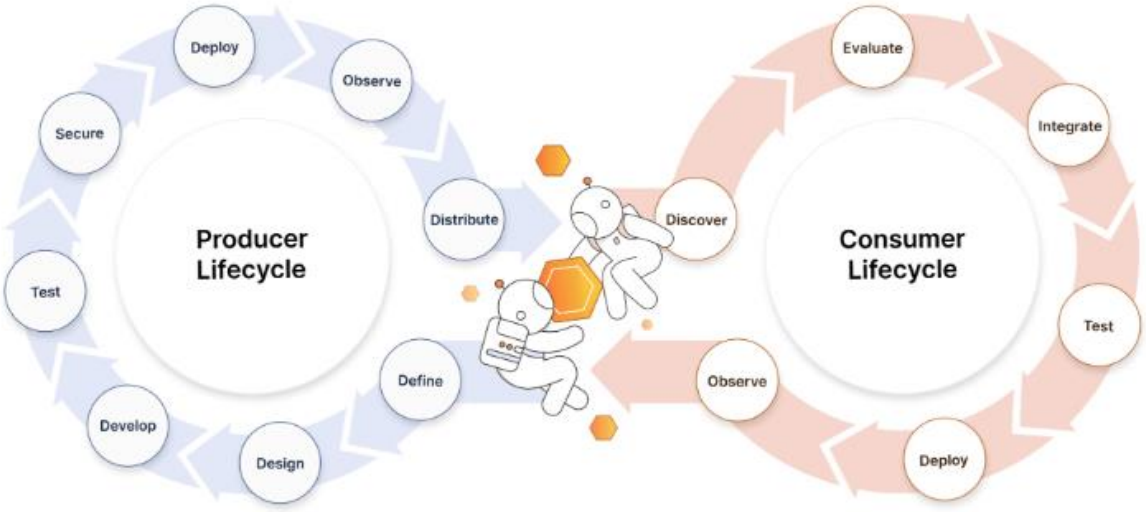

Fig 6: API Lifecycle

6.1. Design-time and runtime governance

External APIs must comply with standards for an interoperable infrastructure. The API governance framework defines rules and processes for standardizing API design, testing interoperability, and fulfilling policy requirements such as security, privacy, and data localization.

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API quality assurance occurs in two stages. At design time, APIs must undergo design reviews, certification testing, and publication in an API catalog. At runtime, they are subject to security and policy checks enforced by an API gateway or similar mechanism.

To be effective, the API governance processes must be clearly documented, continuously communicated, and available for consultation. A comprehensive collection of templates and checklists can facilitate engaging a large number of stakeholders.

Design-time governance should ensure that APIs satisfy the following criteria:

1. Implement stated capabilities and comply with API standards.

2. Support functions for which they are intended.

3. Respond correctly to test cases for positive and negative scenarios.

Interoperability and QA certification testing require a test suite and a testing framework that can simulate individual APIs in isolation, in concert with other APIs, or within a complete ecosystem. Mock environments can be beneficial by permitting early testing of consumer and provider applications even when underlying APIs are still in development.

Equation 5: Reliability equation

$$R(t) = e^{-\lambda t}$$

where

- λ= failure rate
- t= operating time

Derivation

Step 1: Assume constant failure rate λ.

Step 2: Then probability of survival up to time $t$follows the exponential law.

Step 3: Therefore reliability is:

$$R(t) = P(T > t) = e^{-\lambda t}$$

If the system has redundant independent replicas in parallel, reliability becomes:

$$R_{\text{parallel}}(t) = 1 - (1 - R(t))^n$$

Parallel reliability derivation

For $n$identical independent replicas:

Step 1: Probability one replica fails by time t:

$$1 - R(t)$$

Step 2: Probability all $n$fail:

$$(1 - R(t))^n$$

Step 3: Probability at least one survives:

$$R_{\text{parallel}}(t) = 1 - (1 - R(t))^n$$

6.2. Testing, certification, and conformance

Various testing approaches can be used to verify API implementations. Test suites designed for specific features of the API should be created and, whenever possible, jointly developed by multiple organizations that are implementing or consuming the API. Ideally, such suites should be, or should be able to be generated from, formal definitions of the API, possibly complemented by additional test cases or specifications that can be better expressed informally. Notably, organizations developing APIs for public use (or for use by a wider set of partners) should provide a test suite that verifies conformity to the specification together with a mock implementation that enables consumers of the API to develop and test their applications before the actual API is available.

In addition to the testing, organizations should document certification criteria for APIs, based on the existence of a proper test suite and its successful execution. Within a governance framework, APIs should also be marked as compliant or certified. Certification criteria can be extended to cover specific use cases and configurations. Testing for interoperability between applications should be organized on a regular basis to facilitate the development of partnerships.

6.3. Versioning, deprecation, and backward compatibility

The API lifecycle is governed by policies that address versioning, deprecation, and backward compatibility. APIs should undergo versioning whenever backward compatibility cannot be guaranteed, whereas changes that enhance usability, performance, or security require no versioning. Such enhancement change should be communicated to the API consumers in a timely manner. When implementation of a specified feature no longer makes sense, the API provider may decide to remove it. In such a case, the feature should be deprecated before being removed; i.e., some prior announcement must be made about its eventual removal.

Versioning should be done in a manner that is transparent and predictable for API consumers. Two main versioning strategies are commonly used: a dedicated version identifier that changes whenever the API is versioned, and a version identifier builtin to the resource representation of the API. A version identifier of the former type is more commonly used, as it allows consumers to address the appropriate version simply by changing the URI. An API deprecation timeline should be established for each versioned API, specifying a deprecation period before it is removed. As part of the planned deprecation, the deprecated API and its roadmap must be evaluated to identify any changes that should be made to enable future versions to be backwards compatible.

7. Deployment Architectures and Operational Considerations

API gateways, security, and mediation: gateways mediate between APIs and their clients. They enforce security policies, aid in traffic management, accelerate API calls, and simplify client logic. They must support identity and access management, and control API usage and quotas. For APIs dealing with sensitive data, gateways can prevent access if data is subject to specific security classifications. Gateways can also facilitate content negotiation, operate as firewalls, and consolidate log data.

Security mediation patterns depend on the number of APIs accessible through a given gateway. If each API has its own security requirements, the gateway must invoke an IAM system before forwarding a request. If APIs have common security needs, the gateway can be augmented with a security filter to mediate calls to any API defined within expected parameters. The filter must be able to reject invalid requests earlier than a full IAM call would allow. Reusable IAM functionality can be provided through internal APIs, for example, a call to check if a user is authorized to access a given API resource.

Scaling and reliability considerations: gateways serve as ingress points to APIs, so their availability and performance can determine availability and performance. Workloads can be balanced across multiple gateway replicas. For costly operations, redundancy must be built at a deeper level, at the service or data layer. Scaling up through redundant processing may still not satisfy high traffic demand. Functionality can be reconfigured, moving to a service-based or process-based architecture. For APIs requiring very low latency, keeping local copies of frequently requested data can provide significant speedup, with data being updated either periodically or on-demand. Serving from replicas can be performed under heavy data access. Monitoring and tracing allow an organization to better react to failures and test the coverage of its incident response plans.

7.1.API gateways, security, and mediation

API gateways are the point of contact for applications accessing APIs. Their role is threefold: to act as a gate, managing access control and providing the means to authenticate or authorize requests; to enforce policies for the consumption of APIs, such as rate limiting or access conditions based on attributes of users and requesting devices (e.g., location, time of day); and to act as a mediator that transforms requests and responses so that different partners do not need to know how the other party is using its own API.

Because data exchanged between partners may include sensitive information, APIs often require information access management (IAM), which identifies the user (authentication) and verifies that the user is allowed to access the resource (authorization). IAM ensures that a user has the right, opportunity, and capability to access or use resources. IAM solutions typically provide several features, including user storage and lifecycle management; secure access (SSO, RBAC, MFA); fine-grained access control

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policies; user activity logging, breach detection, and alerts; and management of security keys and certificates. IAM products can manage Internet users or internal employees working on various platforms (e.g., Web, mobile, call centers).

Pattern	Description	Use Case	Limitation
RESTful APIs	Request-response model	CRUD operations (EHR access)	Latency issues
Event-Driven APIs	Publish/subscribe model	Notifications (lab results)	Complexity in management
Streaming APIs	Continuous data flow	Real-time monitoring	High infrastructure cost
Hybrid Approach	Combination of above	Complex healthcare systems	Design complexity

Table 3: API Architectural Patterns Comparison

7.2. Scalability, reliability, and observability

Service architecture must accommodate potentially thousands of applications and millions of users performing millions of operations every day. APIs, like Web Applications, must therefore be horizontally scalable. Load balancers, placed in front of API gateways, monitor traffic and adjust, based on preconfigured rules, the pool of gateway nodes. At peak moments requests are routed, e.g., across centers in different geographic locations, to mitigate latency. Vertical scaling is another way to cope with increased load. It consists of adding more memory, CPUs, disk, storage, etc. when more power is needed. This is particularly helpful for scaling apps that require fast storage. If these ladders are operated correctly, the cloud infrastructure becomes a cost-efficient way to resize.

Apart from being scalable and low in latency, APIs must also be reliable. The primary means is redundancy: to have spare copies of the resources so that the failure of one does not affect the overall availability. For APIs, redundancy can be applied in system configuration using a Master-Slave configuration. However, redundancy it not a CMDB and so it will have to be handled manually. Resources must therefore be carefully classified, analyzed, and managed in order to guarantee their redundancy.Like any other IT solutions, APIs must offer complete visibility into the system and its activities both for troubleshooting and global view of what is happening on the network. By having a method for monitoring APIs, the operations team can directly respond to issues with the API layer before they surface as issues for the application.

7.3. Data localization and sovereignty considerations

Data localization requirements impose clear constraints on where data can be stored and which local laws govern data access. Cross-border data flows are also increasingly regulated with restrictions on data transfer and storage outside specific jurisdictions. However, enforcing such requirements in a heterogeneous, decentralized health ecosystem is non-trivial. Data localization rules can either limit data-sharing options by restricting data storage and processing to a single jurisdiction or result in costly moves to a more liberal jurisdiction. Intelligent mediation patterns that consider data locality can mitigate these downsides while addressing dynamic language and jurisdictional requirements.

APIs are interacting with the underlying hardware at much lower levels to achieve finer control over data transfers and deployments. Instead of merely supporting rack-aware location requirements, the API interaction also allows the programmer to fine-tune the physical data layout in a more cost-sensitive way. Data placement constraints are now exposed as first-class objects. During an update, data may be streamed to cheaper locations before finally moving to their destination—enforced by the API system transparently handling dynamic links. Apart from minimizing financial costs for storage, such patterns also seek to minimize response times and avoid wide-area latency. Even region-based replication can now be used selectively to prioritize data freshness—useful in applications where consistency is weaker.

Medical history provides a clear understanding of country-specific medical regulations and localization considerations. An intelligent middleware acts as a translator that governs the interface exposure with web clients, browsers, and the database. This ensures that the data is always in the preferred local language of the client requesting access to the resources as well as fully complies with local data regulations and data locality requirements.

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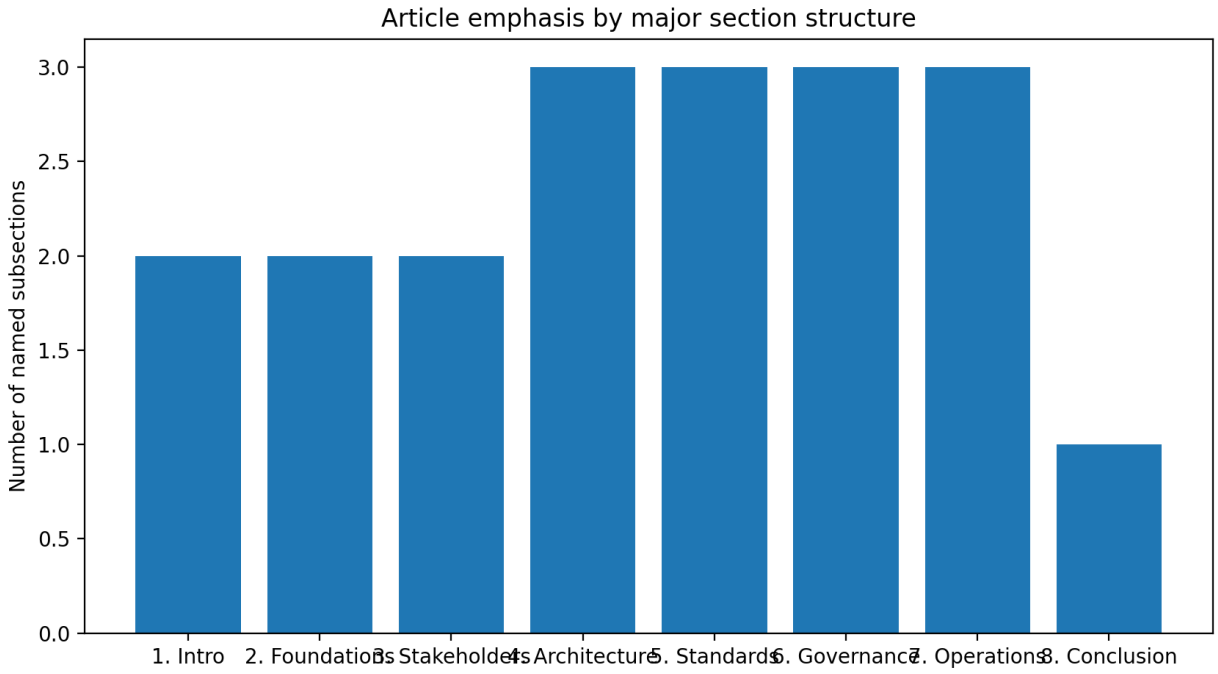

8. Conclusion

Interoperability shapes the ability to exchange and use information. APIs should be treated as strategic artifacts, and API-First Design is a pragmatic action-focused framework to make interoperability a predictable, manageable, and measurable objective. API-First Design begins with an articulation of the core concept, followed by an overview of a broad spectrum of stakeholders, stemming API maturity models, and architectural patterns. The subsequent outline of standards, compliance considerations, and data semantics sets a foundation for the effective governance and management of APIs across the full API lifecycle. The discussion then turns to deployment architecture, operational constraints and strategies, economic modeling, and incentives.

Greater understanding, evidence, and analysis have conveyed convincing evidence of economic value and benefit. However, key elements of comprehensive toolkits remain missing. The API-First Design framework outlines and organizes key considerations but is not a substantive toolkit. Addressing these gaps will take time, focused investment, and careful attention to detail. Progress will finally make interoperability behind health information exchanges a predictable and transparent investment and operating decision instead of a hope and gamble.

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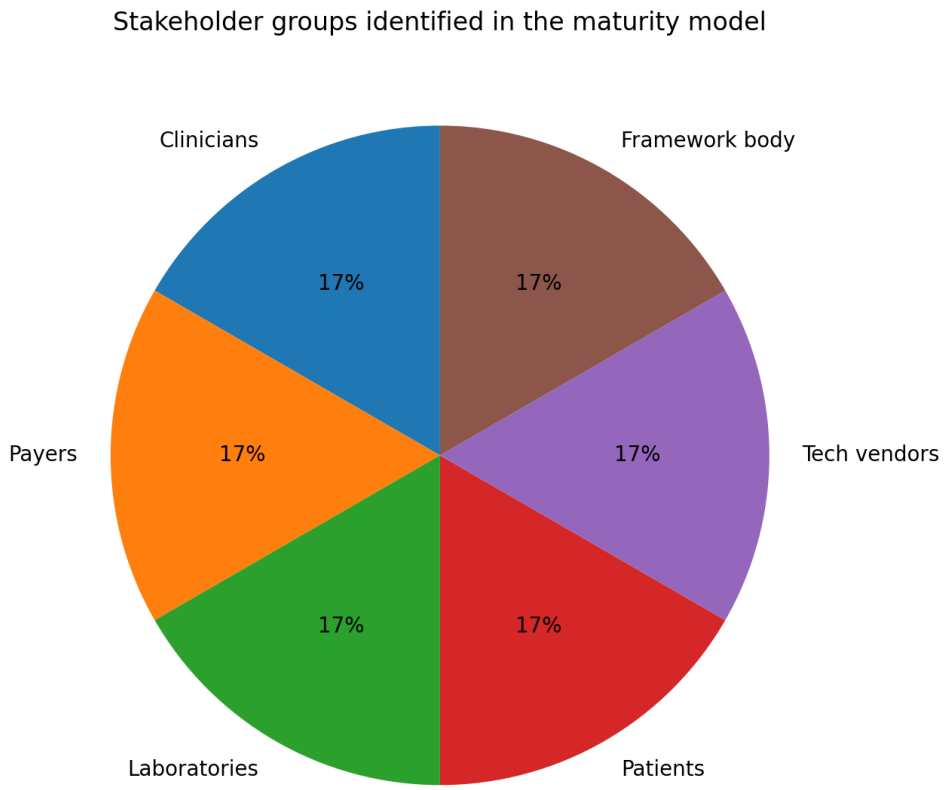

8.1. Emerging Trends

Real-world applications corroborate the perspectives of industry leaders: APIs bring value, and API-First Design accelerates interoperability. Crucial to success is adoption of API-First Design principles for all APIs and concerted planning across all APIs. Healthcare APIs span diverse domains but often lack crucial higher-level quality characteristics, such as reliability and performance. Broader adoption of an API-First mindset coupled with measures to enhance API-First quality characteristics—such as security, extensibility, observability, versioning, and backwards compatibility—will facilitate greater interoperability and unlock the full promise of healthcare APIs. Despite these prospects, further key enablers remain underdeveloped or misaligned.

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