Architecture for Blockchain Applications – Overview, Design Process, and Design Patterns

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Lecture 4 in Ringvorlesung “Blockchain & RPA” @ CAU Kiel

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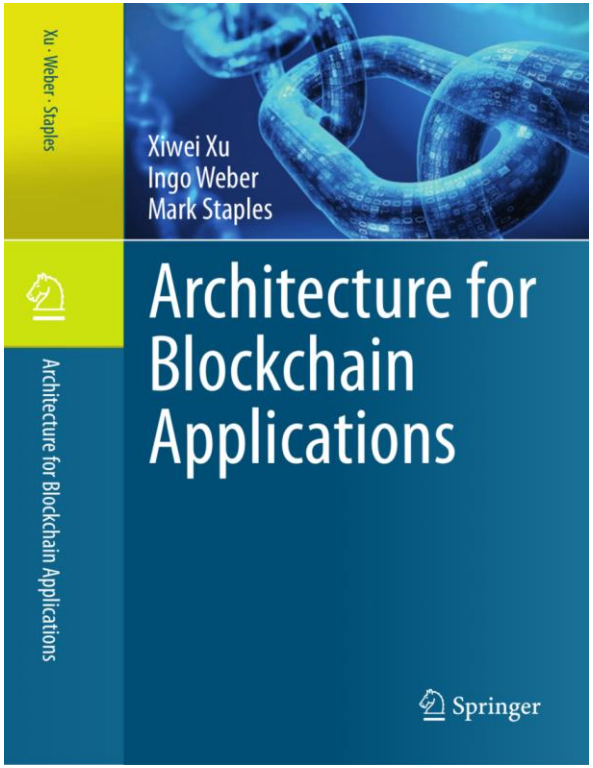
Book for this lecture: Architecture for Blockchain Applications



Xiwei Xu, Ingo Weber, Mark Staples.

Architecture for Blockchain Applications.

Springer, 2019.

Includes definitions of blockchain (concept), DLT, smart contracts, etc.

Blockchain Research with my previous team at Data61 – Overview

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DOMAINS

- Supply Chain / Food Provenance
- Resource handling (energy, water, land, titles)
- Welfare payments
- International trade

GOALS

- Designing Trustworthy Blockchain Systems Using Smart Contracts
- Architecting Blockchain applications using Model-driven development of smart contracts

TECHNOLOGY

- Distributed Ledger Technologies
- Blockchain platforms
- Smart contracts
- On/Off Blockchain storage

OUTCOMES

- Identifying design trade-offs
- Identifying Technical Risks & Opportunities
- Formal and empirical evaluation of Blockchain systems

PRINCIPLES

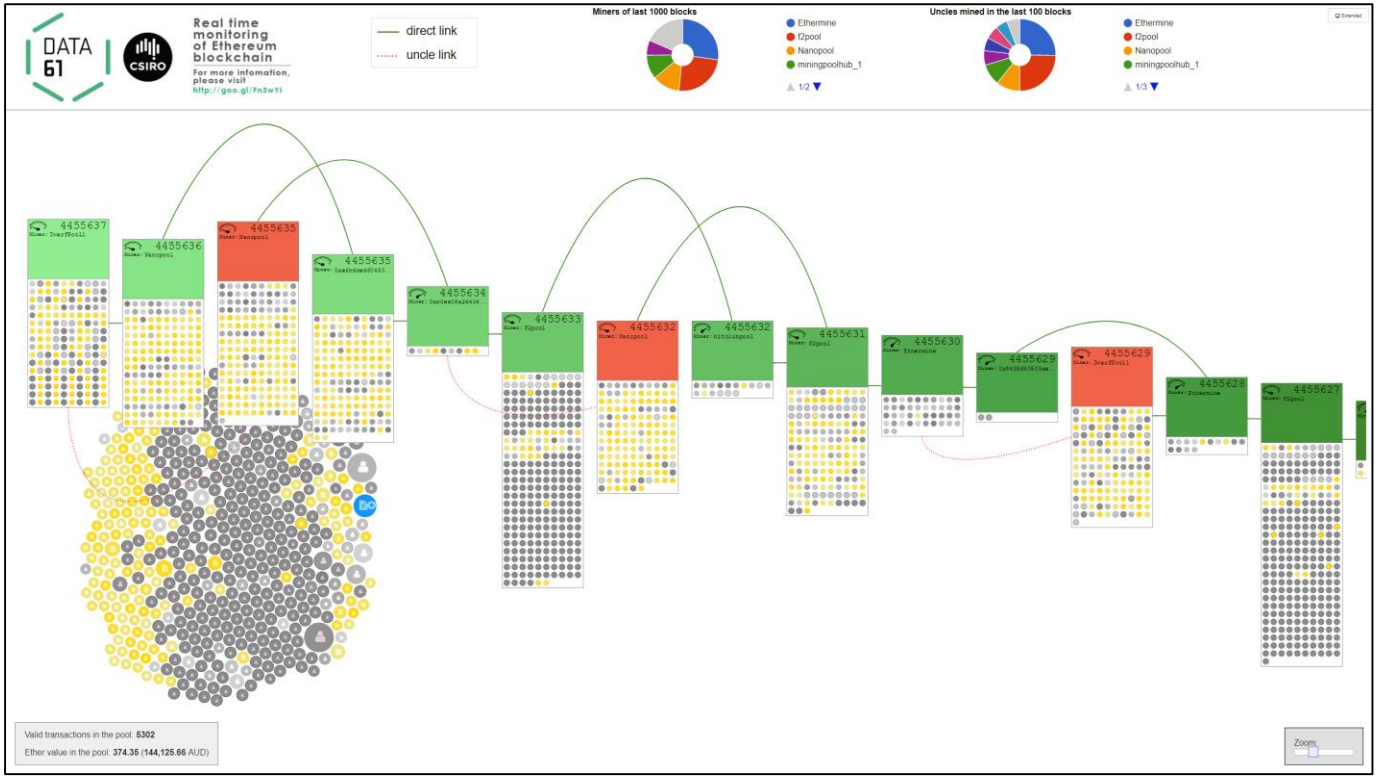
- Software Engineering & Architecture
- Business Process Management
- Cyber Security
- Dependability

What is the Beef about Blockchain?

Video & reports:
https://www.data61.csiro.au/en/Our-Research/Focus-Areas/Distributed-Ledger-Technology-Blockchain

What is a Blockchain?

Visualization of a Blockchain: http://ethviewer.live



Blockchain 2nd gen – Smart Contracts

- 1st gen blockchains: transactions are financial transfers
- Now Blockchain ledger can do that, and store/transact any kind of data
- Blockchain can deploy and execute programs: Smart Contracts
  - User-defined code, deployed on and executed by whole network
  - Can enact decisions on complex business conditions
  - Can hold and transfer assets, managed by the contract itself
  - Ethereum: pay per assembler-level instruction

So what?

- Well, blockchains are exciting because they can be used as a new foundation for re-imagining systems:
  - a neutral infrastructure for processing transactions and executing programs
  - potentially interesting for innovation at **all touch-points** between organizations or individuals
  - ➢ **blockchain applications have the potential to disrupt the fabric of society, industry, and government**
- Blockchains can also be used as a technology platform to handle hard issues of data replication and system state synchronization with high integrity.

Selected Blockchain Projects

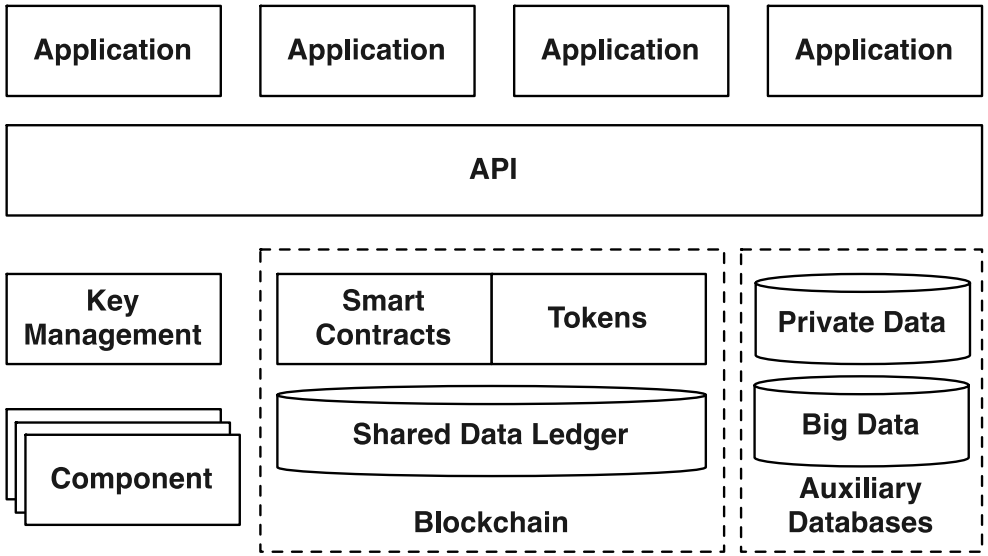
- Australian Securities Exchange:
  - Settlement of trades to be sped up from 2-3 days to minutes, freeing up billions of $$
  - Under development, industry engagement & testing ongoing
  - Go-live of the blockchain system planned for March or April 2021

- Modum.io:
  - Ensure drugs do not exceed a temperature threshold
    - Tamper-proof IoT device & blockchain storage of data
  - Otherwise: use refrigeration trucks, 4-8x pricier

- Australian National Blockchain
  - Joint initiative by IBM, Data61 CSIRO, HSF, KWM
  - Platform for blockchain-based legal contracts
  - For a fee, implement your business contracts in code

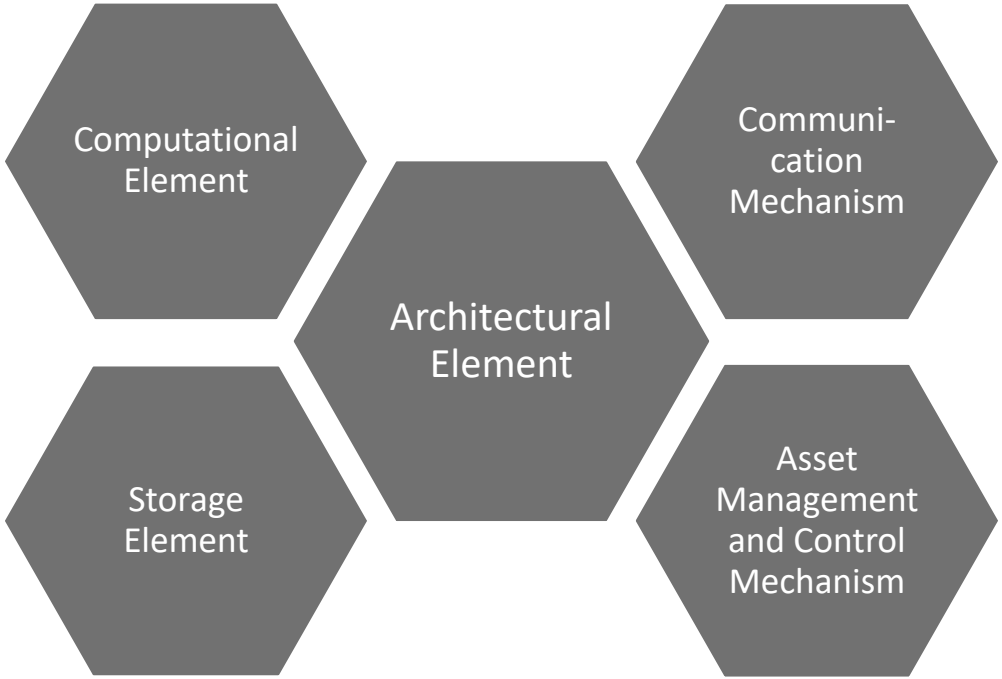
Overview

- Blockchain can be a component of a big software system
- Communicate with other components within the software system



Functions blockchain can provide in an application architecture

- Blockchain as…



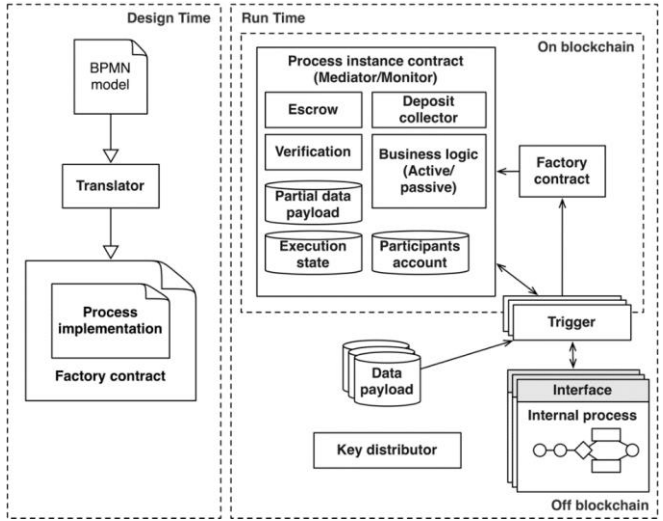
Non-Functional Trade-Offs

- Compared to conventional database & script engines, blockchains have:
  - (-) Confidentiality, Privacy
  - (+) Integrity, Non-repudiation
  - (+ read/ - write) Availability

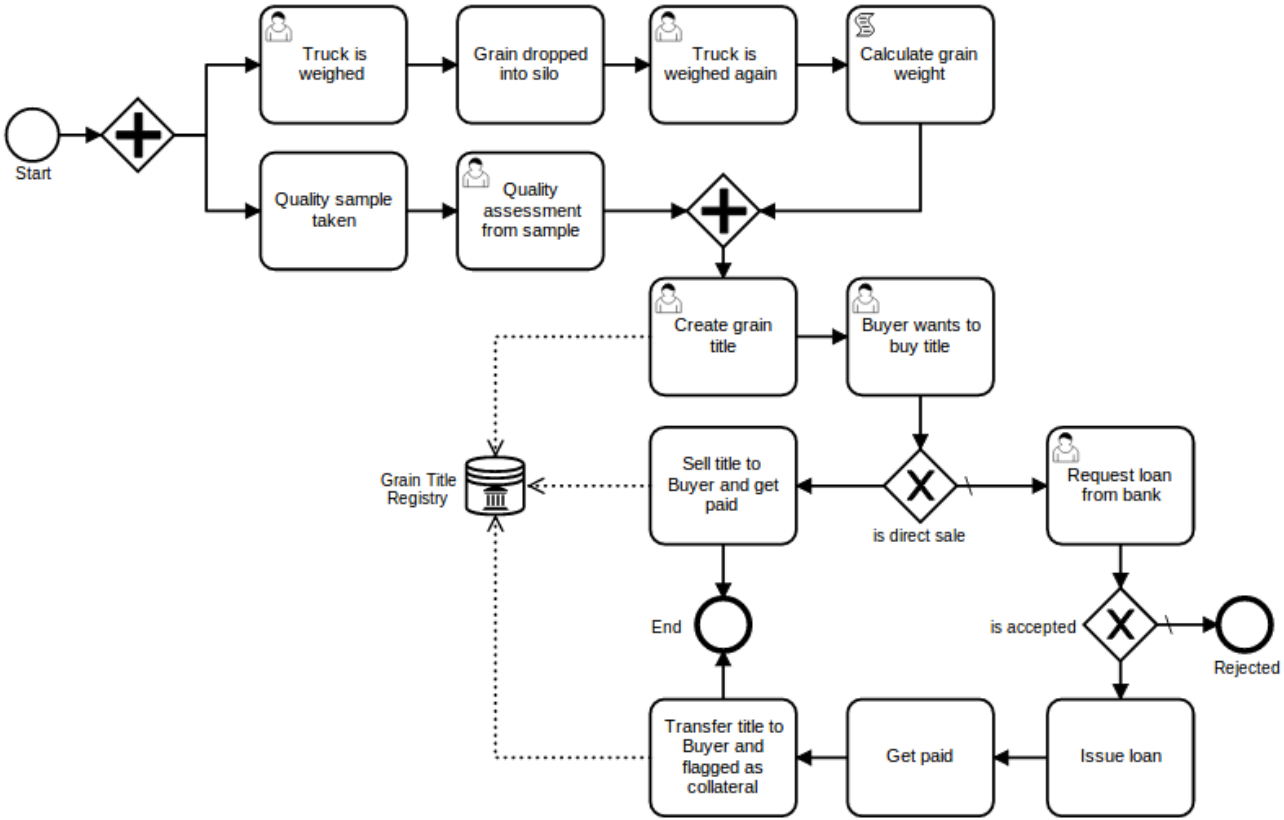
  } Security: combination of CIA properties
  - (-) Modifiability
  - (-) Throughput / Scalability / Big Data
  - (+ read/ - write) Latency

Model-driven Engineering / BPM

- Business Process Execution & Analysis
  - **Untrusted business process monitoring and execution using blockchain**, I. Weber, X. Xu, R. Riveret et al., BPM 2016
  - **Optimized Execution of Business Processes on Blockchain**, L. García-Bañuelos, A. Ponomarev, M. Dumas, I. Weber, BPM 2017
  - **Caterpillar: A blockchain-based business process management system,** O. López-Pintado, L. García-Bañuelos, M. Dumas, I. Weber, BPM 2017 Demo
  - **Runtime verification for business processes utilizing the Bitcoin blockchain,** C. Prybila, S. Schulte, C. Hochreiner, I. Weber, FGCS 2018
  - **Dynamic role binding in blockchain-based collaborative business processes,** O. López-Pintado, M. Dumas, L. García-Bañuelos, I. Weber CAISE 2019
  - **Interpreted execution of business process models on blockchain.** O. López-Pintado, M. Dumas, L. García-Bañuelos, I. Weber. EDOC 2019
  - **Modeling and enforcing blockchain-based choreographies.** J. Ladleif, M. Weske, I. Weber. BPM 2019
  - **Mining blockchain processes: Extracting process mining data from blockchain applications.** C. Klinkmüller, A. Ponomarev, A.B. Tran, I. Weber, and Wil van der Aalst. BPM Blockchain Forum 2019 - Best Paper Award
- Data / Asset Modeling
  - **Regerator: a Registry Generator for Blockchain,** A. B. Tran, X. Xu, I. Weber, CAISE 2017 Demo
- Combined Asset & Process Modeling
  - **Lorikeet: A Model-Driven Engineering Tool for Blockchain-Based Business Process Execution and Asset Management** A. B. Tran, Q. Lu, I. Weber, BPM 2018 Demo



Combining process and data/token models



Tooling: Lorikeet at Design Time

Lorikeet | Home | Design | Manage | Welcome 0x180d34b876DAa90057B2Ec345E82E2B1E9a4A082 | Log Out

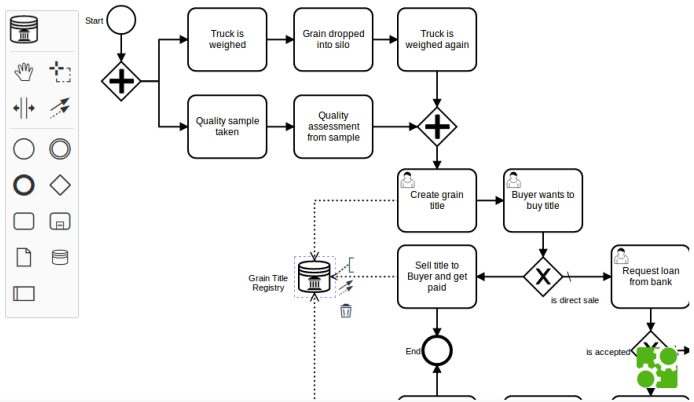
Edit BPMN Design | Compile | Save & Close | Cancel

Business Process Name

GrainSupplyChain

☑ Use Petri-Net Method

Save Model | Source XML



RegistryReference_03z5ksr

General | Listeners | Extensions | Registry Reference

General

Id

RegistryReference_03z5ksr

Smart Contract Output | Solidity Code

```
// -------- REGISTRY INTERFACES
contract GrainTitleRegistry {
    function record_create(uint weight) returns(uint record_id);

    function record_transfer_ownership(uint record_id, address buyer_address, bool is_collateral);
}
// ---------------------------

contract ProcessMonitor {
    //uint preconditions = 0x800;

    function getPreconditions(uint instanceID) internal returns(uint);

    function setPreconditions(uint instanceID, uint preconditions) internal;
    event taskCompleted(uint indexed instanceID, string taskName);



    // ---------- PROCESS VARIABLES
    bool isLoanAccepted;
    bool isDirectSale;
    bytes32 titleId;
    address buyerAddress;
    // ---------------------------

    // -------- REGISTRY CONTRACT ADDRESSES
    address addressOfGrainTitleRegistry = 0x11D6fd252049f869349CAdf4E2df3E17c8539Bf0;
    // -----------------------------------

    function ProcessMonitor() {
        //
        //
        //
        //
    }

    function Issue_loan(uint256 instanceID) returns(bool) {
        uint preconditions = getPreconditions(instanceID);

        if ((preconditions & (0x2 | 0x10000) == (0x2 | 0x10000))) {
            step(instanceID, preconditions & uint(~0x2) | 0x40);
            taskCompleted(instanceID, "Issue_loan");
            return true;
```

Evaluation of Suitability

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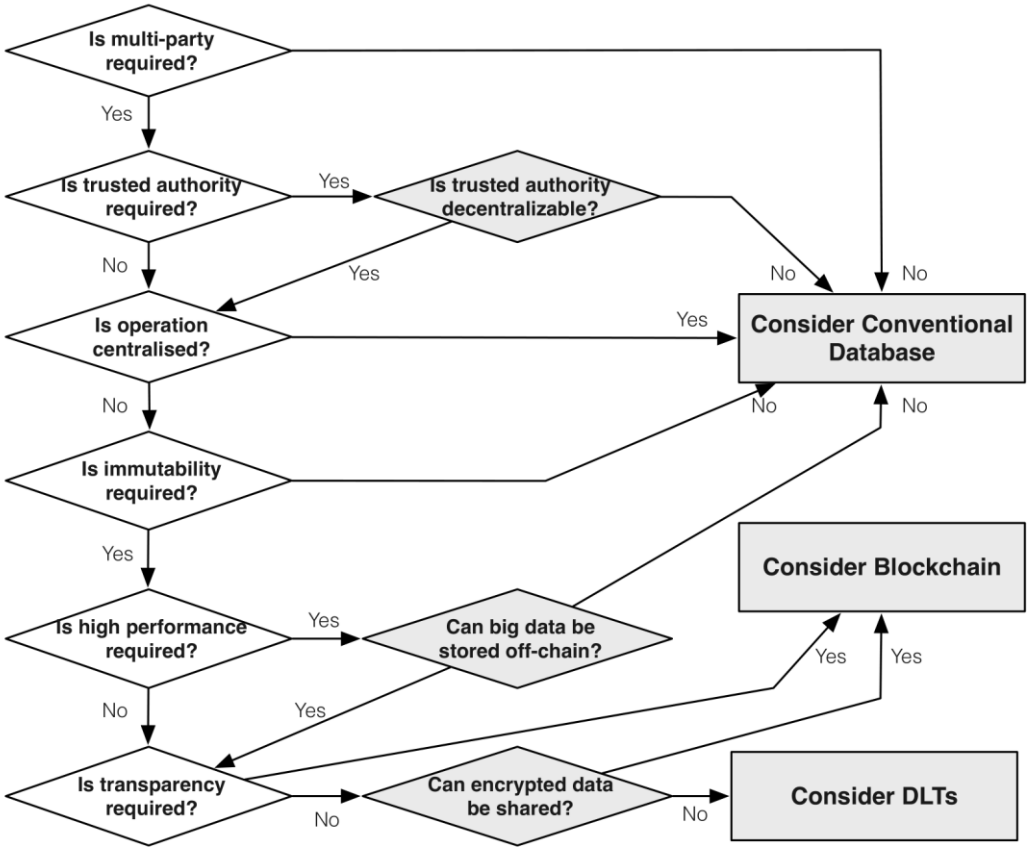
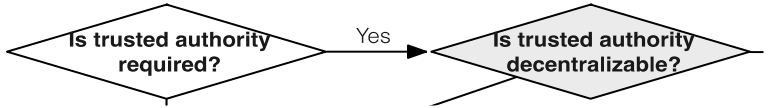
Evaluation Framework



Is Trusted Authority Required? 1/2



- An entity that is relied upon to perform a function (operating a system)
  - Blockchain is **NOT SUITABLE** if a single party can or must be relied upon as a trusted authority
  - Trusted authority implements a traditional centralized solution with conventional technologies

- Scope of the system is important in deciding the question
  - Bank is a trusted authority for bank accounts
  - Central bank is a trusted authority for inter-bank payments

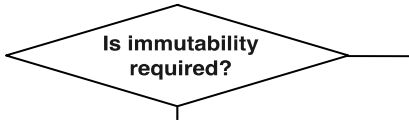
- Trusted authority is a single point of failure
  - Technical single points of failure can be mitigated by using redundancy
  - Single points of organizational or business failure remain present
    - Business failures, service interruptions, data loss or fraud.

Is Trusted Authority Required? 2/2

- Trusted authority is a monopoly or oligopoly service provider
  - "Rent-seeking" behavior is not uncommon
    - Increase one's share of existing wealth without creating new wealth
- A natural trusted authority might be difficult for everyone to accept → reliance on that party
  - Centralization of services can be perceived as a loss of control or power
- Blockchain is **SUITABLE** for system where no single party is acceptable for operating the system
  - Operated jointly by a collective of nodes
  - Does not remove need for trust entirely
    - Users are exposed to risk in use of blockchain technology
    - What is trusted is the software, the incentive mechanism, and "oracles"
  - Distributed Trust
    - Remove the need to trust a single third-party to maintain a ledger.

Is Immutability Required? 1/3

- *Data immutability* means data con not be changed or altered after its creation
  - Immutability supports non-repudiation
    - Assurance that a party cannot deny the authenticity of their signature
- Conventional technologies naturally support mutable data
- Blockchain naturally supports data immutability in the ledger
  - Linking of blocks in a chain of cryptographic hashes supports immutability
  - Data continually replicated across many locations and organization
    - Attempts to change it in one location will be interpreted as an attack on integrity
  - Strong evidence that the transactions were performed by someone with control over corresponding cryptographic keys
- Transaction history is immutable, the latest view of the current state can change



Is Immutability Required? 2/3

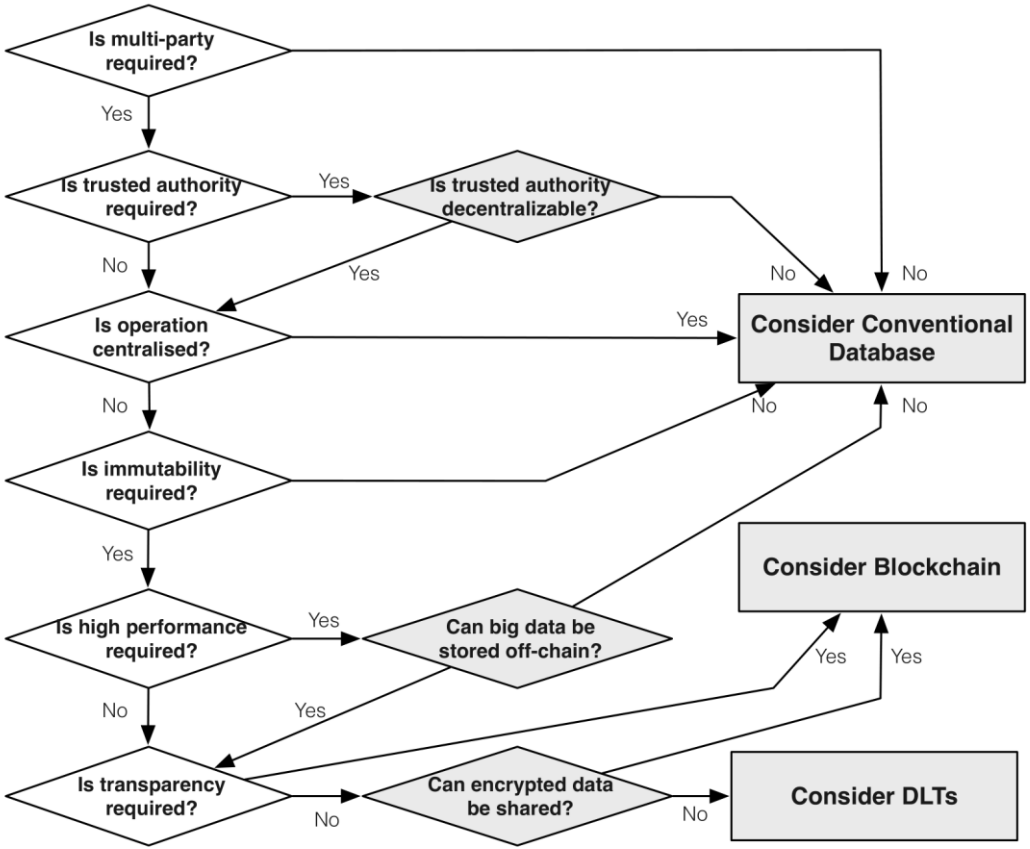
- Impossible to change the transaction history in most blockchains
  - Causes problems if blockchain contains illegal content
  - Court might order that content be removed from a blockchain
- Other issues
  - Disputed transactions
  - Incorrect addresses
  - Exposure / theft or loss of private keys
  - Data-entry errors
  - Unexpected changes to assets tokenized on blockchain
- Other cheaper mechanisms available to prove the originality of data
  - Hashing technology
  - Cryptographically signed data
  - Time-stamped, distributed / federated data stores

Is Immutability Required? 3/3

- Immutability of Nakamoto-based blockchain is a long-run probabilistic durability property
  - Conventional database supports ACID (Atomicity, Consistency, Isolation and Durability)
  - A transaction initially thought by a participant to be committed may later turn out to have been on a shorter chain
  - A transaction is in practice immutable if it has been committed to a blockchain for a sufficiently long time (number of confirmation blocks)

- Blockchain using other consensus mechanism can offer stronger, more conventional immutability
  - E.g. Practical Byzantine Fault Tolerance
  - Small number of known nodes participating in the operation

Evaluation Framework



Design Process for Blockchain-based Systems

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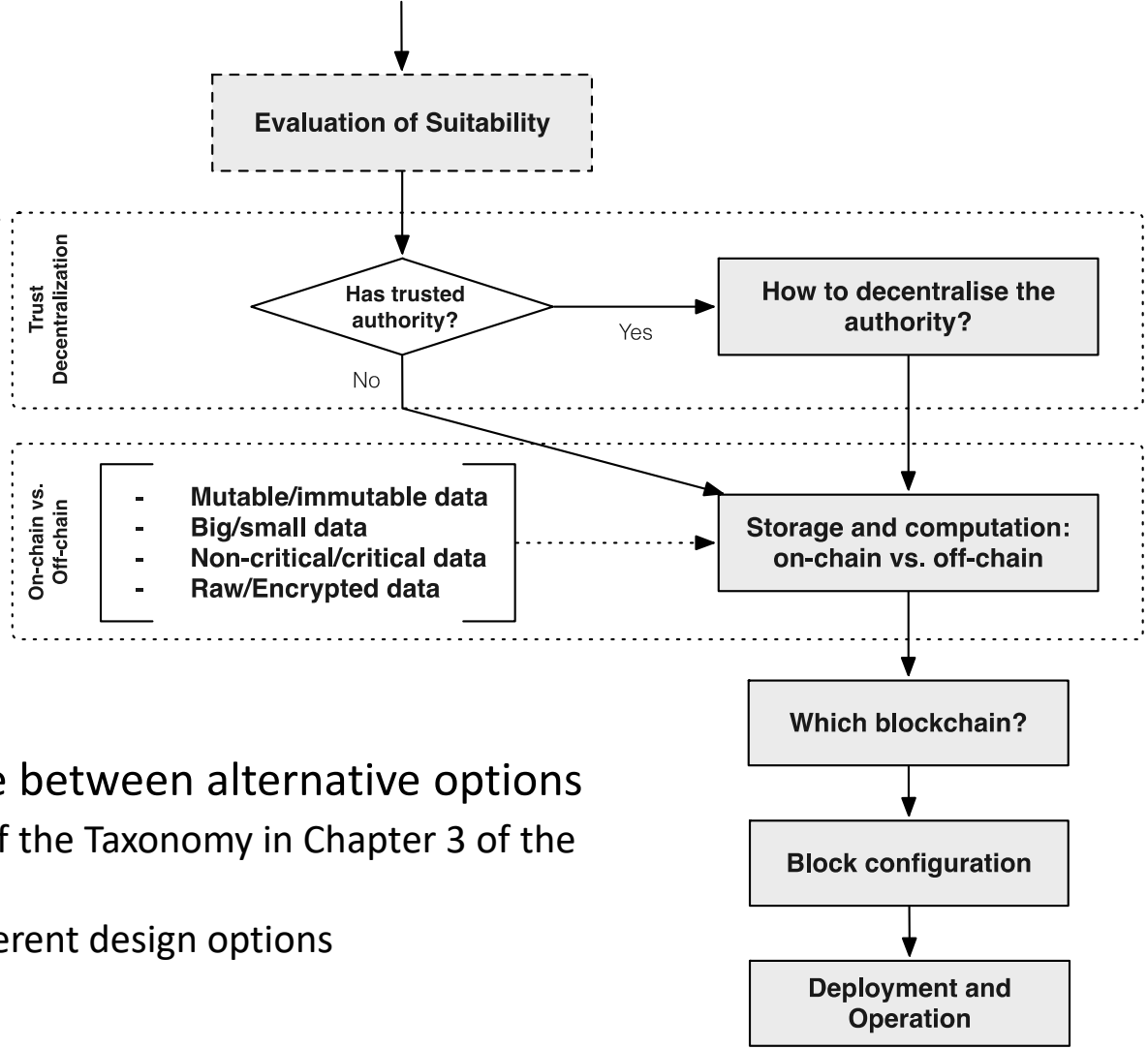
Design Process



- Every step helps to decide between alternative options
  - A guide through the options of the Taxonomy in Chapter 3 of the book
  - Systematic comparison of different design options

Taxonomy

Also consider skills available for a specific platform

Fundamental properties: immutability, non-repudiation, integrity, transparency, equal rights

Blockchain-related design decisions regarding (de)centralisation, with an indication of their relative impact on quality properties

Legend: ⊕: Less favourable, ⊕⊕: Neutral, ⊕⊕⊕: More favourable

Design Decision	Option	Impact: Fundamental properties	Impact: Cost efficiency	Impact: Performance	Impact: #Failure points
Fully Centralised	Services with a single provider (*e.g.*, governments, courts)	⊕	⊕⊕⊕	⊕⊕⊕	1
	Services with alternative providers (*e.g.*, banking, online payments, cloud services)				
Partially Centralised & Partially Decentralised	Permissioned blockchain with permissions for fine-grained operations on the transaction level (*e.g.*, permission to create assets)	⊕⊕	⊕⊕	⊕⊕	*
	Permissioned blockchain with permissioned miners (write), but permission-less normal nodes (read)				
Fully Decentralised	Permission-less blockchain	⊕⊕⊕	⊕	⊕	Majority (nodes, power, stake)
		Fundamental properties	**Cost efficiency**	**Performance**	**#Failure points**
Verifier	Single verifier trusted by the network (external verifier signs valid transactions; internal verifier uses previously-injected external state)	⊕⊕	⊕⊕	⊕⊕	1
	M-of-N verifier trusted by the network	⊕⊕⊕	⊕	⊕	M
	Ad hoc verifier trusted by the participants involved	⊕	⊕⊕⊕	⊕⊕	1 (per ad hoc choice)

Taxonomy

Fundamental properties: immutability, non-repudiation, integrity, transparency, equal rights

Blockchain-related design decisions regarding storage and computation, with an indication of their relative impact on quality properties

Design Decision		Option	Impact			
			Fundamental properties	Cost efficiency	Performance	Flexibility
Item data	On-chain	Embedded in transaction (Bitcoin)	⊕⊕⊕⊕	⊕	⊕	⊕⊕
		Embedded in transaction (Public Ethereum)		⊕⊕⊕⊕	⊕	⊕⊕⊕
		Smart contract variable (Public Ethereum)		⊕⊕	⊕⊕⊕	⊕
		Smart contract log event (Public Ethereum)		⊕⊕⊕	⊕⊕	⊕⊕
	Off-chain	Private / Third party cloud	⊕	~KB Negligible	⊕⊕⊕⊕	⊕⊕⊕⊕
		Peer-to-Peer system		⊕⊕⊕⊕	⊕⊕⊕	⊕⊕⊕
Item collection	On-chain	Smart contract	⊕⊕⊕⊕	⊕⊕⊕⊕ (public)	⊕⊕⊕⊕	⊕
		Separate chain		⊕ (public)	⊕	⊕⊕⊕⊕
Computation	On-chain	Transaction constraints	⊕⊕⊕⊕	⊕	⊕	⊕
		Smart contract				
	Off-chain	Private / Third party cloud	⊕	⊕⊕⊕⊕	⊕⊕⊕⊕	⊕⊕⊕⊕

Taxonomy

Fundamental properties: immutability, non-repudiation, integrity, transparency, equal rights

Blockchain-related design decisions regarding blockchain configuration

Design Decision		Option	Impact			
			Fundamental properties	Cost efficiency	Performance	Flexibility
Blockchain scope		Public blockchain	⊕⊕⊕	⊕	⊕	⊕
		Consortium/community blockchain	⊕⊕	⊕⊕	⊕⊕	⊕⊕
		Private blockchain	⊕	⊕⊕⊕	⊕⊕⊕	⊕⊕⊕
Data structure		Blockchain	⊕⊕⊕	⊕	⊕	⊕
		GHOST	⊕⊕	⊕⊕	⊕⊕	⊕
		BlockDAG	⊕	⊕⊕⊕	⊕⊕⊕	⊕⊕⊕
		Segregated witness	⊕⊕⊕	⊕⊕	⊕	⊕
Consensus Protocol	Security-wise	Proof-of-work	⊕⊕⊕	⊕	⊕	⊕
		Proof-of-retrievability	⊕⊕⊕	⊕	⊕	⊕
		Proof-of-stake	⊕⊕	⊕⊕	⊕⊕	⊕⊕⊕
		BFT (Byzantine Fault Tolerance)	⊕	⊕⊕⊕	⊕⊕⊕	⊕
	Scalability-wise	Bitcoin-NG	⊕⊕⊕	⊕	⊕	⊕
		Off-chain transaction protocol	⊕	⊕⊕⊕	⊕⊕	⊕⊕⊕
		Mini-blockchain	⊕⊕	⊕⊕	⊕	⊕⊕
Protocol Configuration	Security-wise	X-block confirmation	⊕	⊕	⊕	⊕⊕⊕
		Checkpointing	⊕⊕⊕	⊕⊕⊕	⊕⊕⊕	⊕
	Scalability-wise	Original block size and frequency	⊕⊕⊕	n/a	⊕	n/a
		Increase block size / Decrease mining time	⊕	n/a	⊕⊕⊕	n/a
New blockchain	Security-wise	Merged mining	⊕⊕⊕	⊕⊕	⊕	⊕
		Hook popular blockchain at transaction level	⊕⊕	⊕	⊕⊕	⊕⊕⊕
		Proof-of-burn	⊕	⊕	⊕⊕⊕	⊕⊕
	Scalability-wise	Side-chains	⊕⊕⊕	⊕	⊕	⊕
		Multiple private blockchains	⊕	⊕⊕⊕	⊕⊕⊕	⊕⊕⊕

Trade-off Analysis 1/2

Quality	Design decision
Scalability	Blockchain tech platform, block size, block frequency
Security	Consensus protocol
Cost efficiency	Public/Consortium/Private blockchain
Performance	Data structure

- Design decision impact
  - A decision may improve the performance of one quality attribute
  - …but may harm the performance of other quality attributes

Trade-off Analysis 2/2

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Encrypting data before storing it on a blockchain

- Increase confidentiality
- Reduce performance, may harm transparency or independent auditability

Storing only a hash of data on-chain and keeping the contents off-chain

- Improve confidentiality and performance
- Partly undermine the benefit of blockchains in providing distributed trust
- May introduce a single point of failure, thus reducing system availability and reliability

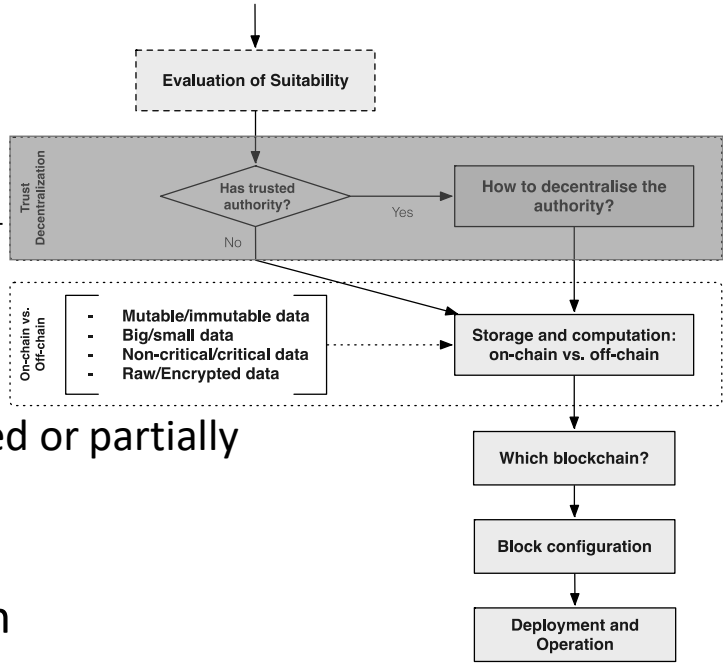
Using private blockchain instead of public blockchain

- Allow greater control over the admittance of processing nodes and transaction into the system
- Increase barriers to entry for participation, thus partly reduce some benefit of using blockchain

Higher number of confirmation blocks

- Increase confidence in integrity and durability of transaction
- Harm latency

Decentralization

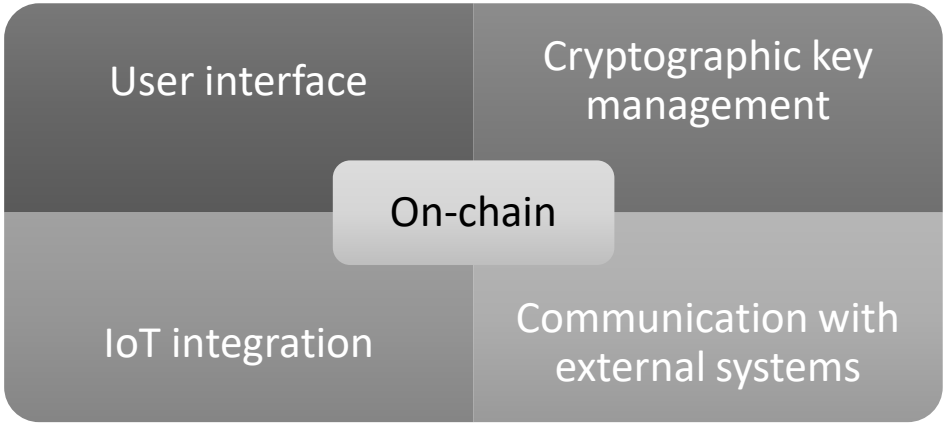


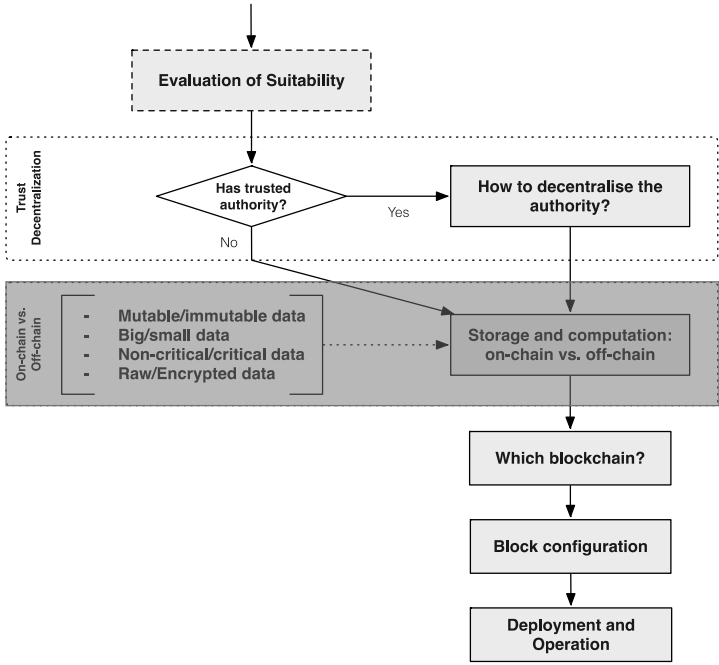
- Blockchain is used in scenarios…
  - …where no single trusted authority is required
  - …where the trusted authorities can be decentralized or partially decentralized

- Spectrum: deployment and operation of a system

- Some components or functions are decentralized while others are centralized

On-chain vs. Off-chain





- Many kinds of data are better stored off-chain
  - Scalability reason—“Big” data
    - “Non-tiny” data may be too large to store on blockchain
  - Confidentiality reason – private data
  - Dealing with legacy database

Design Decisions and Their Impact

Design Decision		Option	Fundamental properties	Impact: Cost efficiency	Impact: Performance	Impact: Flexibility
Data	On-chain	Embedded in transaction (Bitcoin)	⊕⊕⊕⊕	⊕	⊕	⊕⊕
		Embedded in transaction (Public Ethereum)		⊕⊕⊕⊕	⊕	⊕⊕⊕
		Smart contract variable (Public Ethereum)		⊕⊕	⊕⊕⊕	⊕
		Smart contract log event (Public Ethereum)		⊕⊕⊕	⊕⊕	⊕⊕
	Off-chain	Private / Third party cloud	⊕	~KB Negligible	⊕⊕⊕⊕	⊕⊕⊕⊕
		Peer-to-Peer system		⊕⊕⊕⊕	⊕⊕⊕	⊕⊕⊕
Computation	On-chain	Transaction constraints	⊕⊕⊕⊕	⊕	⊕	⊕
		Smart contract				
	Off-chain	Private / Third party cloud	⊕	⊕⊕⊕⊕	⊕⊕⊕⊕	⊕⊕⊕⊕

Computation

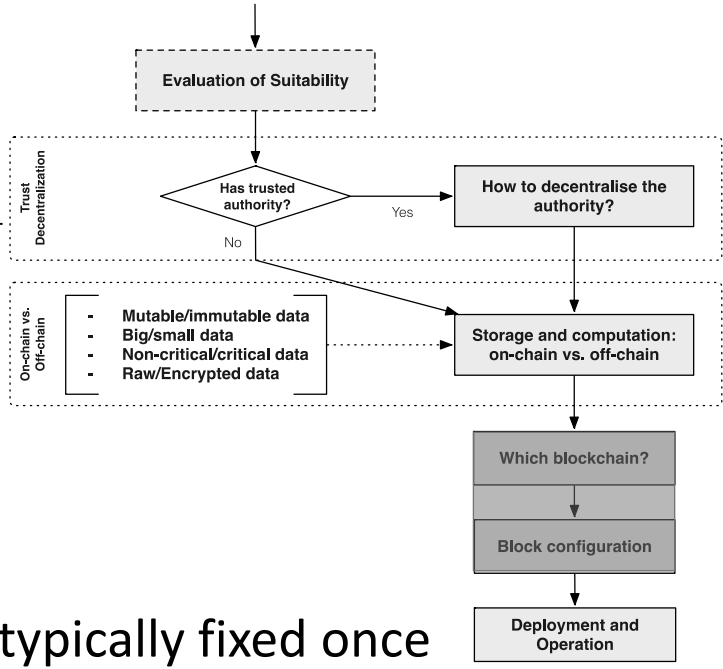
- Different levels of expressiveness of on-chain computation
  - Bitcoin only allows simple scripts and conditions
    - To transfer Bitcoin payment, script must result in “true”
  - Ethereum provides a Turing complete programming language
    - Scope extends far beyond conditional payments
    - Make modification to the working data in smart contract variables
  - DAML (Digital Asset Modelling Language)
    - More expressive than Bitcoin Script
    - Purposefully not Turing-complete: codify financial rights and obligations
      - Allows static analysis

Non-determinism (in practice)

- Code is deterministic, but:
- Blocks impose an order on transactions, by default not controlled
- Resulting non-determinism might affect the execution results

- Benefit of on-chain computation
  - Inherent interoperability among the systems built on the same blockchain network
  - Neutrality of execution environment
  - Immutability of the program code once deployed

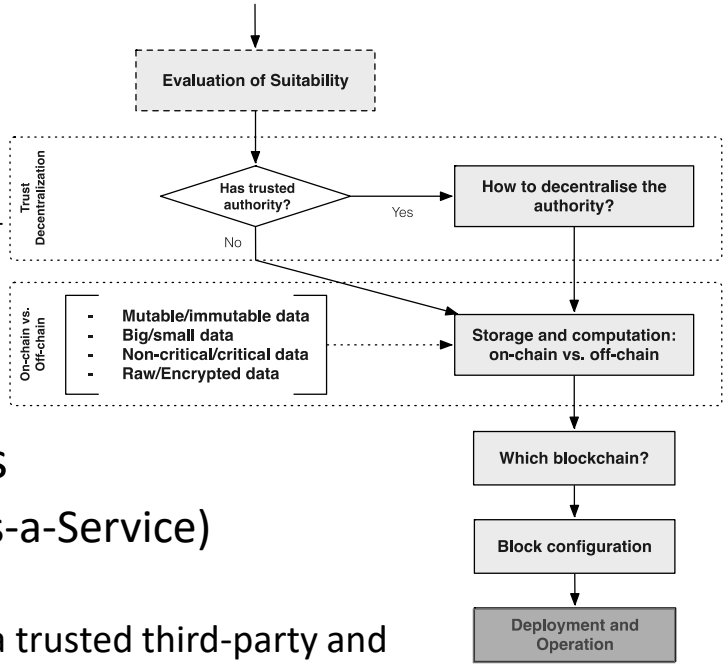
Blockchain Selection



- For blockchain platform selection, consider
  - Requirements of the use case
  - Characteristics of blockchain platform
  - Trade-off analysis

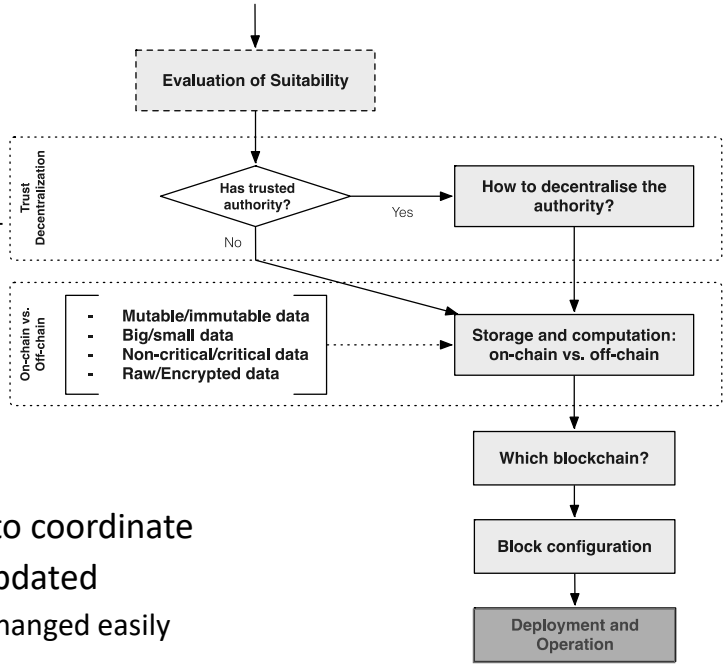
- Consensus protocol and other decisions are typically fixed once blockchain is selected
  - Hyperledger Fabric is an exception
    - Supports pluggable implementations of various consensus protocols
  - Inter-block time is configurable for many consensus protocols
    - For Proof-of-Work: through adjustments to the difficulty of mining, with difficulty adaptation disabled

Deployment



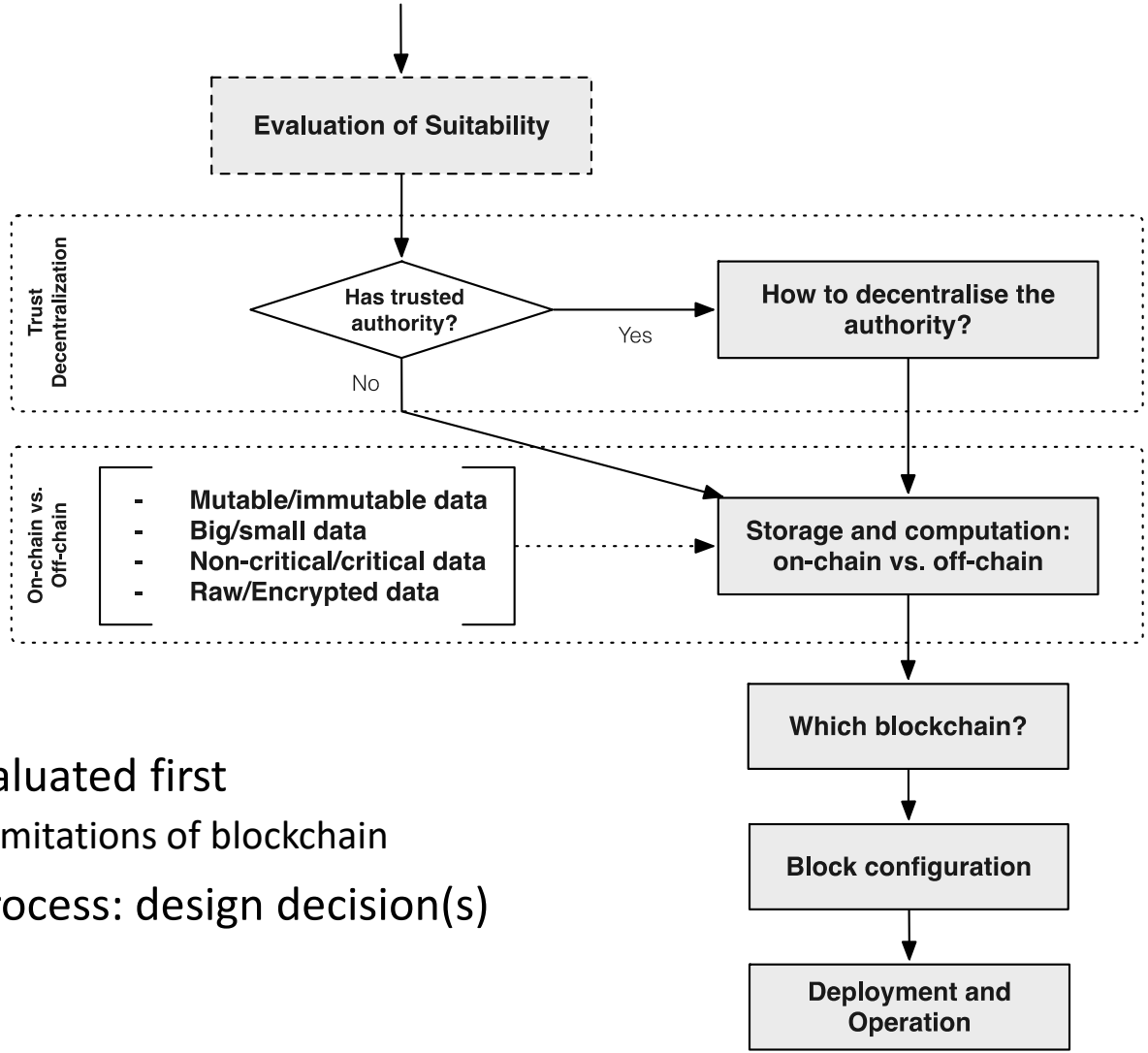
- Deployment has impact on quality attributes
  - Deploying on cloud or using BaaS (Blockchain-as-a-Service)
    - Introduces uncertainty of cloud infrastructure
    - If all nodes use the same cloud provider, it becomes a trusted third-party and a single point of failure
  - Deploying a public blockchain on a VPN (virtual private network)
    - Becomes a private blockchain
    - Permissioned access controls provided at the network level
    - VPN introduces additional network latency overhead

Operation



- Operation challenges
  - Blockchain-based systems can be harder to modify than conventional systems
  - Blockchain platform software running on multiple independently-operating nodes
  - Updating software can by physically and administratively difficult to coordinate
  - Blockchain is immutable by design, so cannot be retrospectively updated
    - Trust is derived partly from the fact that the smart contract cannot be changed easily
- Governance
  - Changes may be made to correct defects, add features or migrate to new IT context
  - More like diplomacy in multi-party system with no single owner
  - Blockchain is ***NOT SUITABLE*** for a system that needs to change frequently
  - Learn from governance in open-source software
  - Governance concerns software development, deployment and operation
  - Immutable smart contract also simplify governance to some degree
    - Smart contract is available for execution while the blockchain operates normally

Summary



- Suitability needs to be evaluated first
  - Fundamental properties and limitations of blockchain
- Each step of the design process: design decision(s)
  - On-chain vs. off-chain
  - Subsidiary design decisions

Design Patterns for Blockchain Applications

Technische Universität Berlin

What is Design Pattern?

- To solve a recurring problem in software development
- Not a finished design that can be transformed directly into code
- A description or template for how to solve a problem
  - Define constraints that restrict the roles of architectural elements
    - Processing
    - Connectors
    - Data
  - Define constraints that restrict the interaction among these elements
- Causes trade-offs among quality attributes

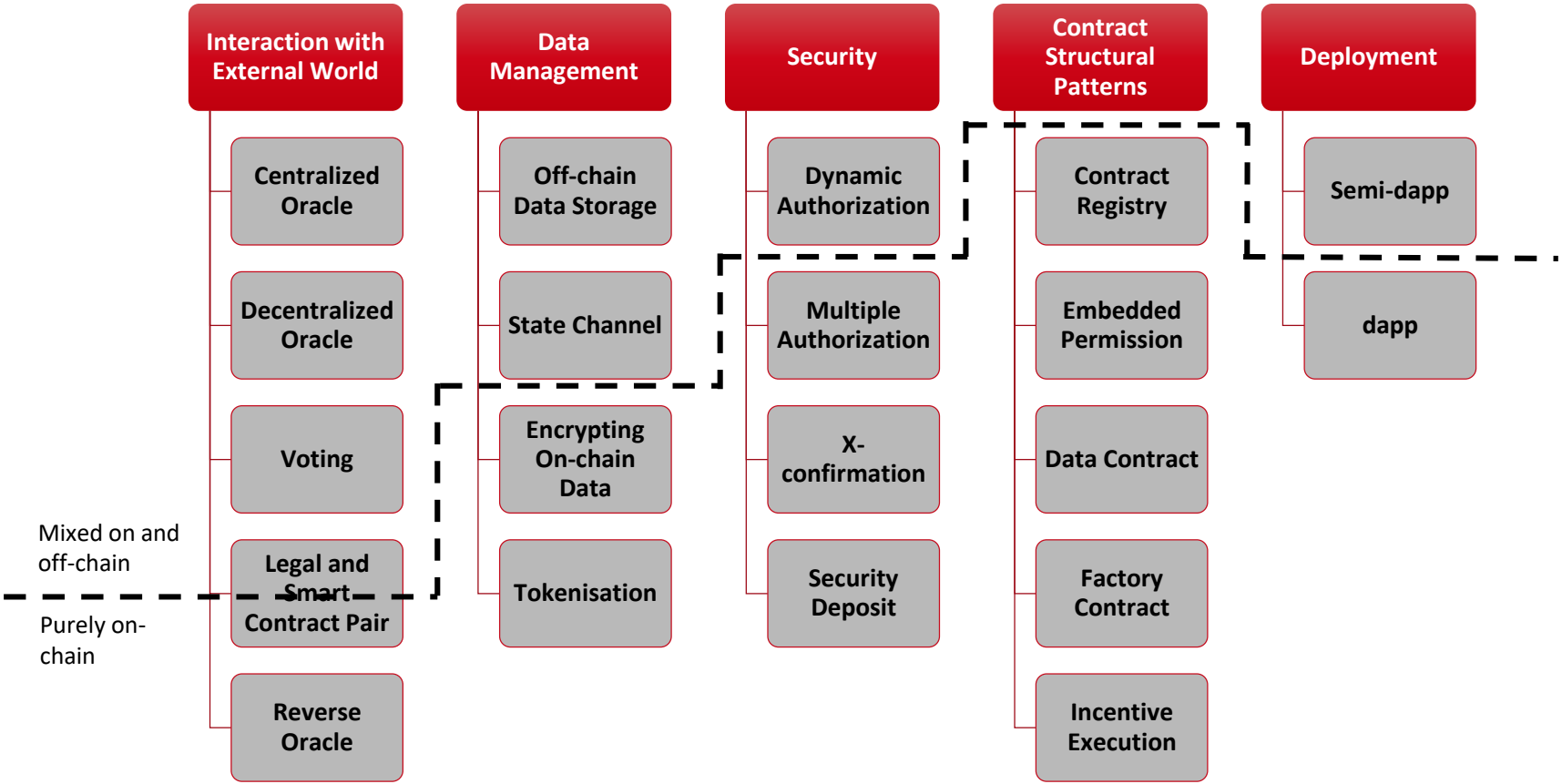
Advantages of Patterns

- Design patterns can speed up the development process by providing tested, proven development paradigms.
  - Design patterns document the efforts of the experts
  - Design patterns concerns with a flexible software architecture

- Effective software design requires considering issues that may not become visible until later in the implementation.

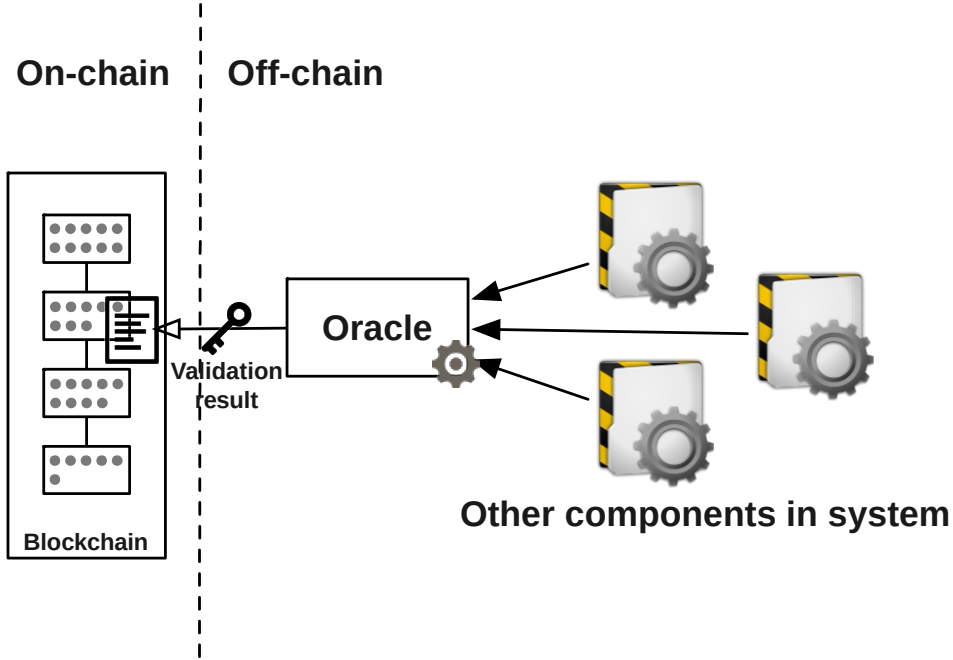
- Reusing design patterns helps to prevent subtle issues that can cause major problems and improves code readability for programmers and architects familiar with the patterns.

Pattern Collection (Chapter 7)



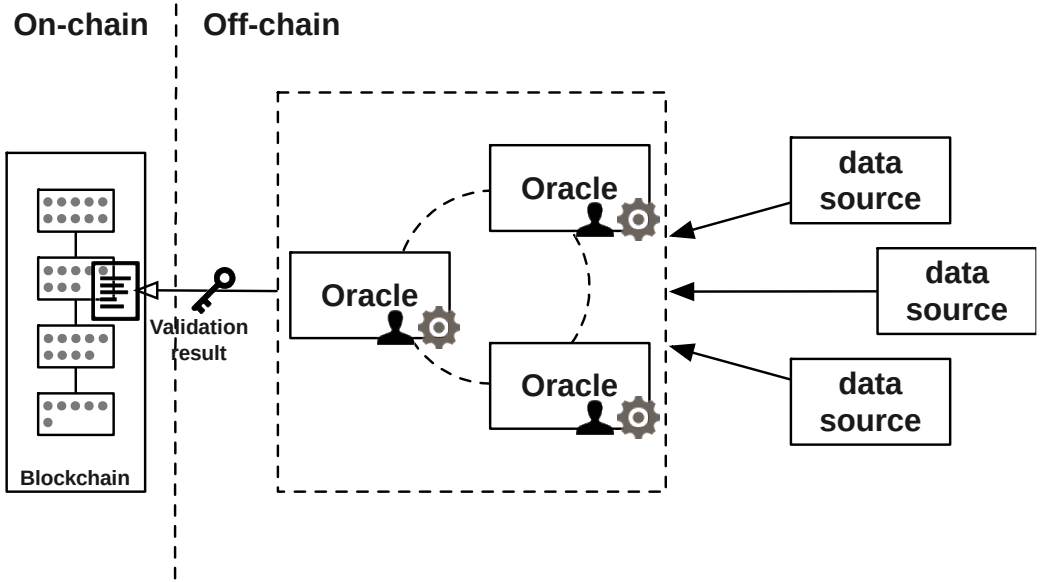
Pattern 1: Centralized Oracle

- **Solution**
  - Oracle assists in evaluating conditions that cannot be expressed in a smart contract
  - Oracle injects the result to the blockchain in a transaction signed using its own key pair
  - Validation of transactions is based on the authentication of the oracle



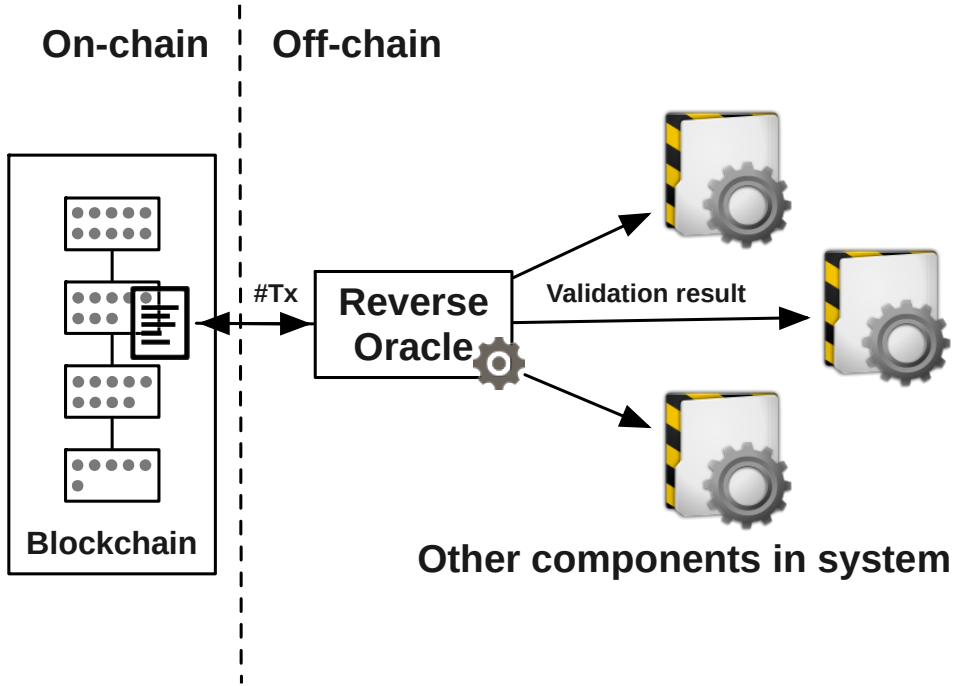
Pattern 2: Decentralized Oracle

- **Solution**
  - Decentralized oracle based on multiple servers and multiple data sources
  - Consensus on the external status, e.g.:
    - K-out-of-M threshold signature



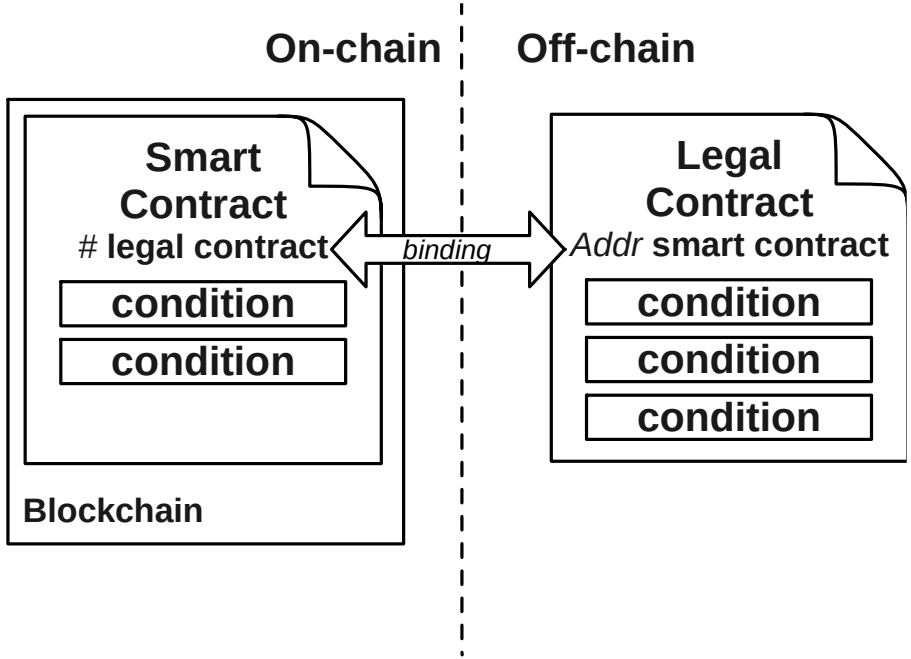
Pattern 4: Reverse Oracle

- **Solution**
  - Transaction ID and Block ID can be integrated into existing system
  - Validation is on blockchain using smart contract
  - An off-chain component is required to query blockchain, which serves as store of current variable values
    - e.g., who is allowed physical access to a device



Pattern 5: Legal and Smart Contract Pair

- **Solution**
  - SC implements conditions defined in the legal agreement
    - Checked and enforced by the smart contract
  - SC has a blank variable to store hash of legal contract
  - SC address included in the legal agreement
  - Legal agreement hash is added to the SC variable, which is immutable after first write



Thank you for your attention!

Architecture for Blockchain Applications – Overview, Design Process, and Design Patterns

Lecture 4 in Ringvorlesung “Blockchain & RPA” @ CAU Kiel

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