Smart digital contracts: Introduction

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Select references

- McCarthy, *The REA Accounting Model: A Generalized Framework for Accounting Systems in a Shared Data Environment*, The Accounting Review, 1982
- Peyton Jones, Eber, *Composing contracts: an adventure in financial engineering (functional pearl),* ICFP 2001
- Andersen, Elsborg, Henglein, Simonsen, Stefansen, *Compositional specification of commercial contracts*, International Journal on Software Tools for Technology Transfer, 2006
- Rambaud, Perez, Nehmer, Robinseon, *Algebraic Models for Accounting Systems,* World Scientific, 2010
- Henglein, *Blockchain deconstructed (abstract),* 2nd Symp. DLT, 2018

Overview

- Tue, 9:00-10:15: Distributed ledger technology and `smart contracts'
- Wed, 14:00-15:15: Algebraic foundations for resource management
- Thu, 9:00-10:15: Compositional contracts and `smart' contract management
- Thu, 2:00-3:15: Contract analysis (and other topics)

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Areas of interest

- Programming language technology
- Theoretical computer science (algorithms, semantics, logic)
- Blockchain technology
- Contract management
- Financial technology
- Enterprise systems

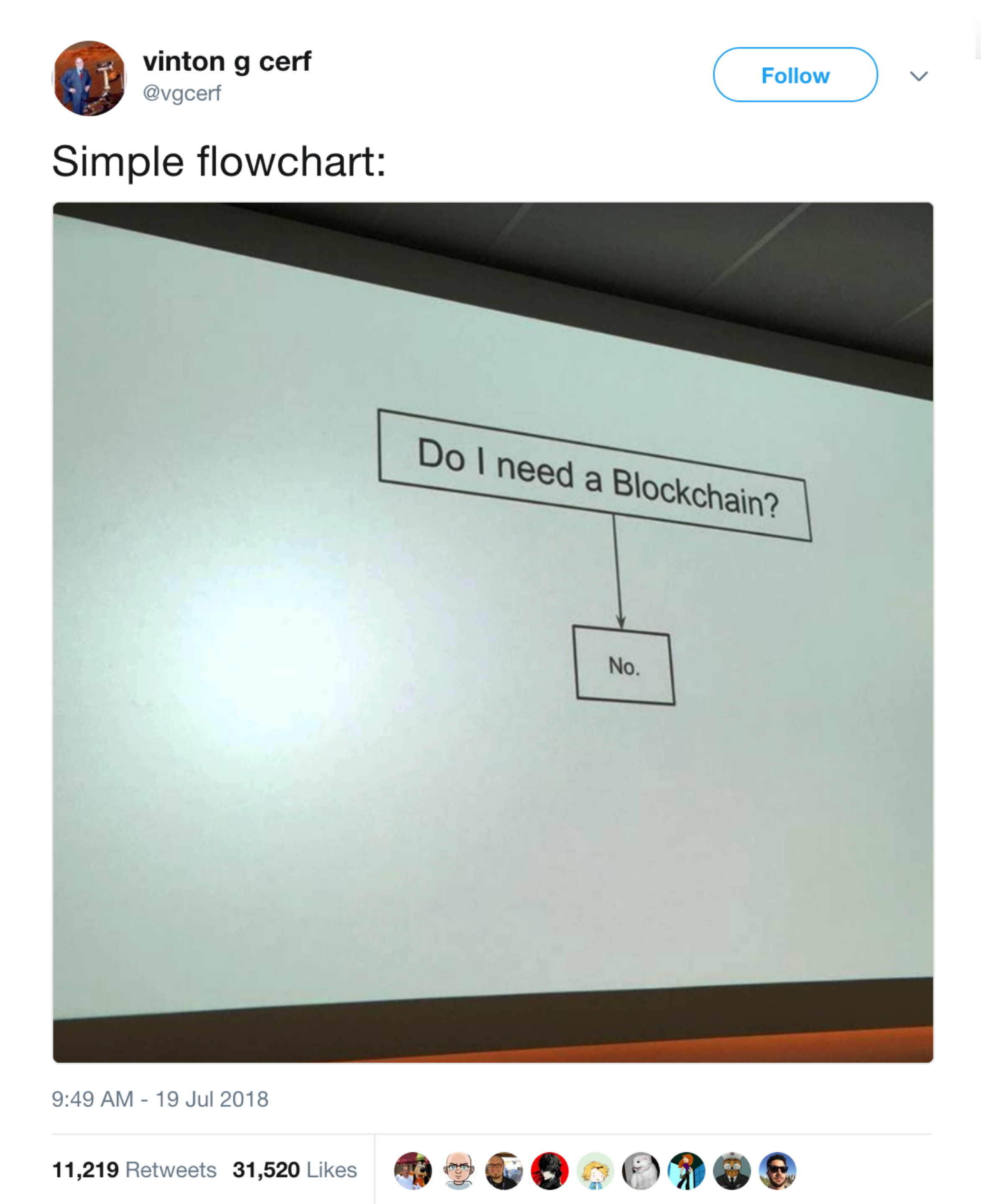
Related background

- European Blockchain Consortium (ebcc.eu)
- Steering committee chair, Innovation network for Finance IT (CFIR.dk)
- Principal investigator, Functional technology for high-performance architectures (FUTHARK)

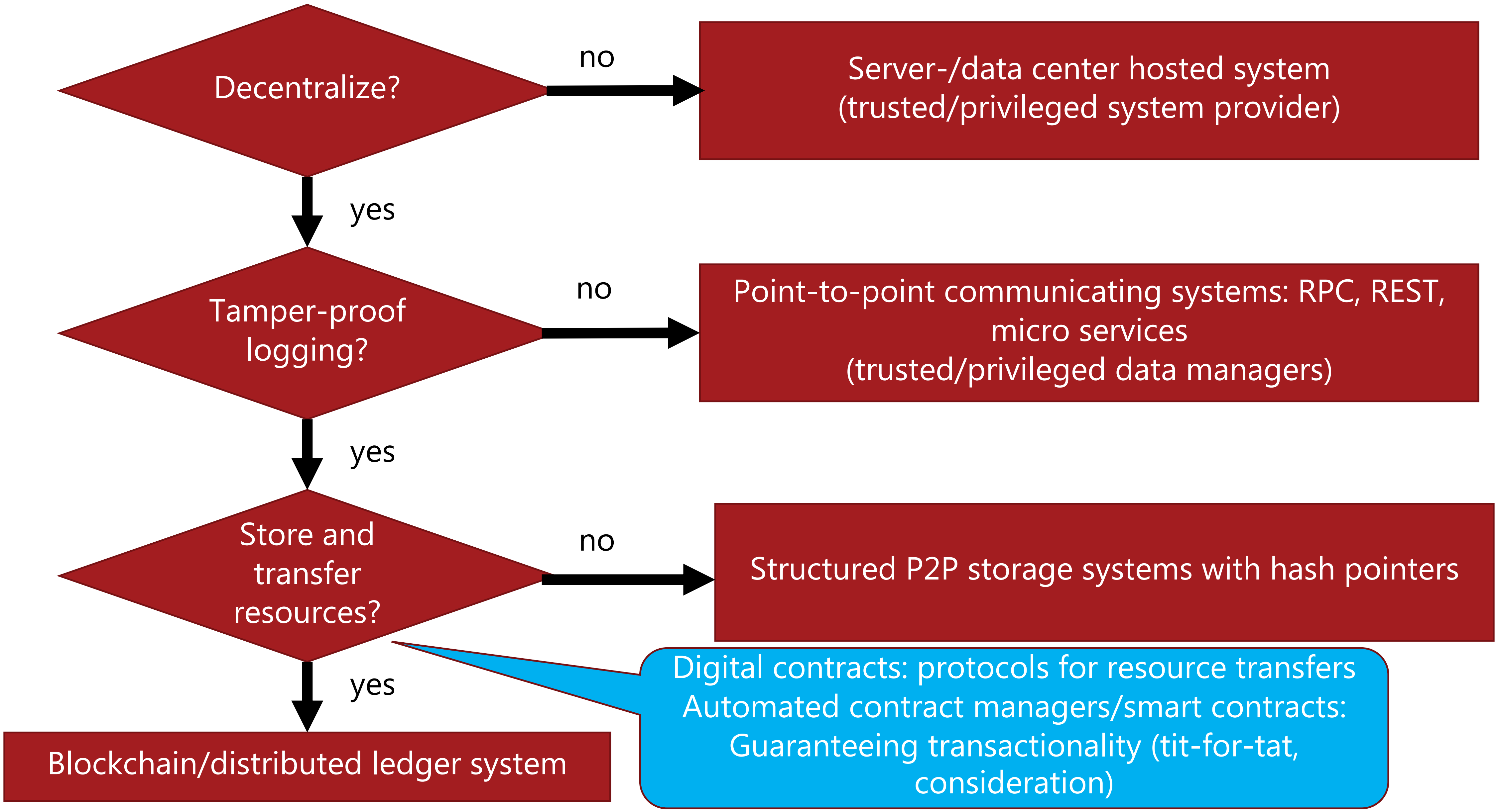
Academic background, affiliations, guest positions

TUM · Rutgers, The State University of New Jersey · NYU · Universiteit Utrecht · University of Copenhagen · IT University of Copenhagen · Cornell University · UNSW Sydney · University of Oxford

Why blockchain?



Why blockchain?



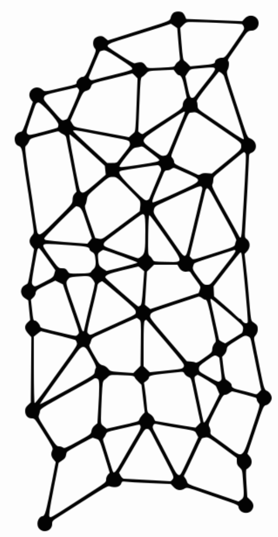
Blockchain/distributed ledger system

A computer system characterized by

- organizational and technical **decentralization**;
- **tamper-proof recording** of digitally signed (real-world) events and their **evidence**;
- digital **resource management**:
  - digital *storage*, *transfer*, transportation, transformation of money, goods and services

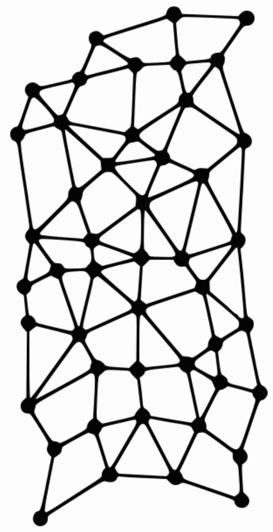
It provides

- consistent, nonrepudiable information across all principals (suppliers, partners, customers, regulators, etc.)
- guarantees against *forging* and *double spending*



Organizational and technical decentralization

- **Technical** decentralization: A distributed peer-to-peer system
- **Organizational** decentralization: No single or select group of organizations controls/has privileged rights to system
  - *Nonpermissioned* ("blockchain"): open and self-authenticating, anybody can host a node, be a user and have multiple/many anonymous identities
  - *Permissioned*: nodes and users are authenticated and identified; may be private, but cannot have multiple identities
- **Governance policy** for regulating membership, functionality, conflict resolution, etc.



Intermezzo: Extended REA accounting model

- **R**esource (= asset): Money, licenses, physical objects (e.g. trucks),…
- Information: Data, invoices,…
- **A**gent: Person, company, institution, autonomous device,…
- Contract: Specification of obligations, permissions and prohibitions
- **E**vent:
  - Atomic event:
    - A transfers R to B
    - A transforms R to R'
    - A informs B of I
    - …
  - Complex event: Set of events that satisfies a given (sub)contract

McCarthy, The REA Accounting Model (1982)
Andersen et al, Compositional specification of commercial contracts (2006)

Tamper-proof recording of events and their evidence

- **Event recording**: Events are stored (eventually, probabilistically) *consistently*, that is, every node in the distributed system gives the same answer when queried about them
- **Tamper-proof**: Stored events cannot subsequently be altered or deleted
- **Evidence**
  - for atomic events:
    - *signature* (by sending agent), plus
    - *supporting evidence* of event actually having happened, e.g. receipt signature, 3d party *validation ("*payment has been performed" [*], "parcel has been delivered"), DNA samples ("this is the same timber as received"), GPS-/time-tagged pictures ("the parcel delivered in your driveway"), IoT device messages ("parcel has been scanned at this time and location"), etc
  - for complex events:
    - (mathematical) *proof* that a particular set of events constitutes a correct execution (by all involved parties) of a particular, mathematically well-specified contract.

[*] In blockchain systems: Payment validation = recording on blockchain

Blockchain/DL systems as digital twins

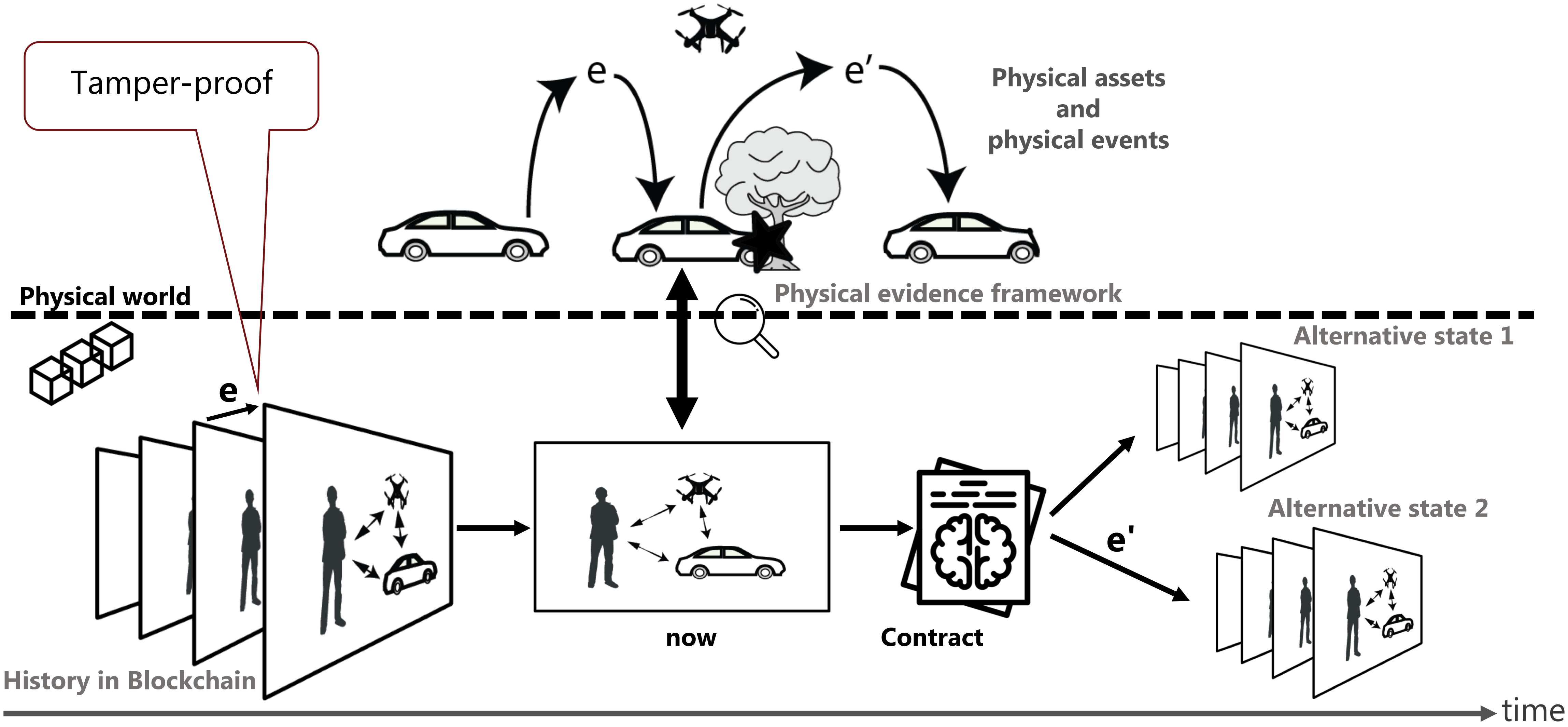


Illustration by Boris Düdder

Digital resource management

- System keeps track of **ownership** and **location** of resources
- Guarantees that digitally represented resources can only be **transferred** and **transported**, *never* erroneously or maliciously duplicated
- Can be decomposed into
  - resource preservation
  - credit limit enforcement

Resource preservation and credit limit enforcement

- **Resource preservation**: *Transfers* keep the sum of all resources invariant:
  - A transfers 50 ETH to B: The *sum* of all ETH is the same. Atomically, after event, A has 50 ETH less; B has 50 ETH more.
  - *We allow negative numbers to be transferred and as account balances!*
- **Credit limit enforcement**: A transfer is only *valid* (and *effected)* if the *credit limits* of each agent are respected. For above transfer of 50 ETH:
  - If A owns 60 ETH and has credit limit 0: Valid. (A owns 10 ETH after transfer.)
  - If A owns 30 ETH and has credit limit 0: Invalid. (No transfer. A still owns 30 ETH.)
  - If A owns 30 ETH and has credit limit 20: Valid. (A "owns" -20 ETH after transfer.)
- No-double-spend guarantee = all agents have credit limit 0.
- UTxO = account where complete balance must be transferred.

Henglein, Blockchain deconstructed (2018), 2nd Symp. on DLT

Why adaptive credit limits instead of just zero credit limit?

- **Full-reserve monetary system**: One agent (the central bank) has no credit limit, all others have credit limit 0.
- **Fractional-reserve monetary system**: A designated set of agents ("banks") have a dynamic non-0 credit limit, all others have credit limit 0.
  - Banks' dynamic credit limits depend on other assets they own, including expected future repayments as part of the contracts (loans, etc.) they have made.
- **Demand-driven production of physical assets**: A car manufacturer has no credit limit (they produce cars on demand), all others have credit limit 0.
  - A car transfer by a car manufacturer need not be validated (``do they even own it?''); they can produce a new one.

Commutativity theorem, part 1

- **Theorem:** If every agent has an infinite credit limit, then all resource transfers are valid and can be executed in arbitrary order. (Each order results in the same state of ownership.)

- **Corollary**: Contract execution involving *k* agents with infinite credit limit requires only consensus by the *k* agents (on the particular execution); no event needs to be validated by a 3d party. Usually *k=2*.

- Loosely: The Internet with TLS for authentication, reliable message delivery, and hashpointers for tamper-proof recording of authenticated message exchanges *is* a permissioned blockchain/DL system *if there are no credit limits.*

Commutative theorem, part 2

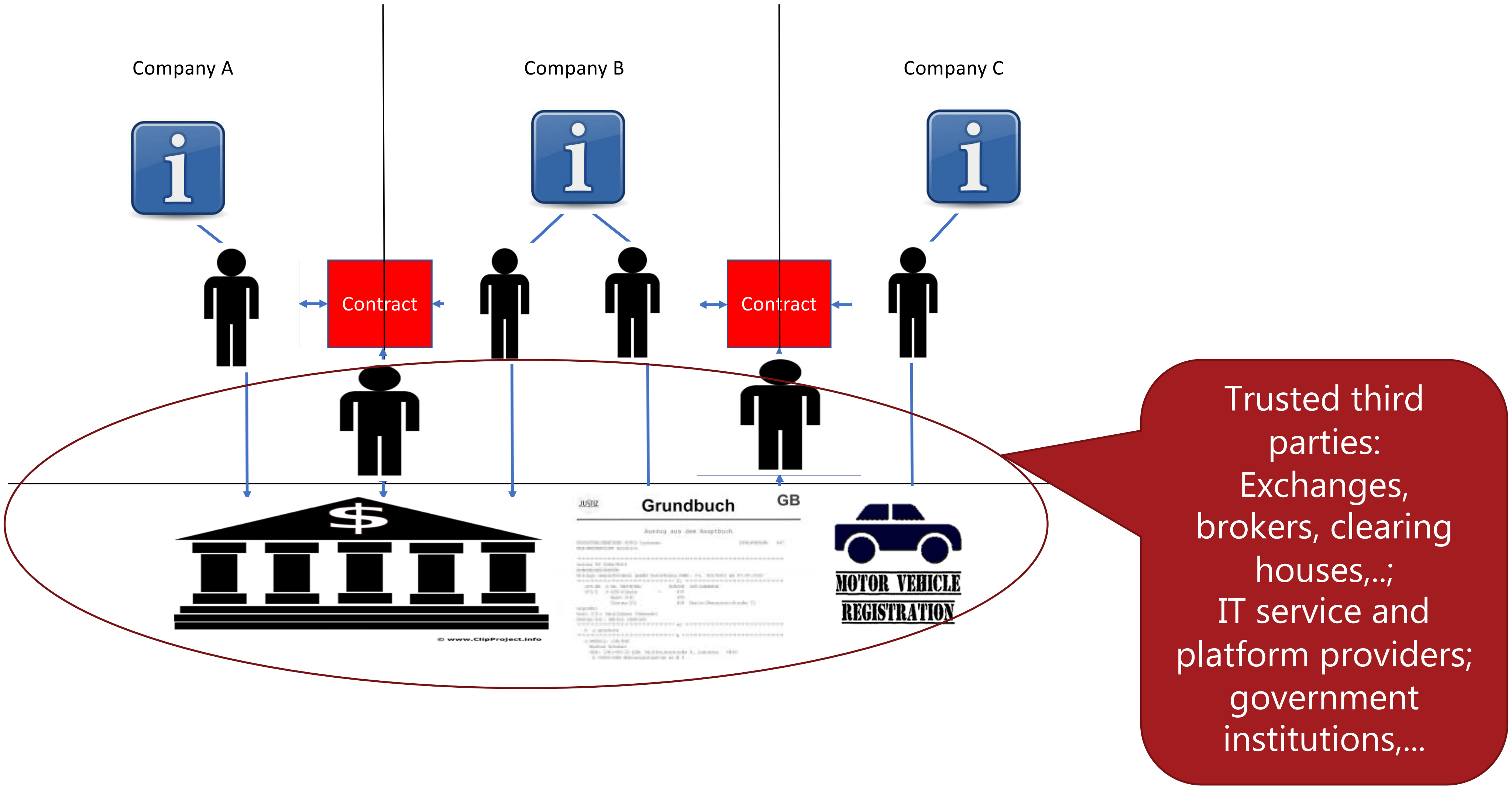
- If some agents have finite credit limits, outside validation of their resource transfers is required.
  - Point-to-point communication between the *k* agents only is *insufficient*.
  - *Some* information about resource transfers must be "leaked" to other nodes for validation.

Henglein, Blockchain deconstructed (abstract), SDLT 2018

Total event ordering

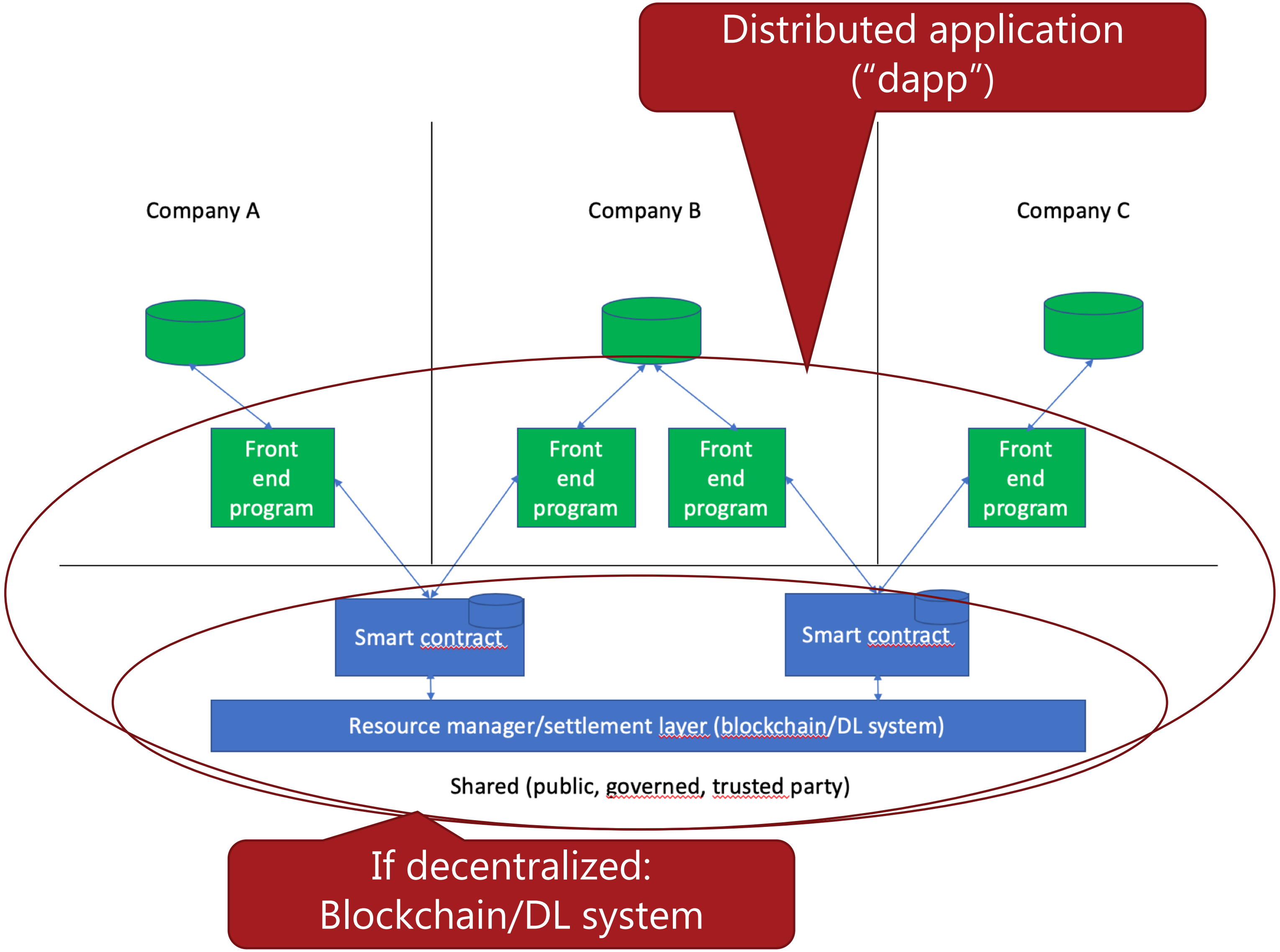
- Total event ordering: Distributed consensus by all non-Byzantine (= correctly executing) nodes on a particular *total order* (= sequence) of events arriving at *any* one non-Byzantine node
  - Very hard problem (impossibility results, tricky algorithms, lower bounds on rounds/complexity, need for randomization, synchronous communication etc.)
- Total event ordering is *sufficient* for resource transfer validation:
  - agree on total order of events, including resource transfers;
  - validate a transfer if, *in that order*, all agents' credit limits are satisfied (= no double-spend).
- Total event ordering is *not necessary* for resource transfer validation:
  - Most resource transfers *commute* with each other:
    transfer(A,B,R); transfer(C,D,Q) = transfer(C,D,Q); transfer(A,B,R) if $\{A,B\} \cap \{C,D\} = \emptyset$
- Total event ordering is the main bottleneck in *large* distributed systems, especially asynchronous ones; nonetheless it is used in most blockchain/DL systems (Bitcoin, Ethereum, Fabric, etc.).

Contract-oriented business architecture with intermediaries



Standard blockchain architecture (without digital contracts)

- Private *front-end program* (wallet management, trading strategy, etc)
- Public *smart contracts* (programs tied to particular blockchain system)
- Public *information* (may be 'off chain', e.g. in IPFS)
- Public *resource manager* (*single* blockchain system)



A CRASH SLIDE ON BLOCKCHAIN AND SMART CONTRACTS

SMART TERM	WHAT IT ACTUALLY MEANS
BLOCKCHAIN	**DISTRIBUTED** APPEND-ONLY TRANSACTION LOG (LEDGER)
SMART CONTRACT (CODE)	CLASS (IN JAVA-LIKE LANGUAGE)
SMART CONTRACT (EXECUTING)	PROCESS (OBJECT [= CLASS INSTANCE])
OBJECT MESSAGES	ORDINARY MESSAGES **LINEAR RESOURCE TRANSFERS**

The price of expressiveness: unpredictability

- Smart contract: any program, written in **Turing-complete, feature-rich** programming language (Solidity, Kotlin, Go, ⋯)
  - **+** : Expressive, familiar
  - **-** : **Very undecidable properties** (*), even with *full access to the source code*

- Smart contracts without support for reasoning for *qualitative and quantitative safety* are dangerous
  - Move money, not just bits
  - Invite honeypotting

(*) Undecidable and statically hard and/or cumbersome to analyze

Example: Ethereum Vulnerabilities

LUU, CHU, OLICKEL, SAXENA, HOBOR, MAKING SMART CONTRACTS SMARTER (2016)

- Transaction-order dependence: Messages may have different effect depending on their order of arrival
  - Who controls the process scheduler (= message sequencer)? Some *miner*: Front-running
- Time-stamp dependence: Smart contracts may have different executions depending on the time stamp on a transaction block
  - Who controls the time stamping of transaction blocks? Some miner: Clock manipulation
- Exception handling, gas management fragility: Subtle differences in exception semantics, limited run-time stack
  - Provoking out-of-stack and gas exhaustion exceptions: Any user
- Programming language complexities:
  - Exception handling subtleties (send vs. call)
  - Reentrancy vulnerability (DAO hack)
  - Implicit method forwarding (multi-sig exploit)

Example: Reentrancy vulnerability

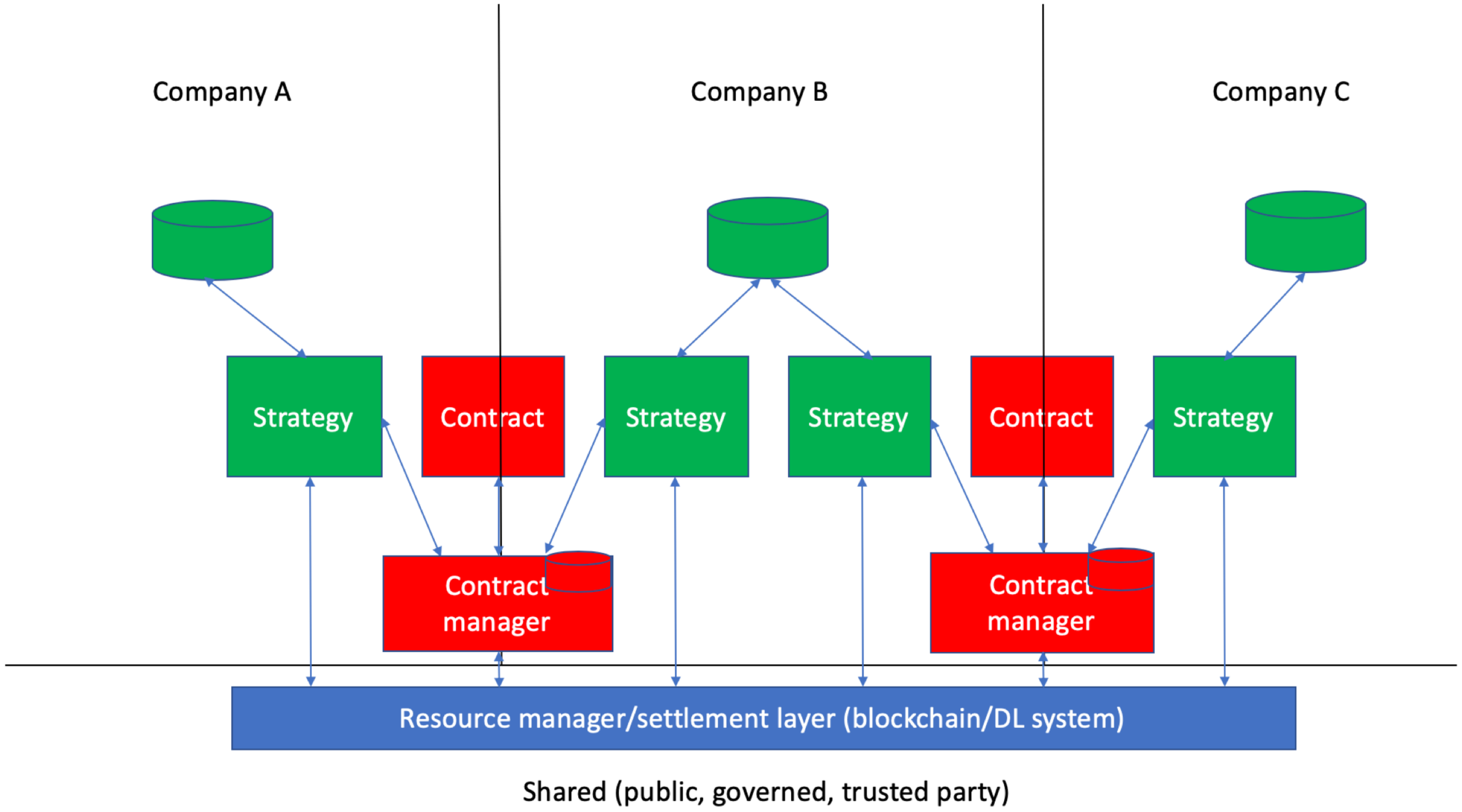
```
contract SendBalance {
 mapping (address => uint) userBalances;
 bool withdrawn = false;
 function getBalance(address u) constant returns(uint){
  return userBalances[u];
 }
 function addToBalance() {
  userBalances[msg.sender] += msg.value;
 }
 function withdrawBalance(){
  if (!(msg.sender.call.value(
    userBalances[msg.sender])())) { throw; }
  userBalances[msg.sender] = 0;
 }}
```

Figure 7: An example of the reentrancy bug. The contract implements a simple bank account.

LUU, CHU, OLICKEL, SAXENA, HOBOR, MAKING SMART CONTRACTS SMARTER (2016)

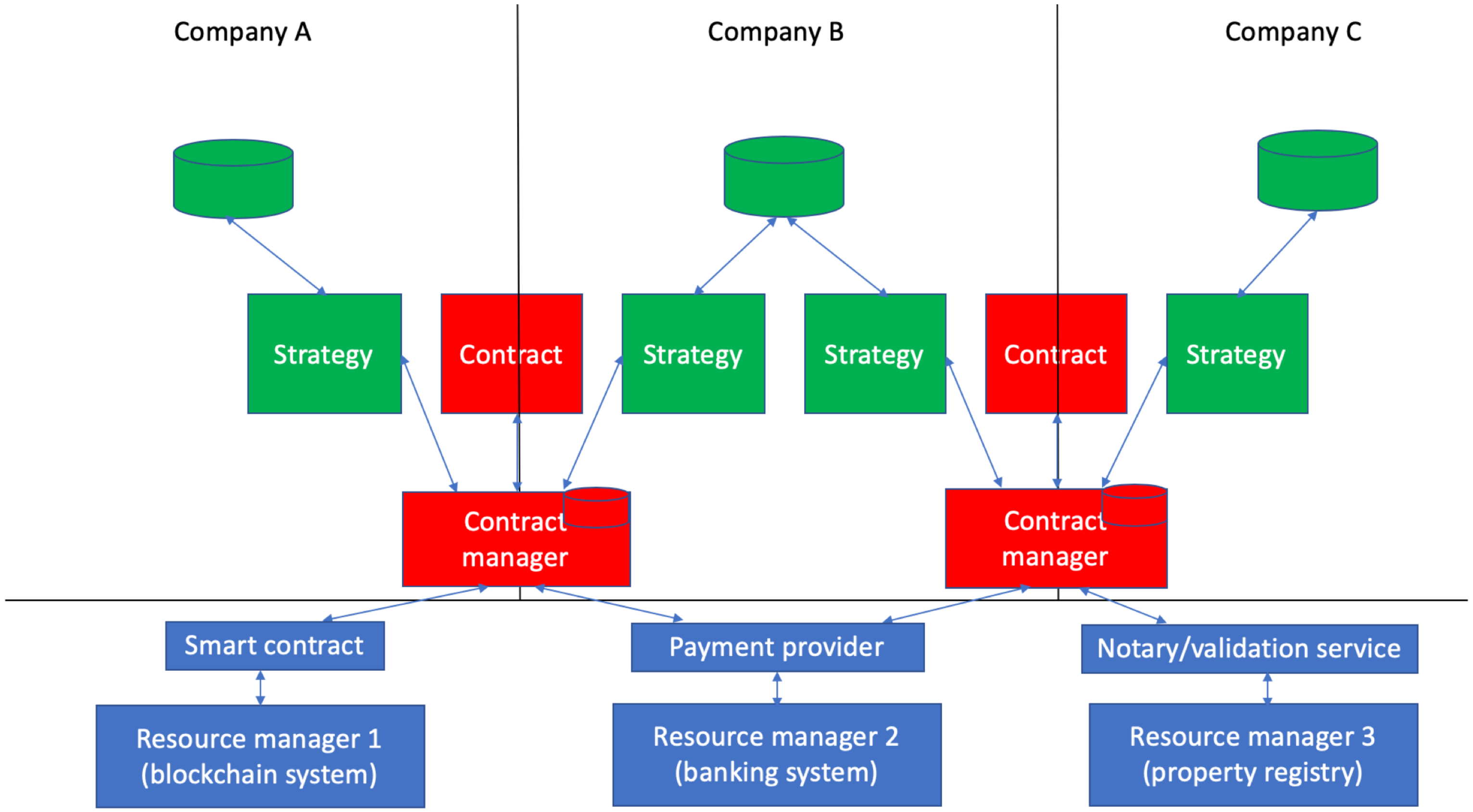
Contract-oriented IT architecture with digital contracts and contract managers (generic smart contracts)

- …
- Confidential *contract managers*:
  - **Smart contracts** for escrow, trade finance, public funding, etc.
  - Secure cryptographic **exchanges** and **auction systems**
  - **Contract execution** monitoring (encompassing procure-to-pay)



Contract-oriented IT architecture with digital contracts and contract managers (generic smart contracts)

- …
- Confidential *contract managers*:
  - **Intelligent contract management** (monitoring, arbitration, escrow, collateral management, etc.)
  - **Transactional resource management** of **multiple** resource managers



multiple resource managers

Consequences

- Separation of **contract life cycle management** from **contracts**
  - Contracts **portable** (CSL), quantitatively **analyzable**, **domain-oriented** (`zero programming')
  - Contract life cycle managers **generic** (any contract), in **any implementation language** (Kotlin, Go, Java, Haskell,…), **instrumentable**, **changeable** (adding escrow, collateral management, etc., without changing contracts)
- Separation of **resource management** from **contract management**
  - Increased scalability 1: Event log *per contract,* no/few dependencies across contracts
  - Increased scalability 2: Aggressive partitioning of agents and resources (sharding, channels, etc.)
  - Increased **privacy** (contract and contract execution not disclosed to resource manager)
- Precise, mathematical **semantics**
  - Mathematical guarantees, formal verification, static analysis (no hacks possible)

Observations

- Popular blockchain and DL systems employ replicated state machine architecture (unstructured P2P system): High redundancy, high message traffic
- Total event order consensus: Distributed consensus on a specific total order of transactions is sufficient, but not necessary for resource transfer validation
  - Many possibilities of distribution/parallelization by *partitioning*, increasingly recognized (sharding, state channels)
- Hash pointer graphs have multiple uses.
  - For tamper-proof, *confidential* recording of events making up execution of *specific* contract. (Note: Not confidential, but public, in Ethereum and similar blockchain systems)
  - For tamper-proof, *public* recording of total order of validated resource transfers.

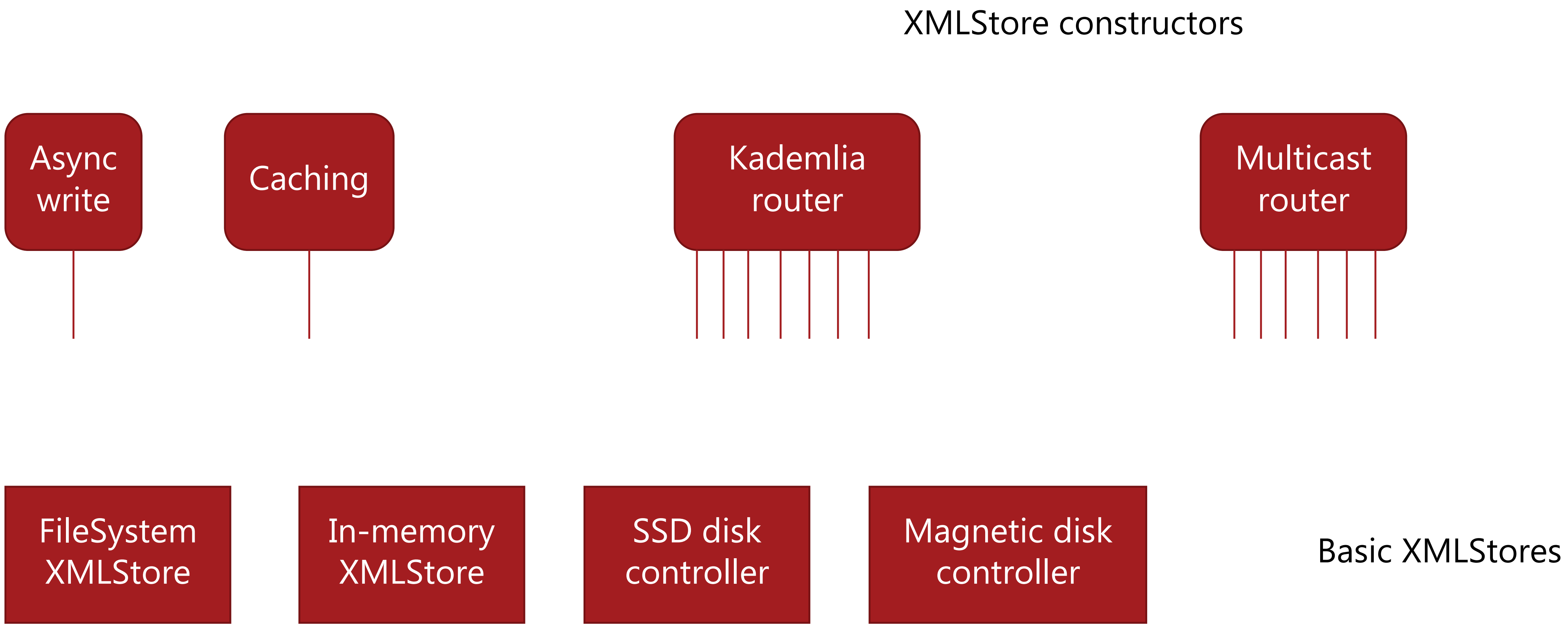
Open problems

- Fully exploit resource transfer commutativity
  - Current blockchain/DL systems solve an unnecessarily hard problem: distributed consensus on total order of *all* events across *all* contracts.
  - Exploit that (certain) subsets of transfers can be validated and effected independent of each other.
- Ideas for *specialized* distributed consensus protocols for scalability:
  - Hierarchical clearing and settlement, as in banking systems with *real-time gross settlement* via central bank (hierarchical "sharding" by partititioning of agent accounts)
  - Time- and resource-sensitive validation (bigger transfers require more time for validation)
  - Insurance (appyling transaction fees to cover losses due to overdrafts detected too late)
  - …

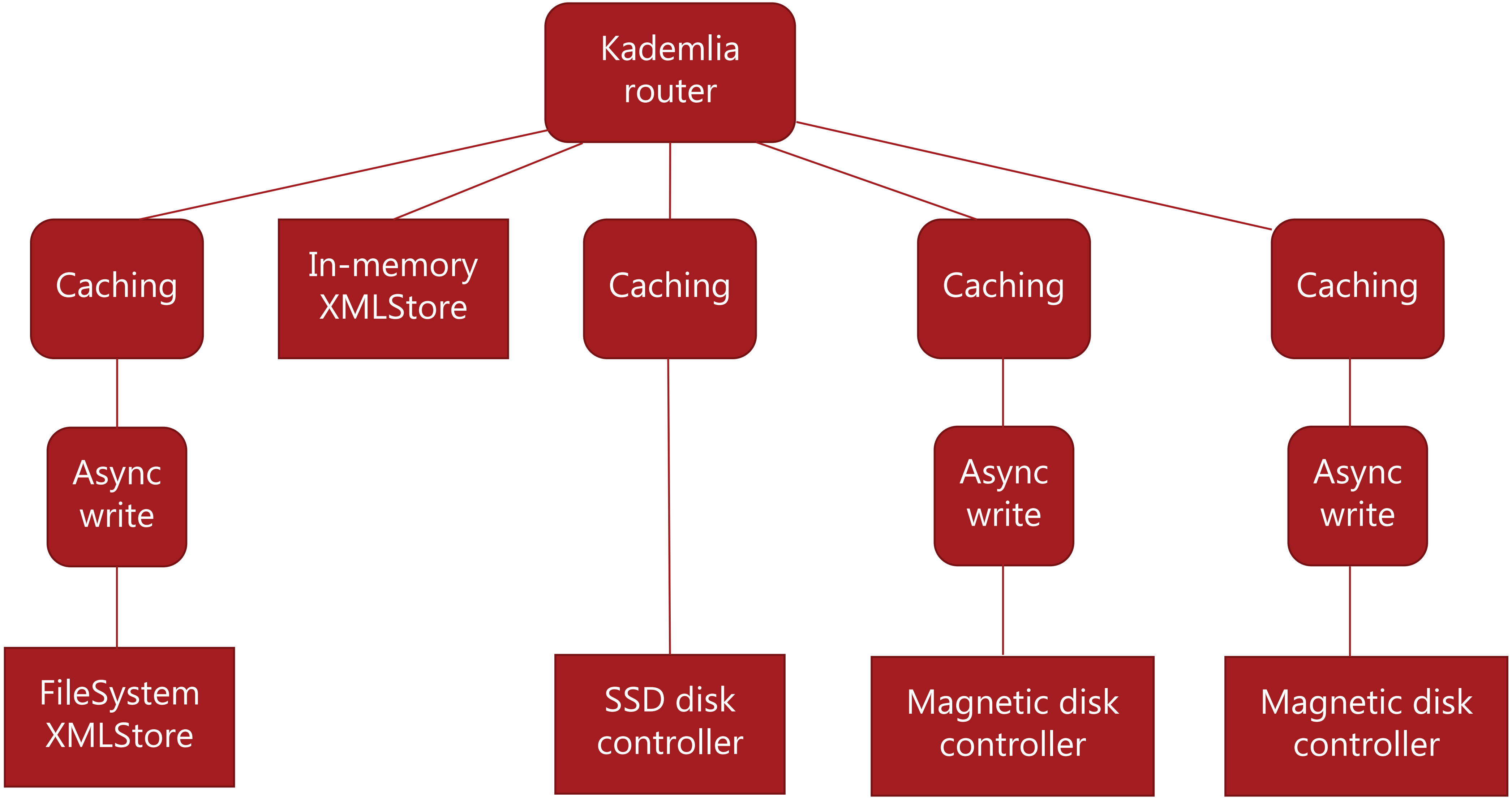
Plan X

- Programmable platform for distributed storage and applications
- Data model: Raw data (bits), *immutable* location-independent references (value references), mutable references (pointers), and sequences/stream of such
  - Key aspect: Value references, guaranteed immutable and location independent
- Architectural components:
  - XMLStore: Programmable, compositional save/load-architecture for storing and retrieving immutable and mutable data
  - MergeLang: User-definable updating of mutable data, based on 3-way merging
  - Distributed applications: XMLStore with exec-interface for executing code stored as structured data in XMLStore
  - Distributed garbage collection, deduplication, etc: Systems components for memory deallocation, optimization, etc.
- Conceived of in 2001 at ITU. Projects in 2001-2004 at DIKU and ITU.
  - 20 B.S. and M.S. projects, multiple faculty, ~1 GB of code and test data

XMLStore components



Example: Structured P2P store by composing XMLStore components



Resource ownership consensus by 3-way merging

- Maintain account balance in replicated updatable reference
- Formulate updating as applying an update function to balance
- Merge multipe updates into joint update function during replica synchronization
- Observation: Almost all resource updates commute -> update joining is (almost) commutative

To be continued…

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