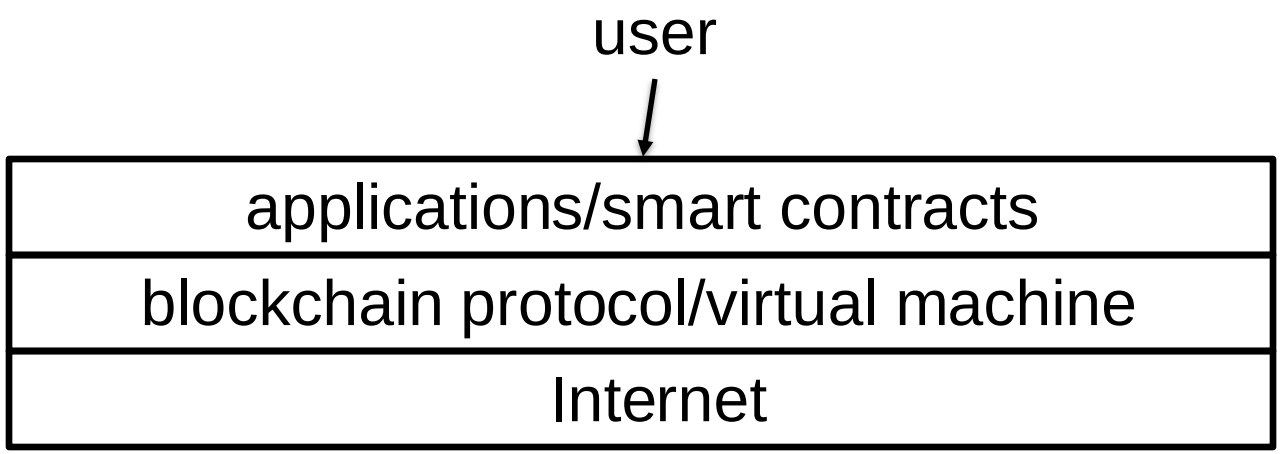
Lecture #2: State Machine Replication

COMS 4995-001:
The Science of Blockchains
URL: https://timroughgarden.org/s25/

Tim Roughgarden

Recap: A Cartoon of Web3



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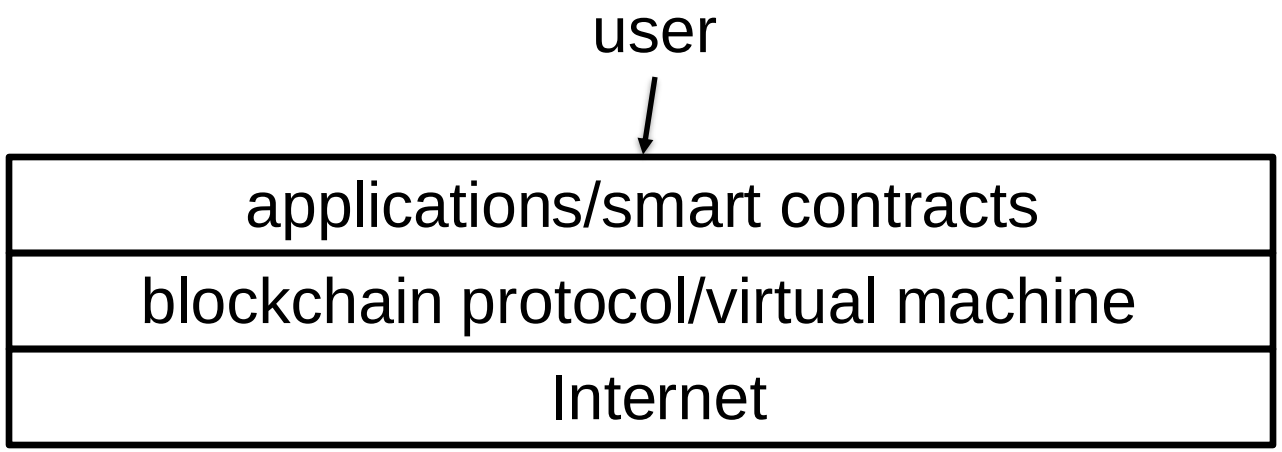

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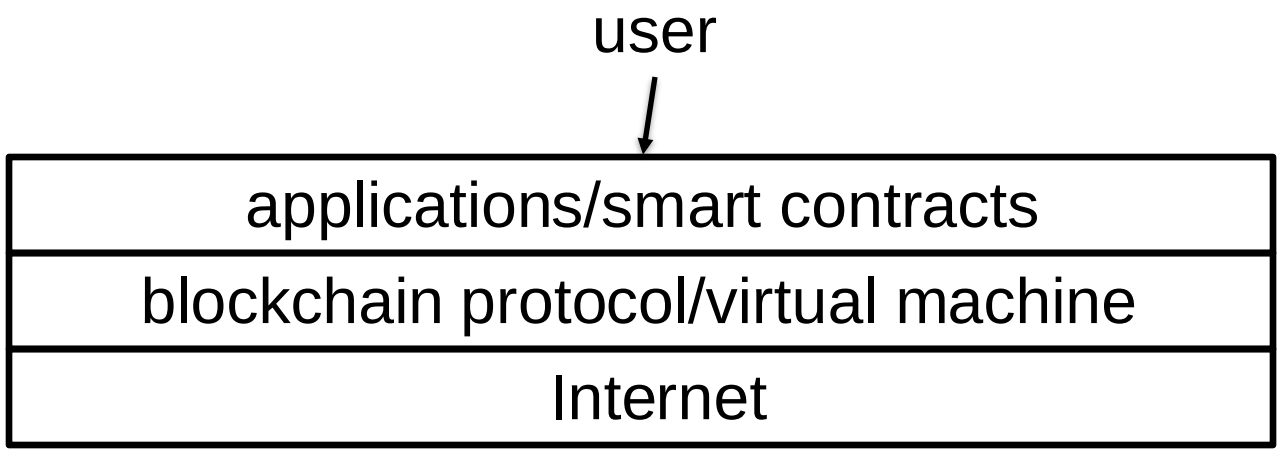

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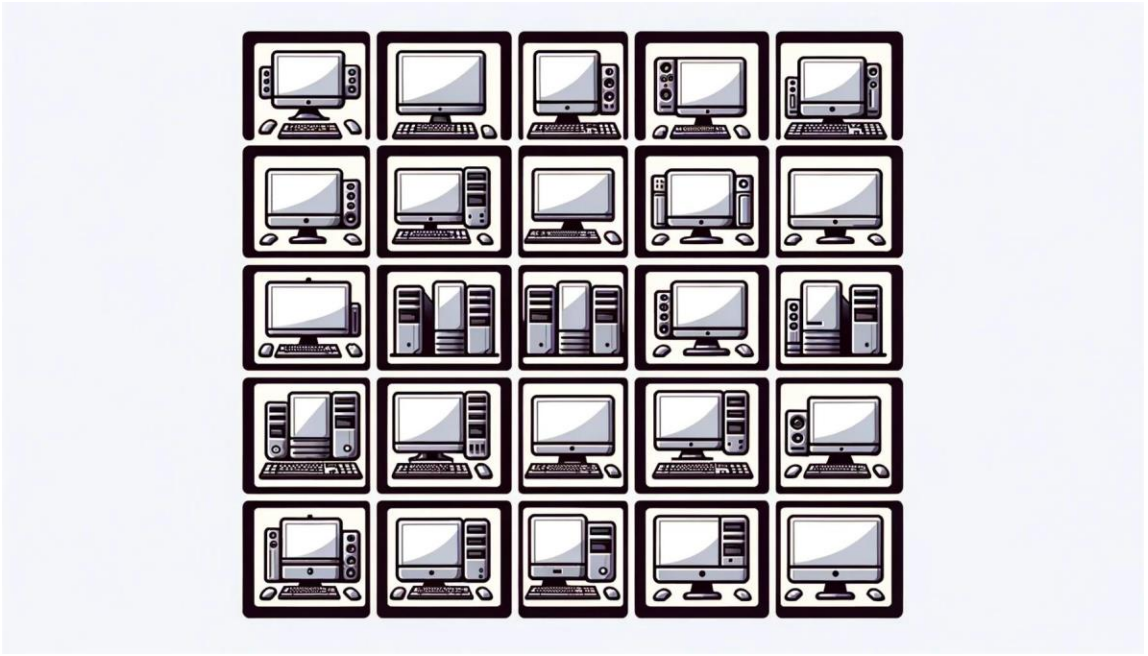
- like an operating system, a blockchain protocol:
  - acts as a “master program” to coordinate all apps/smart contracts
  - provides a virtual machine to developers of applications
- like the Internet, “decentralized” -- the product of collaboration between many physical machines, no one owner/operator

The Computer in the Sky



network of physical computers

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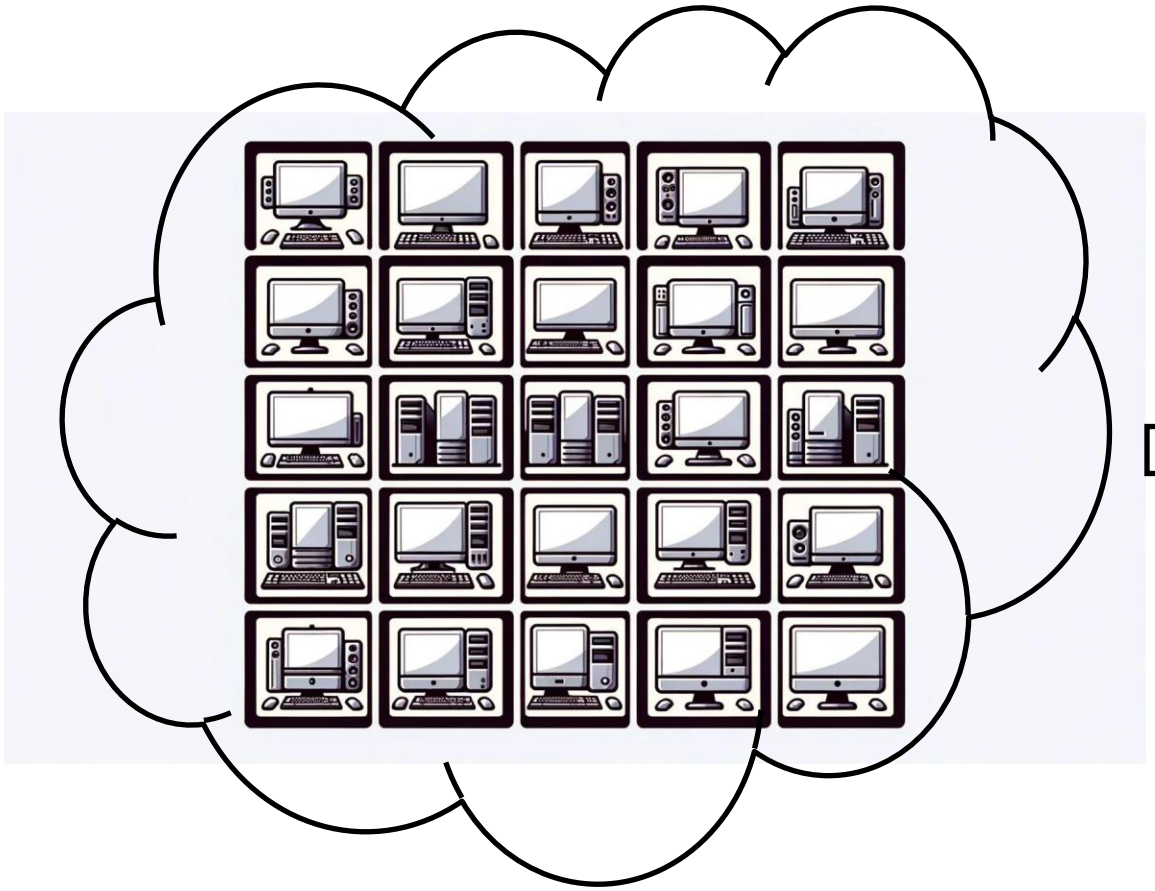

network of physical computers
+ blockchain protocol

simulated (virtual) computer

Goals for Lecture #2

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3. Challenges to consensus: faulty validators (crash vs. Byanztine), message delays (synchronous vs. asynchronous).
   - validators, communication network might not behave as expected
4. Security thresholds.
   - threshold of faulty validators at which consensus becomes impossible

Some Terminology

Validators: physical machines running a blockchain protocol.

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Block: sequence of transactions (➔ sequence of VM instructions).

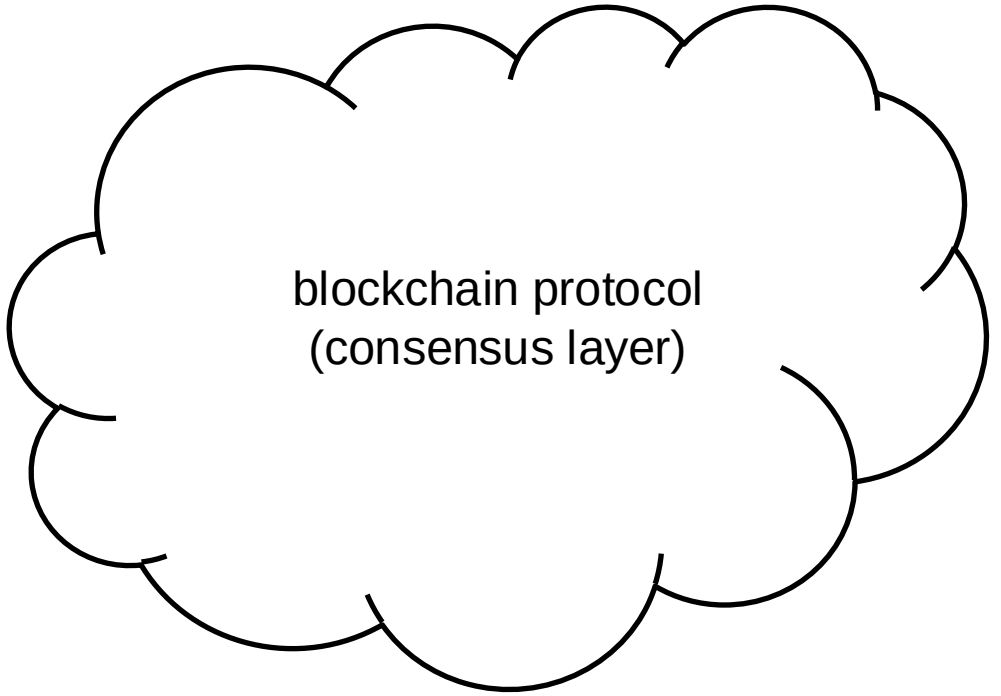
- for now, assume can be of unbounded size

Responsibilities of a Blockchain Protocol

Consensus: decide on a sequence (aka “chain”) of blocks.

- note: all validators must agree on this sequence!
- blocks keeping getting added (one-by-one) as long as there are transactions to process
- not obvious how to do this, subject of next 5 lectures

The Consensus Layer



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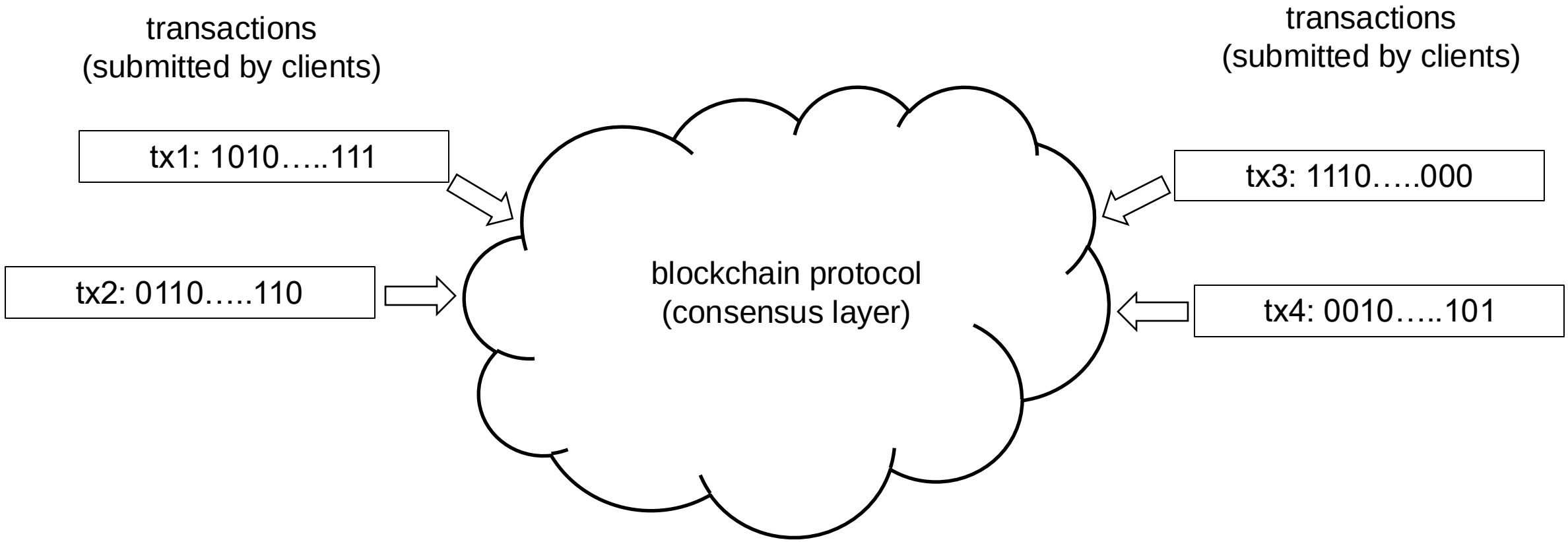

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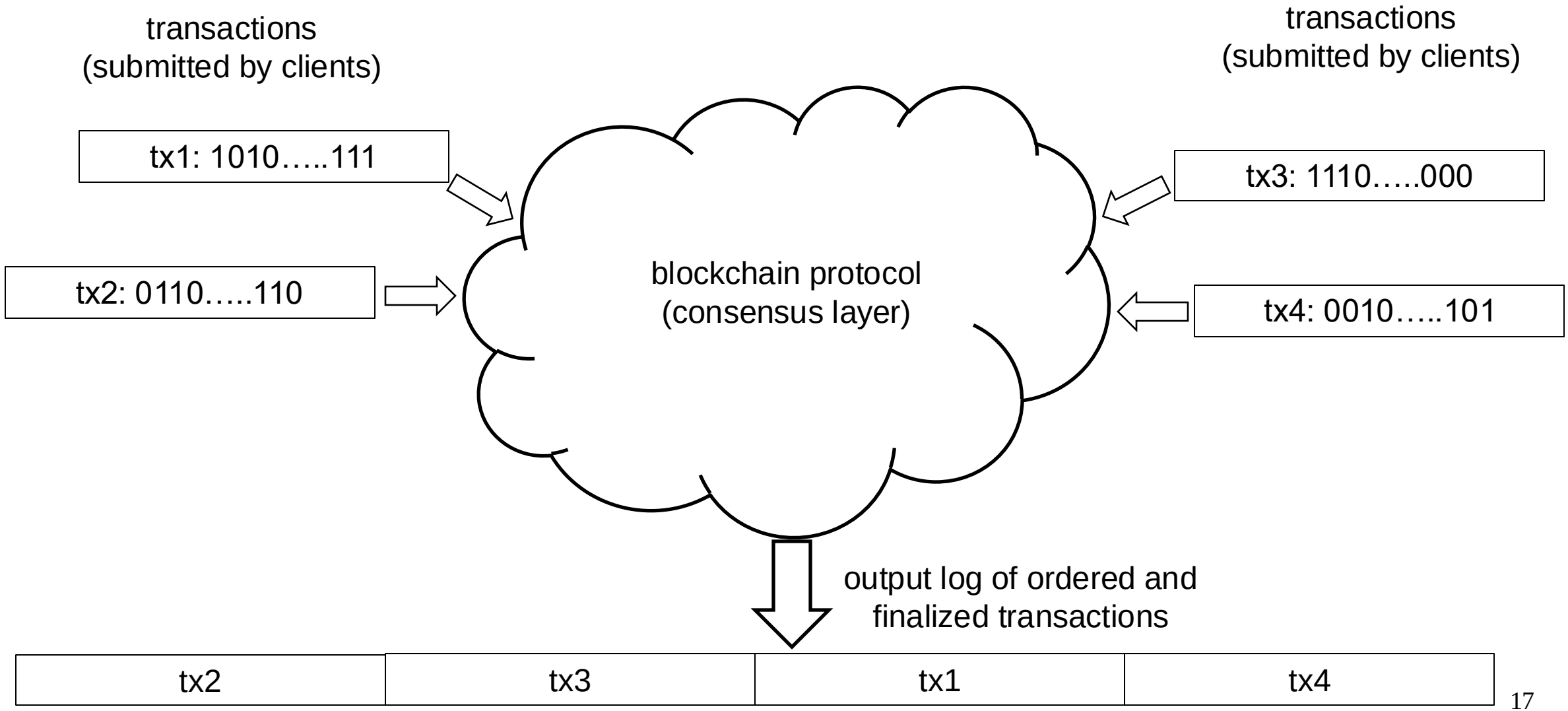

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Execution: keep state of the virtual machine up-to-date.

- new block added ➔ execute the corresponding snippets of code (do computations, update variable values, etc.)
- subject of lectures 8+9 (concludes Part I of course)

Consensus: Getting Started

Consensus: keep validators in sync despite failures and attacks.

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Standing assumptions:

1. Fixed and known set of n validators. (E.g., n=22 or 100.)
   - each with known ID and IP address (will communicate over Internet)
   - a.k.a. “permissioned” or “proof of authority” blockchain protocol
   - i.e., randos can’t just join the validator set
   - will relax in Part III of course (”permissionless” protocols including Bitcoin, Ethereum, etc.)

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2. All validators have same notion of time (“synchronized clocks”).
   - approximately true in practice, won’t worry about this further

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SMR: version of consensus appropriate for a blockchain protocol.

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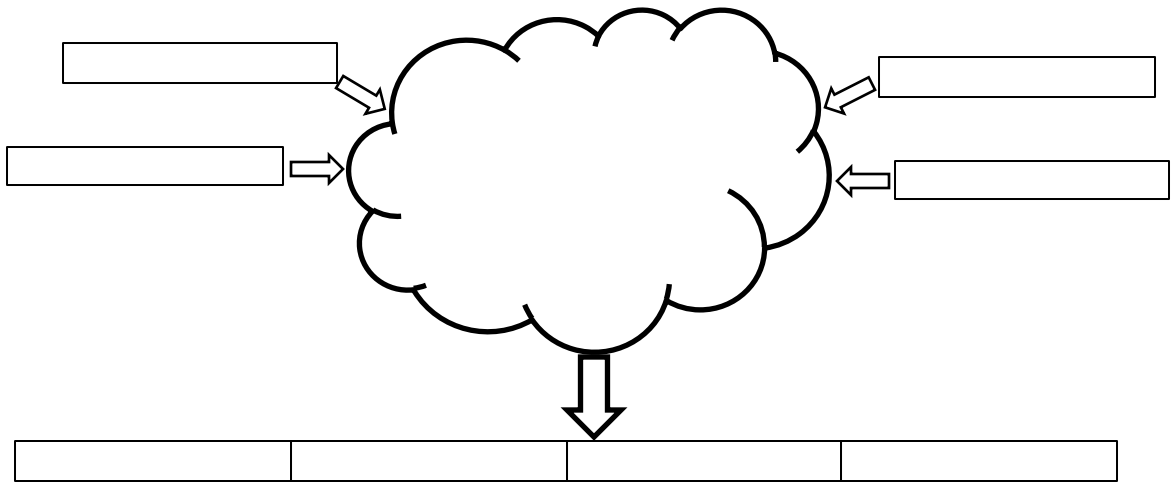

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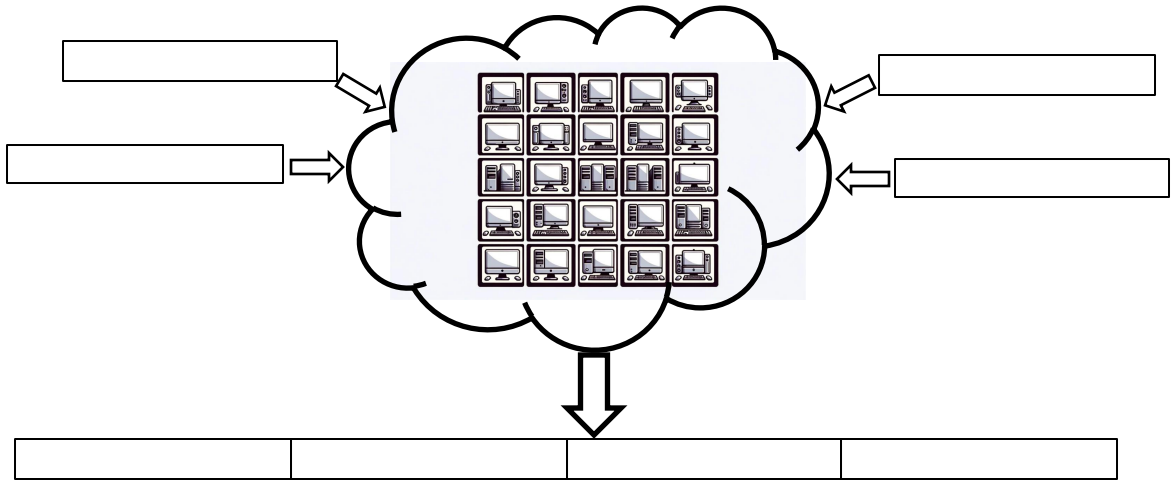

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Goal: a protocol that satisfies consistency and liveness.

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Protocol: code run by each validator. Each time step:

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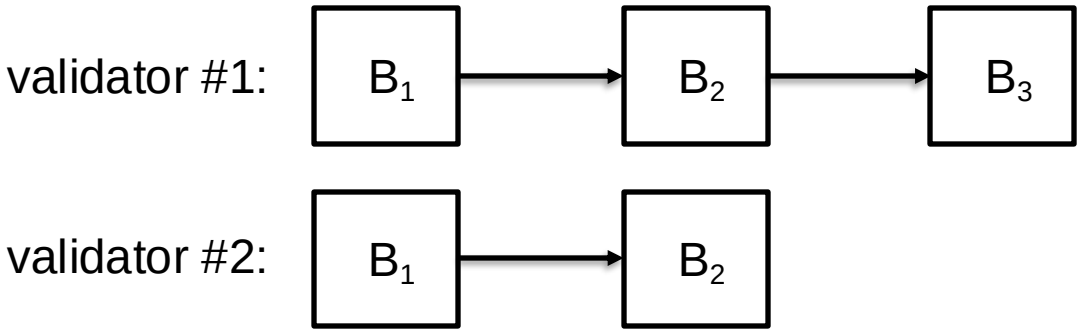

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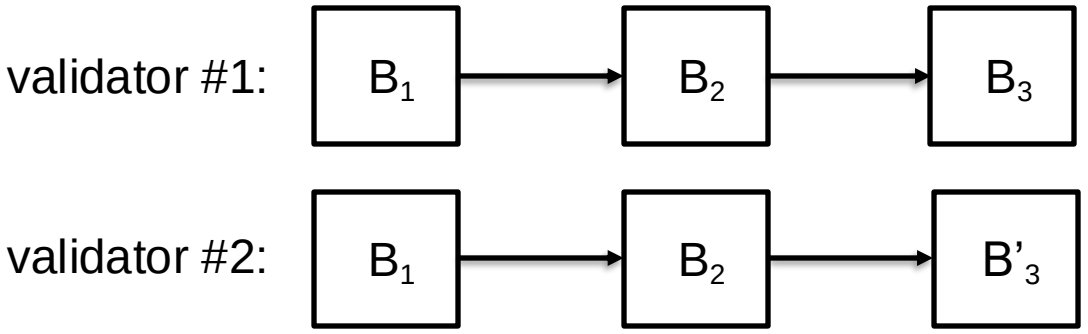

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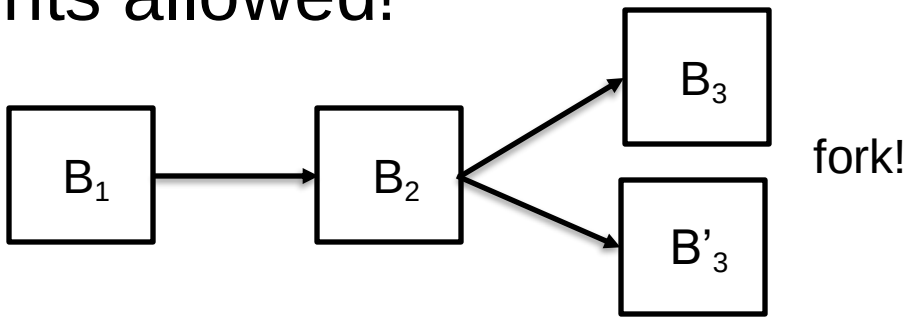
  - i.e., no "forks" allowed



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- practically relevant strengthening: also want bounded *latency*

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  - perhaps due to problem with network (e.g., congestion, or DoS attack)

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- next: can make SMR easier/harder by allowing less/more severe validator faults and network unreliability

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Faulty validators (hard mode): *“Byzantine” faults.*

- a faulty validator can behave arbitrarily
  - e.g., hard-to-model software bug, or maybe just a bad actor

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Unreliable network (easy mode): *synchronous network.*

- for known parameter Δ, every msg delivered in $\leq \Delta$ time steps
  - e.g., 1 time step = 1 millisecond, Δ=2000 (i.e., $\leq$ 2 seconds)

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Unreliable network (hard mode): *asynchronous network.*

- all messages eventually delivered, but no bound on delay

A Road Map to Practical SMR Protocols

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crash faults +
synchronous network

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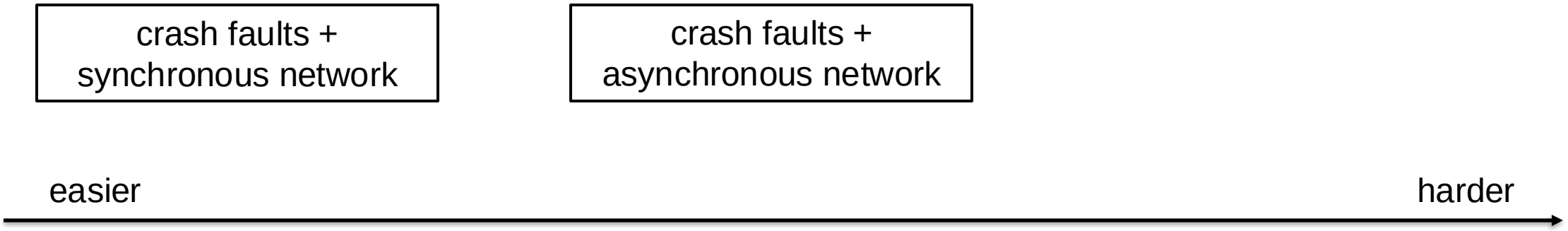

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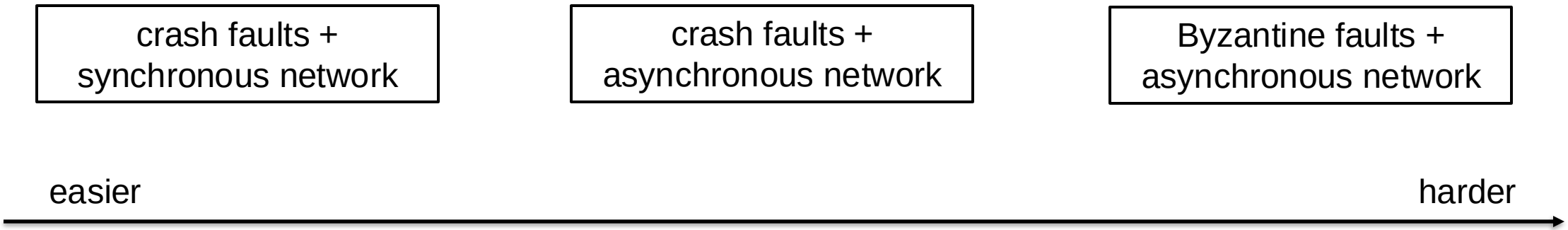

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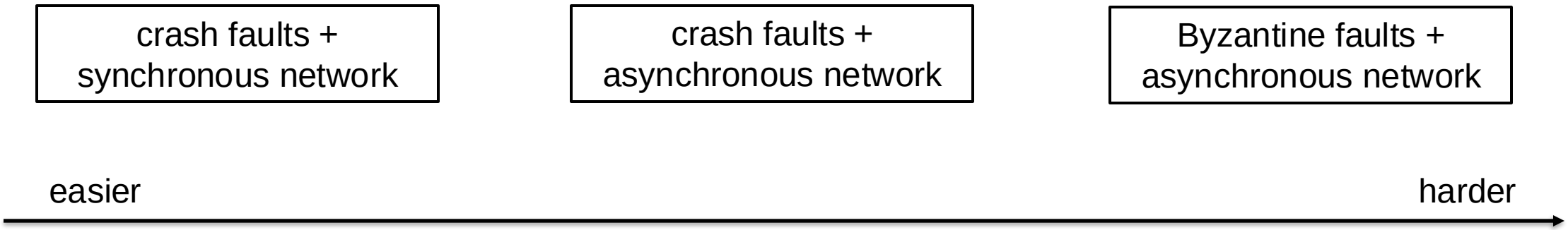

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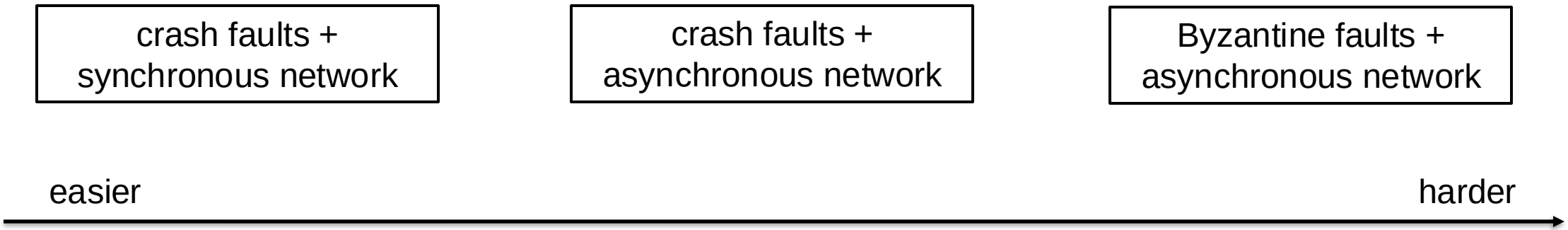

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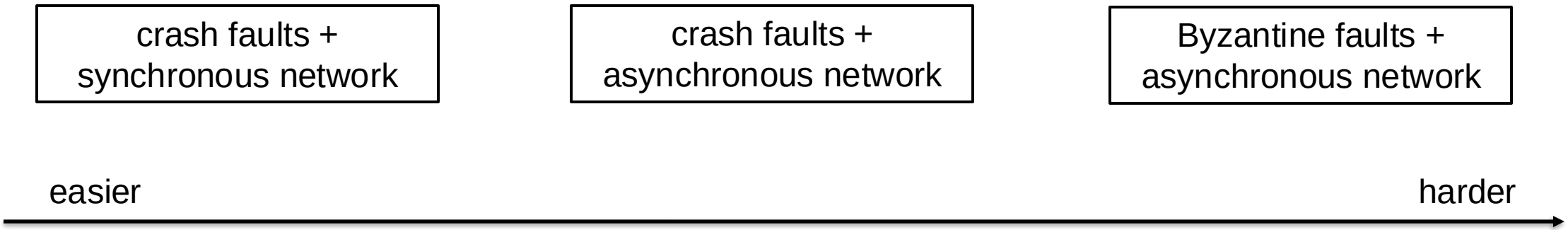

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3. Simpler protocols toward the left, more complex toward the right.

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Moral: crucial to have validator set of mostly reliable operators!