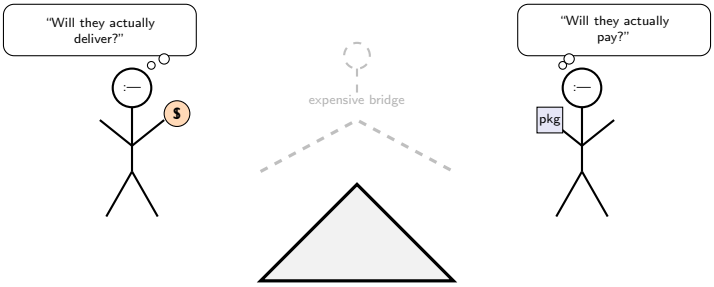
Blockchain Fundamentals

Lesson 05

Digital Finance



Every transaction needs trust. The question is: who provides it?

Outline

Learning Objectives

By the end of this lesson, you will be able to:

1. **Explain** the trust problem in digital transactions and how blockchain provides a technological solution
2. **Compare** major consensus mechanisms and their tradeoffs using basic game theory intuition
3. **Describe** smart contract functionality and the concept of digital goods
4. **Distinguish** between public, private, and consortium blockchains and their use cases
5. **Evaluate** blockchain applications in financial services (payments, settlement, securities)

Blockchain is not a database – it is a trust machine that replaces intermediaries with mathematics.

Why Is Trust the Most Expensive Ingredient in Finance?

Every financial transaction requires trust. Traditional trust costs a fortune: lawyers for contracts, banks for payments, courts for enforcement.

Every financial transaction requires **trust** – confidence that the counterparty will fulfill their obligations. Traditional trust mechanisms:

1. **Intermediaries** (third parties that guarantee settlement)
   - Banks clear payments, stock exchanges match trades (L01 intermediation)
   - Cost: fees, delays, operational risk
2. **Legal systems** (courts enforce contracts)
   - If counterparty defaults, you sue
   - Cost: lawyers, time, uncertainty
3. **Reputation** (repeated interactions build trust)
   - Works in closed networks (known counterparties)
   - Fails with strangers or one-time transactions

Blockchain proposes a fourth mechanism: algorithmic trust.

- Trust through transparent, verifiable computation rather than through institutions
- Replace costly intermediaries with open-source software and cryptography

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Traditional trust is expensive – blockchain proposes to replace it with transparent computation.

Why Can't You Copy-Paste a Digital Dollar?

The problem: Physical cash is **self-enforcing** – you cannot spend the same $10 bill twice (it changes hands). Digital data can be copied infinitely at zero cost.

Before blockchain: Trusted intermediary maintains authoritative ledger

- Bank tracks balances centrally
- When Alice sends $10 to Bob, bank debits Alice's account and credits Bob's
- Bank prevents Alice from spending same $10 twice
- *Single point of failure* (bank outage, fraud, censorship)

Blockchain solution: Distributed ledger where network collectively validates

- All participants have copy of transaction history
- Network consensus determines which transactions are valid
- No single party controls ledger (no single point of failure)
- *Trade-off:* Slower, more energy-intensive, less privacy than centralized database

Key insight: The double-spending problem is why digital money needs *either* a trusted bank *or* a distributed consensus mechanism.

The double-spending problem is the fundamental reason digital money needs either a bank or a blockchain.

How Does Blockchain Make Digital Things Scarce?

Economic properties of goods:

Property	Definition	Example
Rival	One person's use prevents another's	Physical cash, seat on airplane
Non-rival	One person's use doesn't diminish another's	Digital file, idea, broadcast
Excludable	Can prevent access (property rights)	Private property
Non-excludable	Cannot prevent access	Public park, clean air

Digital goods are **non-rival** and have near-zero marginal cost to reproduce.

- Great for information goods (knowledge, software, media)
- *Problem for money:* If I send you a digital token, I still have the original file

Blockchain's innovation: Make digital tokens **rival** (like physical cash)

- When Alice sends 1 BTC to Bob, Alice's balance decreases by 1 BTC
- Network consensus enforces scarcity (fixed supply, no copying)
- Creates *digital scarcity* – a non-copyable digital asset

Making digital tokens rival – like physical cash – is blockchain's fundamental innovation.

Is a Blockchain a Database or a Trust Machine?

Databases are fast and cheap. Every company uses them. But they require trusting the database operator — and in finance, that trust has been betrayed repeatedly.

Definition: A blockchain is a **distributed, append-only ledger** that records transactions across a network of computers (**nodes**) without a central authority.

Core properties and what they solve:

Property	Implementation	Trust Problem Solved
Decentralization	No single controlling node	No single point of failure or censorship
Immutability	Cryptographic chain of blocks	Cannot rewrite history after consensus
Transparency	Public transaction history	Anyone can verify (open audit trail)
Consensus	Network agreement protocol	Prevents double-spending without intermediary

Key distinction: Database vs. Trust Machine

- Traditional database: Fast, efficient, *requires trusting the database operator*
- Blockchain: Slower, redundant, *trust minimized through transparent computation*
- Use blockchain when trust costs exceed efficiency costs

A blockchain is not a database – it is a trust machine that replaces intermediaries with mathematics.

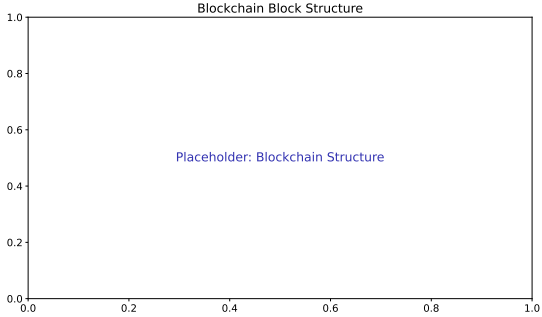
How Does Changing One Block Break the Entire Chain?

Block anatomy:

- **Block header** (metadata):
  - Current block hash
  - Previous block hash (creates chain)
  - Timestamp
  - Nonce (PoW puzzle solution)
  - Merkle root (transaction summary)
- **Block body** (data):
  - List of transactions
  - Digital signatures

Cryptographic hash function:

- Deterministic (same input → same output)
- One-way (cannot reverse)
- Collision-resistant (two inputs unlikely to have same hash)
- Avalanche effect (small change → completely different hash)



How immutability works:

- Each block contains hash of previous block
- Changing data in block 100 changes its hash
- Block 101's "previous hash" no longer matches
- *Entire chain breaks* from that point forward
- Network rejects modified chain (consensus rules)

Changing one block breaks the entire chain – this is how immutability works.

What Happens Between Clicking "Send" and Confirmation?

Transaction lifecycle:

1. **Creation**: Alice wants to send 1 BTC to Bob
   - Alice signs transaction with her **private key** (proves authorization)
   - Transaction includes: sender address, recipient address, amount, timestamp, signature
2. **Broadcast**: Alice sends transaction to network
   - Transaction propagates peer-to-peer across nodes
   - Enters **mempool** (waiting area for unconfirmed transactions)
3. **Validation**: Nodes verify transaction
   - Check digital signature (is Alice authorized to spend?)
   - Check balance (does Alice have 1 BTC?)
   - Check format (valid transaction structure?)
4. **Inclusion in block**: Miner/validator selects transaction from mempool
   - Bundles transactions into new block
   - Solves consensus mechanism (PoW puzzle or PoS selection)
5. **Confirmation**: Block added to chain
   - Transaction considered **confirmed** after 1 block
   - More blocks $\rightarrow$ higher **finality** (harder to reverse)
   - Bitcoin: 6 confirmations standard ($\approx$ 1 hour)

Digital signatures prove authorization without revealing the private key – asymmetric cryptography in action.

How Do Strangers Agree When Some of Them Are Liars?

The problem (Lamport, Shostak, Pease, 1982): Multiple generals surround a city. They must coordinate attack or retreat. Some generals are **traitors** who send conflicting messages. How do **loyal generals** agree on a plan?

Mapping to blockchain:

- Generals $\rightarrow$ Nodes in network
- Traitors $\rightarrow$ Malicious/faulty nodes
- Agreeing on attack/retreat $\rightarrow$ Agreeing on transaction history
- Byzantine Fault Tolerance (BFT): System functions correctly even when some nodes are dishonest

Why this is hard in distributed systems:

- No shared clock (cannot rely on timestamps)
- Messages may be delayed, duplicated, or lost
- Cannot distinguish between malicious node and network failure
- Sybil attack risk: Attacker creates many fake identities (fake generals)

Game theory insight: Consensus mechanisms make *honest behavior incentive-compatible*

- Align individual incentives (profit) with network security
- Make cheating *more expensive* than honest participation

The Byzantine Generals Problem (Lamport, 1982) is the theoretical foundation of all consensus mechanisms.

Why Does Bitcoin Burn More Energy than Argentina?

How it works:

- **Miners** compete to solve computational puzzle (find nonce such that block hash $<$ target)
- First to solve broadcasts block to network
- Other nodes verify solution (easy to check, hard to find)
- Winner receives **block reward** (new coins + transaction fees)

Security mechanism: Cost of solving puzzle makes cheating expensive

- To rewrite history, attacker must re-mine all subsequent blocks
- Requires $>$ 50% of network's computational power (**51% attack**)
- *Opportunity cost:* Honest mining more profitable than attacking

Difficulty adjustment: Network adjusts puzzle difficulty to maintain target block time

- Bitcoin: 10 minutes average, adjustment every 2,016 blocks ($\approx$ 2 weeks)
- More miners join $\rightarrow$ difficulty increases $\rightarrow$ block time stabilizes

Energy consumption as design feature:

- Not a bug – energy expenditure is the *cost of security*
- Bitcoin: $\approx$ 150 TWh/year (comparable to Argentina)
- Environmental criticism led to development of alternative mechanisms (PoS)

PoW security comes from making cheating more expensive than honest participation.

Can Economic Bonds Replace Energy as a Security Mechanism?

How it works:

- **Validators** stake tokens as collateral (lock up for fixed period)
- Network selects validator proportional to stake size (not computational power)
- Selected validator proposes new block
- Other validators attest to block validity
- Validators earn transaction fees (no block reward inflation in mature networks)

Security mechanism: Economic bonds replace energy expenditure

- Malicious behavior $\rightarrow$ **slashing** (lose staked tokens)
- Stake acts as *collateral* (skin in the game)
- Attacking network destroys your own investment

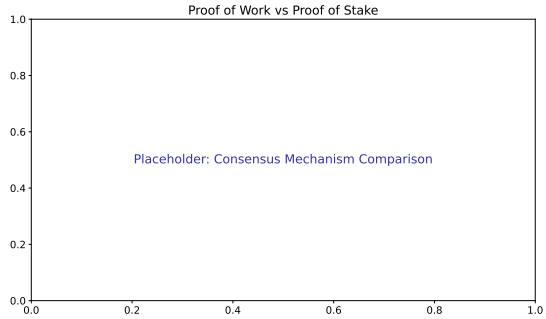
Ethereum Merge (September 2022): Ethereum switched from PoW to PoS

- Energy consumption reduced by $\approx 99.95\%$
- From ≈ 80 TWh/year to ≈ 0.01 TWh/year
- Maintained security while dramatically reducing environmental impact

Nothing-at-stake problem: In PoW, mining on wrong chain wastes electricity. In PoS, validators could validate multiple chains simultaneously (no cost). *Solution:* Slashing penalties for validating conflicting blocks.

PoS replaces energy expenditure with economic bonds – both create cost of cheating.

Which Consensus Mechanism Wins – and What Does It Sacrifice?



Key observations:

- **PoW**: Maximum decentralization, proven security, but energy-intensive
- **PoS**: Energy-efficient, faster, but concentration risk
- **BFT**: Fast finality for known validator sets, limited scale

Comparison dimensions:

Property	PoW	PoS	BFT
Energy use	Very high	Very low	Low
Throughput (tx/sec)	Low (7)	Medium (30)	High (1000+)
Decentralization	High	Medium	Low
Security model	Computational	Economic	Validator set
Finality	Probabilistic	Fast	Instant
Sybil resistance	Hash power	Stake	Identity
Censorship resistance	High	Medium	Low

Economic intuition:

- PoW: Pay with electricity (flow cost)
- PoS: Pay with capital lockup (stock cost)
- BFT: Pay with centralization (trust cost)

No free lunch: Every mechanism trades off decentralization, security, and scalability.

No consensus mechanism is best on all dimensions – each makes different tradeoffs.

When Should You Use a Public vs. Private Blockchain?

A Swiss bank wants to settle bonds on blockchain. An anonymous user wants to send crypto to a stranger. They need completely different blockchains — because they have completely different trust requirements.

Classification by access control:

Type	Characteristics	Advantages	Disadvantages
Public (permissionless)	• Anyone can read, write, validate • Full decentralization • Open network (Bitcoin, Ethereum)	• Maximum trust minimization • Censorship resistant • Transparent	• Lower throughput • Higher latency • No privacy
Private (permissioned)	• Single org controls access • Validator set known • Example: Walmart supply chain	• Higher throughput • Lower latency • Privacy control	• Centralized trust • Single point of failure • Less transparent
Consortium (hybrid)	• Multiple orgs share control • Pre-selected validator nodes • Example: R3 Corda (banks)	• Balanced decentralization • Regulatory compliance • Governance structure	• Coordination costs • Semi-centralized • Limited openness

Trust economics: Choice depends on existing trust between participants

- **Low trust** (strangers, adversarial) → Public blockchain
- **Medium trust** (regulated entities) → Consortium
- **High trust** (single org, subsidiaries) → Private or traditional database

The choice depends on how much trust already exists between participants.

How Do You Choose the Right Blockchain for a Financial Use Case?

Decision framework based on trust economics:

1. **Do participants already know each other?**
   - YES → Private/consortium may suffice
   - NO → Public blockchain provides trust layer
2. **Is regulatory compliance required?**
   - YES → Permissioned (KYC/AML identity requirements)
   - NO → Public blockchain possible
3. **Is transaction privacy important?**
   - YES → Private/consortium (selective disclosure)
   - NO → Public blockchain transparency acceptable
4. **What throughput is needed?**
   - HIGH (Visa-scale: 65,000 tx/sec) → Private/consortium
   - MEDIUM (payment settlement: 100s tx/sec) → Consortium
   - LOW (final settlement: 10s tx/sec) → Public blockchain viable

Real-world example: SIX Digital Exchange (SDX)

- Swiss stock exchange for tokenized securities
- **Permissioned** blockchain (consortium model)
- Participants: Regulated banks and financial institutions
- Rationale: Identity requirements (no anonymous participants), high throughput, regulatory compliance

Most financial blockchain applications use private chains because regulated entities already have identity frameworks.

What If Contracts Could Enforce Themselves?

Traditional contracts require lawyers to write, courts to enforce, and months to resolve disputes. What if the contract could read its own conditions and execute automatically — with no lawyer, no court, no delay?

Definition: A **smart contract** is a self-executing program stored on a blockchain that automatically enforces the terms of an agreement when predefined conditions are met.

How they work:

- **Code as law:** Contract logic encoded in software (if-then rules)
- **Deterministic execution:** Same inputs always produce same outputs (no discretion)
- **Immutable:** Once deployed, cannot be changed (bugs are permanent)
- **Transparent:** Code is publicly auditable on blockchain
- **Automated:** No intermediary needed to enforce (reduces counterparty risk)

Connection to L01 transaction costs:

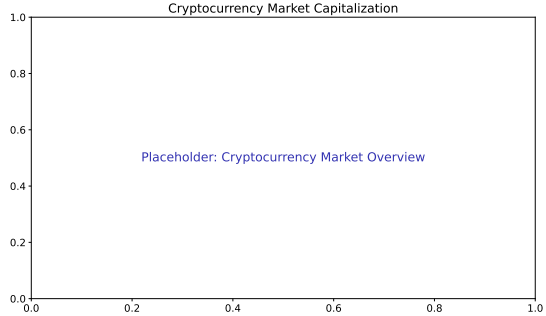
- Traditional contracts: High *enforcement costs* (courts, lawyers, time)
- Smart contracts: Low enforcement but high *writing costs* — upfront complexity vs. reduced disputes

Example: Decentralized lending (Aave, Compound)

- User deposits collateral (e.g., 150% of loan value)
- Smart contract automatically issues loan
- If collateral value drops below threshold, contract liquidates position
- No credit check, no loan officer, no manual intervention

Smart contracts lower contracting costs – but bugs in code are also immutable.

Why Does It Matter Whether a Token Is a Security or a Utility?



Token standards:

- **ERC-20:** Fungible tokens – cryptocurrencies, stablecoins
- **ERC-721:** Non-fungible tokens (NFTs) – unique digital assets

Stablecoins: Cryptocurrencies pegged to stable asset

- USDC, USDT (fiat-backed, 1:1 USD)
- DAI (crypto-collateralized)

Token taxonomy:

Type	Purpose & Regulatory Treatment
Cryptocurrency	Medium of exchange, store of value. Commodity (CFTC) or currency.
Utility token	Access to product/service (e.g., Filecoin). Generally not securities.
Security token	Investment contract (equity, debt). Subject to securities regulation (SEC, FINMA).
Stablecoin	Pegged to fiat. Payment use case. Growing regulatory scrutiny.

Tokenization of real-world assets (RWA):

- Represent physical assets on blockchain
- Examples: Real estate, bonds, art
- Benefits: Fractional ownership, 24/7 trading
- Challenge: Oracle problem (on/off-chain)

The token taxonomy matters because each type has different regulatory treatment.

What Can Go Wrong with Smart Contracts and Blockchains?

1. **Smart contract vulnerabilities**
   - **Bugs are permanent:** Immutability means coding errors cannot be fixed after deployment
   - **Example:** The DAO hack (2016) – $60M stolen due to reentrancy vulnerability in Ethereum smart contract
   - **Mitigation:** Formal verification, extensive audits, bug bounties, upgrade patterns (proxy contracts)

2. **The Oracle Problem**
   - Smart contracts cannot directly access real-world data (stock prices, weather, election results)
   - **Oracle:** Third-party service that feeds external data to blockchain
   - **Problem:** Reintroduces trust (oracle becomes single point of failure)
   - **Solutions:** Decentralized oracles (Chainlink), cryptographic proofs, multiple data sources
   - *Fundamental limitation:* Blockchain consensus cannot verify off-chain facts

3. **Scalability constraints**
   - **Gas fees:** Computational cost of smart contract execution (Ethereum: $1-$50 per transaction)
   - **Throughput:** Ethereum $\approx$ 30 tx/sec (vs. Visa 65,000 tx/sec)
   - Layer 2 solutions: Rollups, sidechains (trade-off with security)

4. **Legal and regulatory uncertainty**
   - **Swiss DLT Act (2021):** Legal framework for tokenized securities, digital shares
   - **MiCA (EU, 2024):** Markets in Crypto-Assets regulation – comprehensive crypto rulebook
   - Open questions: Cross-border enforcement, liability for code bugs, legal status of DAOs

The oracle problem is fundamental: smart contracts are powerful but blind to the real world.

How Can Layer 2 Solutions Break the Scalability Trilemma?

Theory: The scalability trilemma means Layer 1 blockchains cannot scale without sacrificing decentralization or security. Layer 2 solutions process transactions *off-chain* and periodically settle on Layer 1.

Solution	How It Works	Example	TPS
State channels	Two parties transact off-chain; settle final state on-chain	Lightning Network	1M+
Optimistic rollups	Bundle transactions; assume valid; allow fraud proofs	Optimism, Arbitrum	2,000+
ZK-rollups	Bundle transactions; prove validity cryptographically	zkSync, StarkNet	2,000+
Sidechains	Independent chain with own consensus, bridged to main chain	Polygon PoS	7,000+

Trade-offs:

- State channels: highest speed but limited to two-party interactions
- Optimistic rollups: simpler but 7-day withdrawal delay (challenge period)
- ZK-rollups: instant finality but complex cryptography (computationally expensive)
- Sidechains: fastest but weaker security guarantees (own validator set)

Financial relevance: Layer 2 makes DeFi usable for retail users (sub-$0.01 fees vs. $10+ on Ethereum L1).

Layer 2 solutions address the scalability trilemma by processing transactions off-chain while inheriting Layer 1 security.

Can You Prove Something Without Revealing What You Know?

Theory: A zero-knowledge proof (ZKP) allows one party (prover) to prove a statement is true to another party (verifier) *without revealing the underlying data*.

Analogy: Proving you know a password without revealing the password; proving you are over 18 without revealing your birthdate.

Three properties of ZKPs:

1. **Completeness:** If the statement is true, the verifier will be convinced
2. **Soundness:** If the statement is false, the prover cannot convince the verifier
3. **Zero-knowledge:** The verifier learns nothing beyond the truth of the statement

Financial applications:

- **Privacy-preserving transactions:** Prove sufficient balance without revealing exact amount (Zcash)
- **KYC without data sharing:** Prove identity verified without exposing personal data
- **Compliance:** Prove regulatory compliance without revealing proprietary trading data
- **ZK-rollups:** Prove thousands of transactions are valid without re-executing them

Limitation: Computationally expensive to generate proofs; complex to implement correctly.

Zero-knowledge proofs solve a paradox: proving you know something without revealing what you know.

Where Does Blockchain Actually Reduce Costs in Finance?

Framework: Which transaction cost (from L01) does blockchain reduce?

1. Cross-border payments

- **Problem:** Correspondent banking network slow (2-5 days) and expensive (6-8% fees)
- **Blockchain solution:** Direct settlement without intermediaries (Ripple, Stellar)
- **Cost reduced:** Intermediation layers (fewer correspondent banks)
- **Status:** Operational for remittances, limited adoption for large transfers (regulatory hurdles)

2. Securities settlement

- **Problem:** T+2 settlement (2 days after trade, from L06 preview) creates counterparty risk
- **Blockchain solution:** Near-instant settlement (delivery-vs-payment on shared ledger)
- **Cost reduced:** Settlement risk, clearing house fees, reconciliation overhead
- **Example:** Australian Securities Exchange (ASX) planned blockchain settlement system (delayed to 2025+)

3. Trade finance

- **Problem:** Letters of credit require physical documents, multiple intermediaries (banks, insurers, shippers), long delays
- **Blockchain solution:** Digitize documents on shared ledger (we.trade platform)
- **Cost reduced:** Document handling, verification delays, fraud risk
- **Challenge:** Network effects (requires buy-in from all parties in supply chain)

Blockchain's value in finance is proportional to the trust and settlement costs it eliminates.

Why Hasn't Blockchain Replaced Traditional Finance Yet?

Gartner Hype Cycle observation:

- Peak hype: 2017-2018 ("blockchain will revolutionize everything")
- Trough of disillusionment: 2019-2020 (few production systems)
- Slope of enlightenment: 2021+ (realistic use cases emerge)

What works:

- **Settlement:** Where speed and trust matter more than throughput (SDX, ASX projects)
- **Cross-border payments:** Where cost of correspondent banking is high (remittances)
- **Tokenization:** Fractional ownership of illiquid assets (real estate, private equity)

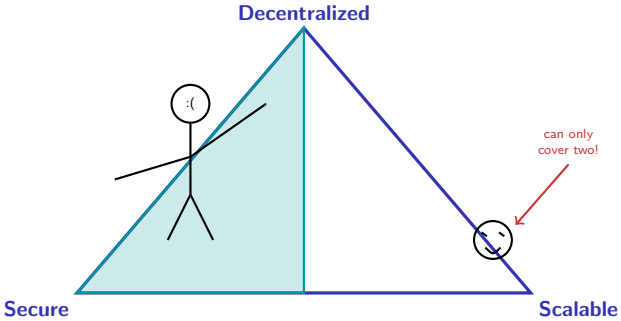
What is overhyped:

- Replacing all databases with blockchain (when trust is not the problem)
- High-frequency trading on public blockchains (throughput insufficient)
- Complete disintermediation (regulation requires identity, accountability)

The Scalability Trilemma (Vitalik Buterin):

- **Three properties:** Decentralization, Security, Scalability
- **Trade-off:** Can optimize for any *two*, but not all three simultaneously
- Public blockchains prioritize decentralization + security, sacrifice scalability
- Private blockchains prioritize security + scalability, sacrifice decentralization
- *Implication:* No single blockchain design suits all use cases

The scalability trilemma explains why blockchain has not replaced traditional finance wholesale.



You can pick two. The third is always the one you wanted most.

Summary

Key takeaways from Lesson 05:

1. **Trust economics:** Blockchain replaces costly trust mechanisms (intermediaries, courts, reputation) with algorithmic trust through transparent computation and cryptography.
2. **Consensus mechanisms:** PoW, PoS, and BFT make different tradeoffs between decentralization, security, and scalability. Each aligns incentives through costs (energy, capital lockup, or centralization).
3. **Smart contracts:** Reduce enforcement costs but introduce coding risk. The oracle problem limits connection to real-world data. Token taxonomy determines regulatory treatment.
4. **Financial applications:** Blockchain adds value where trust and settlement costs are high (cross-border payments, securities settlement). The scalability trilemma explains why adoption is selective, not universal.

Connecting to course themes:

- **L01 (Financial Systems):** Blockchain as alternative to intermediary-based trust (banks, exchanges)
- **L06 (Financial Markets):** Settlement finality and T+2 problem addressed by distributed ledger
- **Forward:** Next lesson explores traditional financial market infrastructure that blockchain aims to disrupt

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Next lesson: Financial Markets – where blockchain's settlement promise meets traditional market infrastructure.