Blockchains & Cryptocurrencies

Introduction

Instructor: Matthew Green
Johns Hopkins University - Fall 2024

My background

- Mainly work in applied cryptography
  (TLS, messaging systems, privacy-preserving protocols, cryptocurrencies)

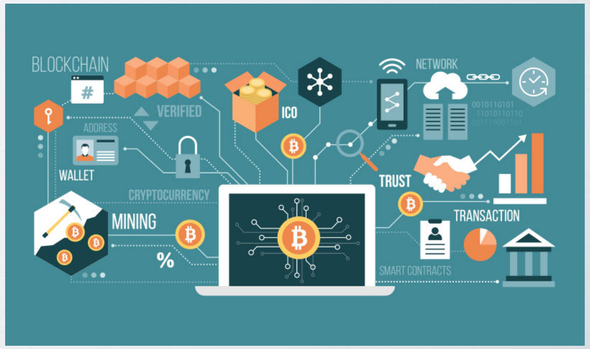
- I co-founded a private cryptocurrency (**Zcash**) and boy was that weird

- Also helped start some companies:

  - **Aleo** (ZK smart contracts)
    Sealance (regulatory compliance)
    Bolt (custody)

What is a blockchain?

- A data structure
- A specific type of decentralized ledger (DLT) or "consensus network"
  - Used for building decentralized cryptocurrencies such as Bitcoin, Ethereum
  - Many other applications: distributed Domain Name system (DNS), supply chain, Public-Key Infrastructure (PKI), decentralized finance, etc.



Course objectives

- Understanding the mechanics of blockchains and consensus networks
- Understanding the necessary cryptographic background
- Exploring applications of blockchains to cryptocurrencies and smart contracts
- Learning to use some common DLT technologies
- Understanding limitations of current blockchains/DLT tech

Course objectives (contd)

- Introduction to recent exciting research
- **Main course goal:**
  Extend this research
  - Entrepreneurial or research projects by student teams
  - These can be major projects, or even small applications

Disclaimer

This is not a finance course on cryptocurrencies. You should not expect to be taught how to invest in cryptocurrencies or how to become a millionaire overnight.

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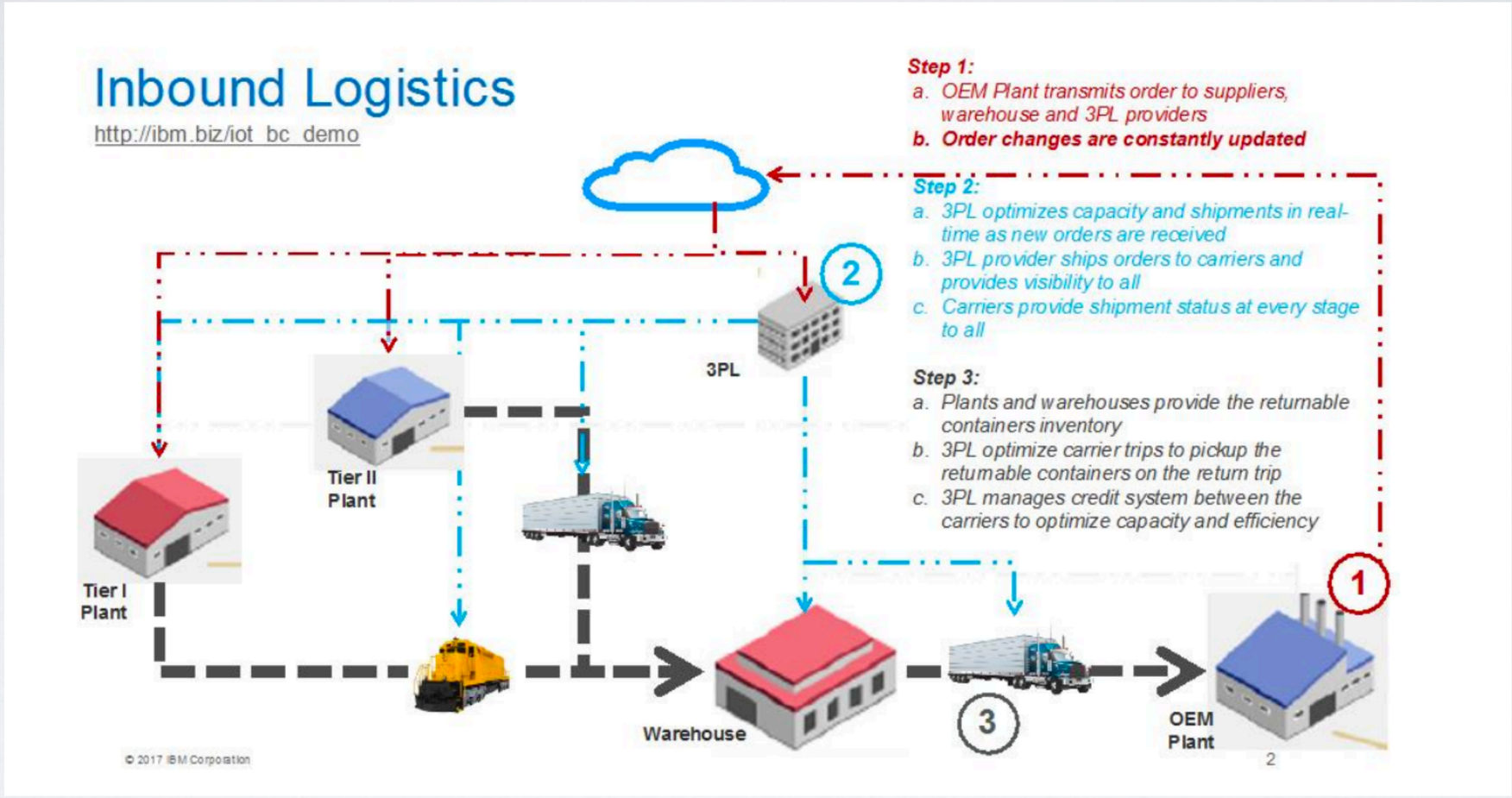
(Unless you're already a billionaire — then we can certainly help you become a millionaire.)

Pre-requisites

- No background in cryptography is necessary. However, the following are expected:
  - Basic mathematical maturity
  - Comfort with basic probability
  - Familiarity with asymptotic (Big-O) notation
  - Programming capability (in Python/Java, etc.), willingness to learn a new, weird language and also Git

Boring course logistics



Source: https://www.ibm.com/blogs/internet-of-things/blockchain-automotive-supply-chain/

Resources

- **Course website & syllabus:**

  https://github.com/matthewdgreen/blockchains2024

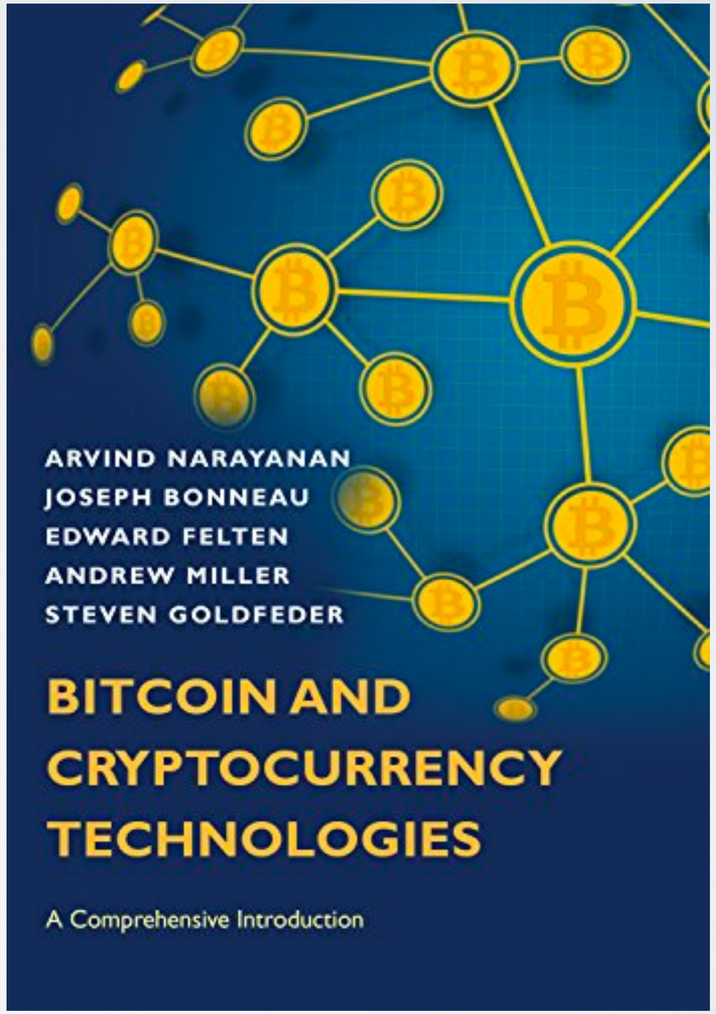
  (Or visit Piazza)

- **Piazza:** https://piazza.com/class/m04rcy3qx082v5

  Search for JHU 601.441/641 2024, or course title

Texts/Readings

- **Text:** NBFMG (right)
- However, many readings will be drawn from online papers and resources
- Readings on syllabus are assigned the day they are listed, will be discussed during the following lecture



Texts/Readings

Course Syllabus

matthewdgreen edited this page 4 minutes ago · 1 revision

Dates and topics are subject to change. Reading is assigned on the day specified, and will be discussed in the following class.

8/26/2024: Introduction

- Reading: NBFMG Chapter 0

8/28/2024: Crypto Background

- Reading: NBFMG Chapter 1
- Reading: Shafi+Mihir's Notes (Chapter 8 and 10)

TA & Office Hours

- **TAs/CAs:**
  - Brennon Brimhall
  - *Office hours TBA*

Grading & Exams

- **Grading:**

  60% assignments+exams,
  40% project

- **Exams:**

  Midterm exam:
  Final exam: as assigned by JHU

- **Assignments:**

  Programming & written, submit
  via Gradescope.

Course project

- This is a research-quality project, conducted by groups of 1-3 students. You must have instructor approval for your project topic.
- There will be a list of project ideas on the course website. Other ideas are also fine with approval.
- Deliverables: new software, high-quality written report, detailed presentation (choose 2)
- **1-page proposal due 9/30**

Honor Code

- Except where explicitly marked, assignments and exams are individual work. You're expected to do your own work on these. Don't give or receive exam-specific assistance on these.
  - This particularly includes code you find on the Internet
  - We disallow use of LLM type tools (e.g., ChatGPT)
- See the JHU academic integrity code.
- Exceptions for general-purpose programming advice, etc.

Honor Code ++, Cryptocurrency edition

- Many legal aspects are unsettled in the blockchain/ cryptocurrency space
- E.g., what happens if you discover and exploit a vulnerability in an experimental blockchain project?
- In this course we practice responsible disclosure. If this comes up e.g., in your course project, **see the TA or instructors.**

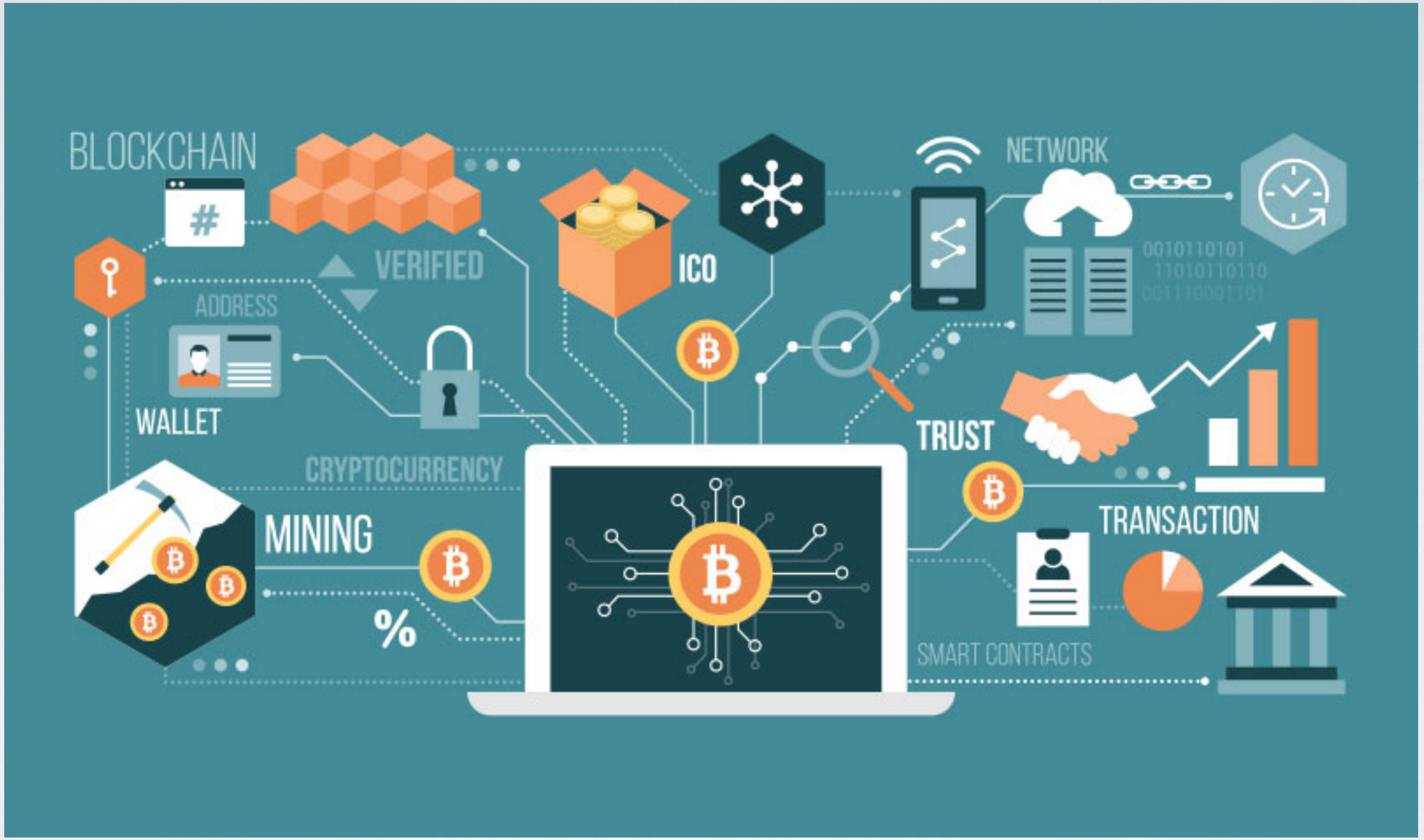
News

- Read the news!!
- CoinDesk, CoinTelegraph, Hacker News, etc.
- X/Twitter (ugh): maybe @VitalikButerin, @pwuille, @IOHK_Charles, @ethereumJoseph, @starkness, @adam3us, etc.
- Lots of network-specific forum sites, Discords, etc.

Any other questions?

- Come and ask after class, or send a note via Piazza

Towards blockchains



Source: https://www.intheblack.com/articles/2018/03/22/blockchain-future-record-keeping

Cryptocurrencies Aren't 'Crypto'

As the price of Bitcoin and Ethereum skyrocket, and more and more people who are unfamiliar with technology join in the craze, words start to lose their original and correct meaning.

3,500
3,000
2,500
2,000
1,500
capitalization in billion U.S. dollars
Jul 30, 2014
Dec 24, 2014
Jun 03, 2015
Oct 28, 2015
Mar 23, 2016
Aug 17, 2016
Jan 11, 2017
Jun 07, 2017
Nov 01, 2017
Mar 28, 2018
Aug 22, 2018
Jan 16, 2019
Jun 12, 2019
Nov 06, 2019
Apr 01, 2020
Sep 02, 2020
Jan 27, 2021
Jun 23, 2021
Nov 17, 2021
Apr 13, 2022
Sep 07, 2022

- **Whether you love it or hate crypto…**
  - Cryptocurrencies are exerting a massive influence on society and the field of CS
  - Most people's first major exposure to cryptography and distributed systems
  - That's both a good thing and a bad thing
    - The good: we get to deploy some really exciting new cryptography
    - The bad: if you stare into the abyss…

Digital payments before blockchains: 1980s-2007

CREDIT CARD
0123 4567 8901 2345
CARDHOLDER NAME


Harrah's Council Bluffs
1 Harrah's Blvd. Council Bluffs, IA 51501
CASHOUT TICKET
VALIDATION 51-3601-7245-2982-3145
07/31/2010 18:13:16 TICKET # 7680
ZERO DOLLARS AND SEVENTEEN CENTS
$0.17
Ticket Void after 90 days ASSET# 1724

1980s: Retail Payments

- **Goal: Digital payment system that**
  - Allows payments between customers and merchants (c2m)
  - Or between individual customers (c2c)
- **Strong cryptographic security**
- **Privacy**

1980s: Retail Payments

- **Some of the earliest ideas:**
  - Let's make digital cash!
  - Let's make digital checks!

“Digital cash”

- **Intuition:**
  - Bills are just paper objects that have some data on them
  - Why not convert them into digital files?
  - I can “spend” a bill by sending the file to you and deleting my copy

The "double spending problem"

- Obviously this idea does not work:
  - A malicious payer can simply retain a copy of the bill, and then spend it a second time with someone else
  - We call this the "double spending problem" (DSP)
- How do we prevent double spending?

The "double spending problem"

- Two common solutions to the DSP
  - **Online solution:** have a centralized party that records transactions
    - Can be serial numbers of bills, and who owns them now
    - Can be a full ledger of account/balances (more like "checks")
  - **Offline solution:** build computers that never misbehave (i.e., they always delete the original copy of the bill…)

Offline cash

- **Some of the earliest ideas:**
  - BankAmericard ATMs, 1980s: recorded debit balance on magstripe
  - A few more recent systems use offline "smartcards" to store balances
  - These almost always get broken if the values are high enough

Source: https://www.elprocus.com/working-of-smart-card/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USSB95321 PROGRESSIVE FR2739587

Experts Videos

$1.5M Robbery of Bellagio Casino Foiled Thanks to RFID Chips

By **Aaron Saenz** - Feb 12, 2011 51,689

If you're thinking of robbing a Las Vegas casino, and you're not George Clooney, I have a word of advice: give up now. As Anthony Carleo recently found out, even if you leave the casino in one piece, the chips you stole are going to be worthless long before you make your get away. The 29 year old suspect is accused of robbing the Bellagio on December 14th of 2010, stealing chips whose face value totaled around $1.5 million dollars. Their real value, however, was zero. Thanks to RFID tags embedded inside them, the chips with denominations of $100 to $25,000 could be immediately deactivated rendering them unredeemable for cash value. Watch CCTV footage from the December 14th robbery in the video clip below, followed by the recent press conference from the Las Vegas Police concerning Carleo's arrest. Stealing worthless chips and then getting caught trying to sell them to undercover officers? Danny Ocean this guy is not.

The many problems of online cash

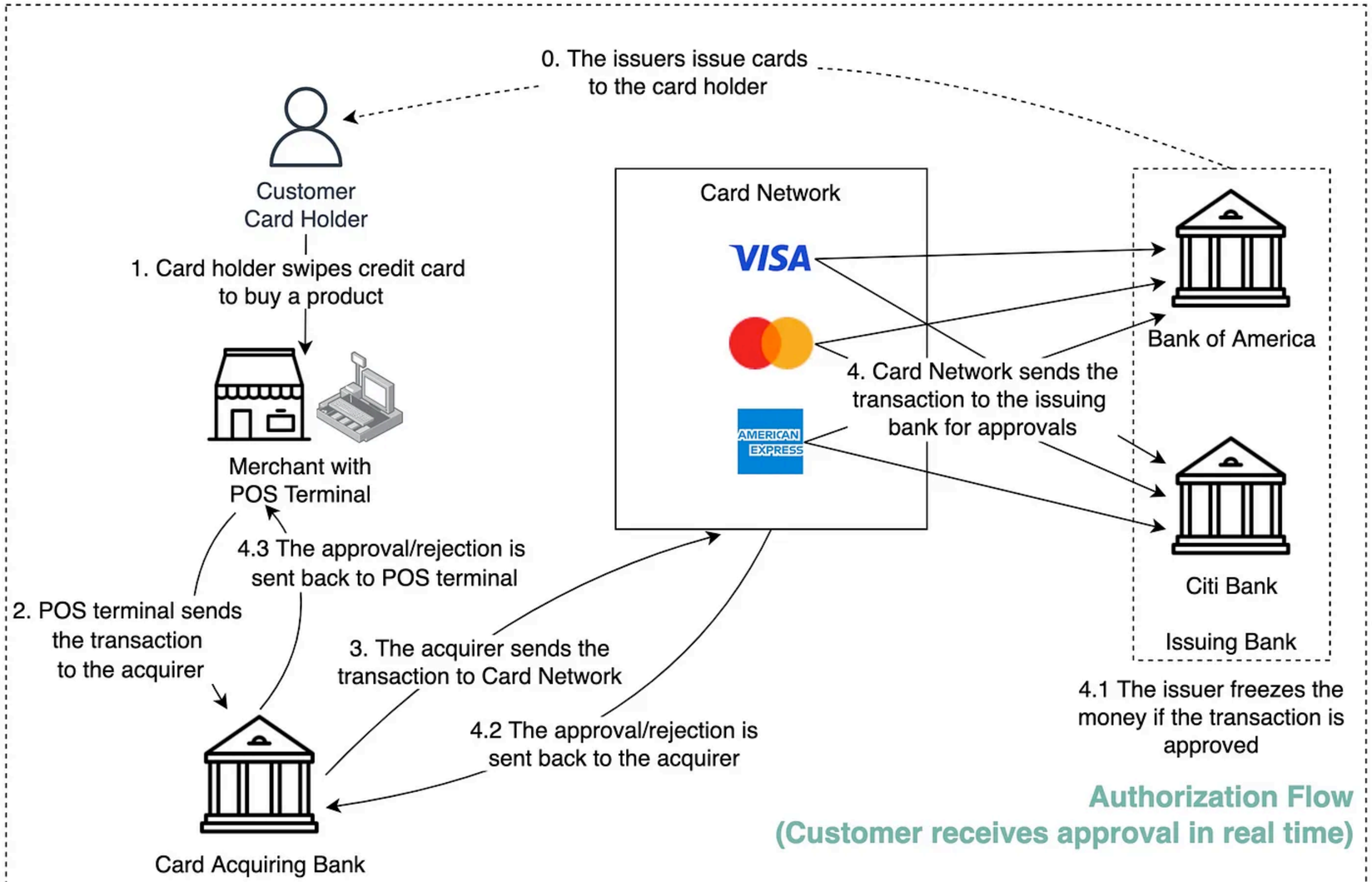
- **Double spending**
  - To capture double spending you usually need a (trustworthy?) online party
- **Integration with “real money”**
  - If you’re using fiat currency, you need to settle to that currency
  - If it’s some new form of cash, who mints it?
- **Identity & authorization**
  - How do I know you have the right to spend?
- **Privacy**
  - The ledger sees all transactions

Centralized electronic $

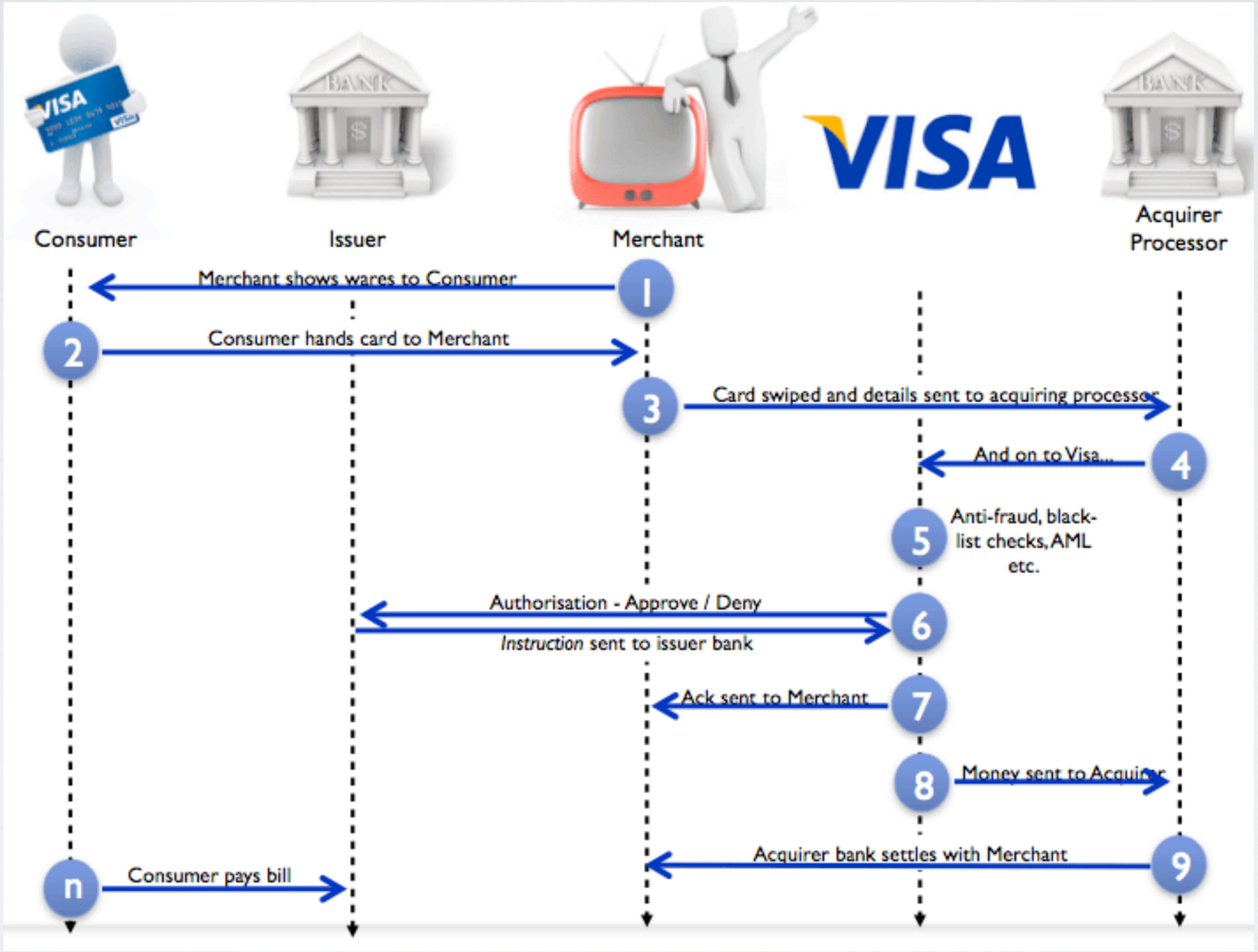
- Use a centralized bank database ("ledger") to record account balances
  - Require merchants/ATMs to contact the bank for approval
  - Ledger can be "account-based" or "transaction-based"
    - Typically it's both, and the two are reconciled

How does VISA Work?

blog.bytebytego.com

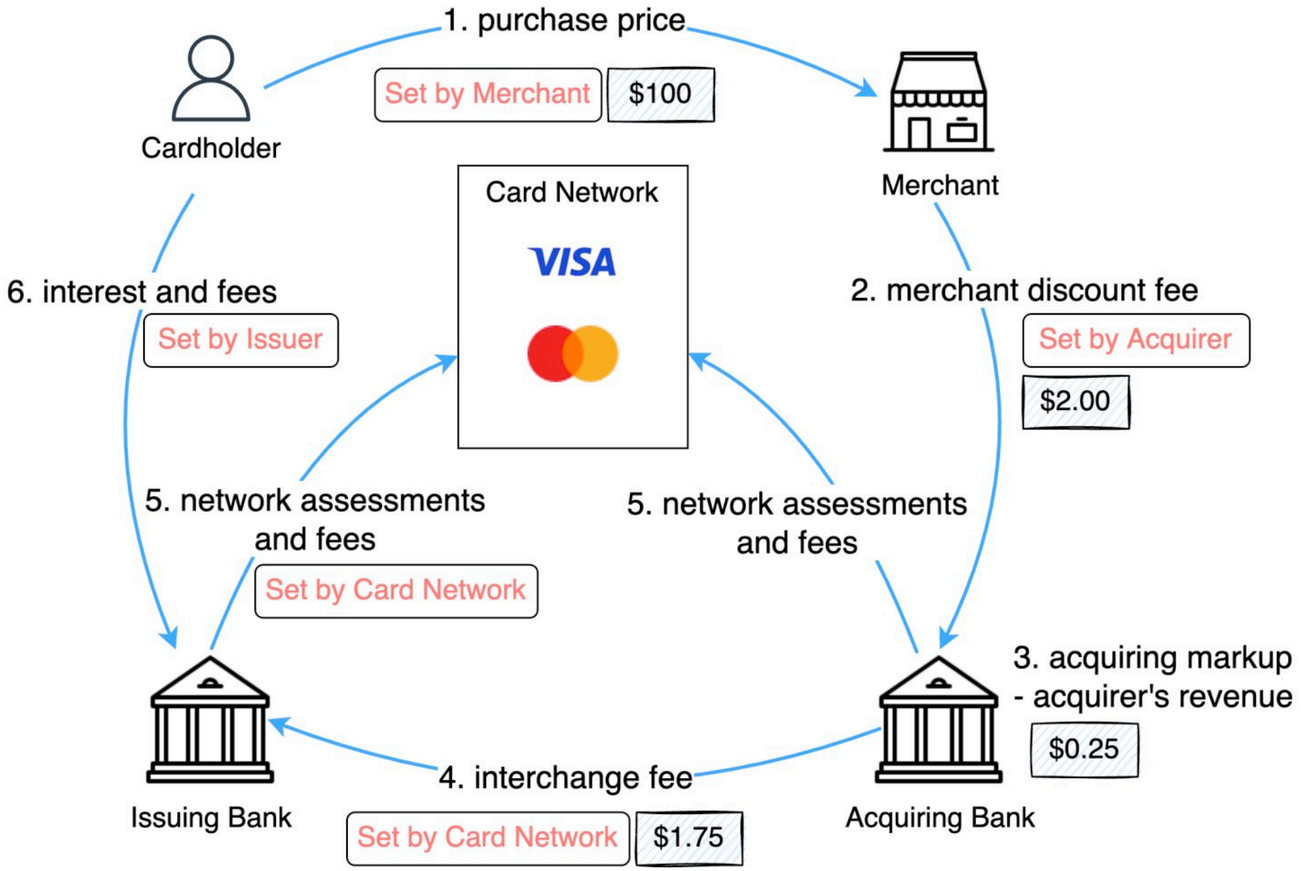


Credit card networks (2)



How does VISA Make Money?

blog.bytebytego.com



merchant discount fee = interchange fee + acquiring markup

$2.00 $1.75 $0.25

The merchant needs to compensate issuer and acquirer

Trust relationships

- In any system, parties must trust other parties to:
  - Correctly record transactions
  - Settle those transactions into actual "money"
  - This requires some degree of trust and creditworthiness between parties
  - As the number of parties increases, it becomes infeasible: hence the use of "hub and spoke" trust architectures

e-Cash

- Devised by Chaum, Chaum/Fiat/Naor, Brands, etc.
  - Move to a "cash" model, with added privacy
  - Individuals would carry redeemable tokens
  - Reduces the problem to detecting double spending and user privacy

Chaum (CRYPTO '83)

Payer

σ

(Blind) signature

sk

Bank

pk

Merchant

Redeem/
verify not previously
spent

CHL (Eurocrypt '05)

σK

(Blind) signature

sk

Payer

pk

Bank

$SN = PRF(K, i)$

$NIZK\ \Pi$

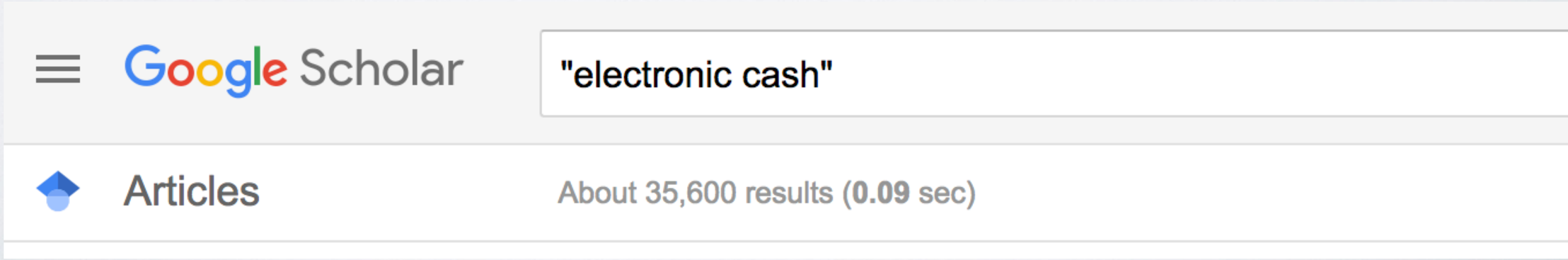
Merchant

For I = 1 to N

Redeem/
verify not previously
spent

e-Cash

- Huge number of academic works / practical improvements
  - Online schemes / offline schemes
  - (Offline required using tamper-resistant storage)
  - Main research problem continued to be privacy



Why did centralized e-Cash fail?

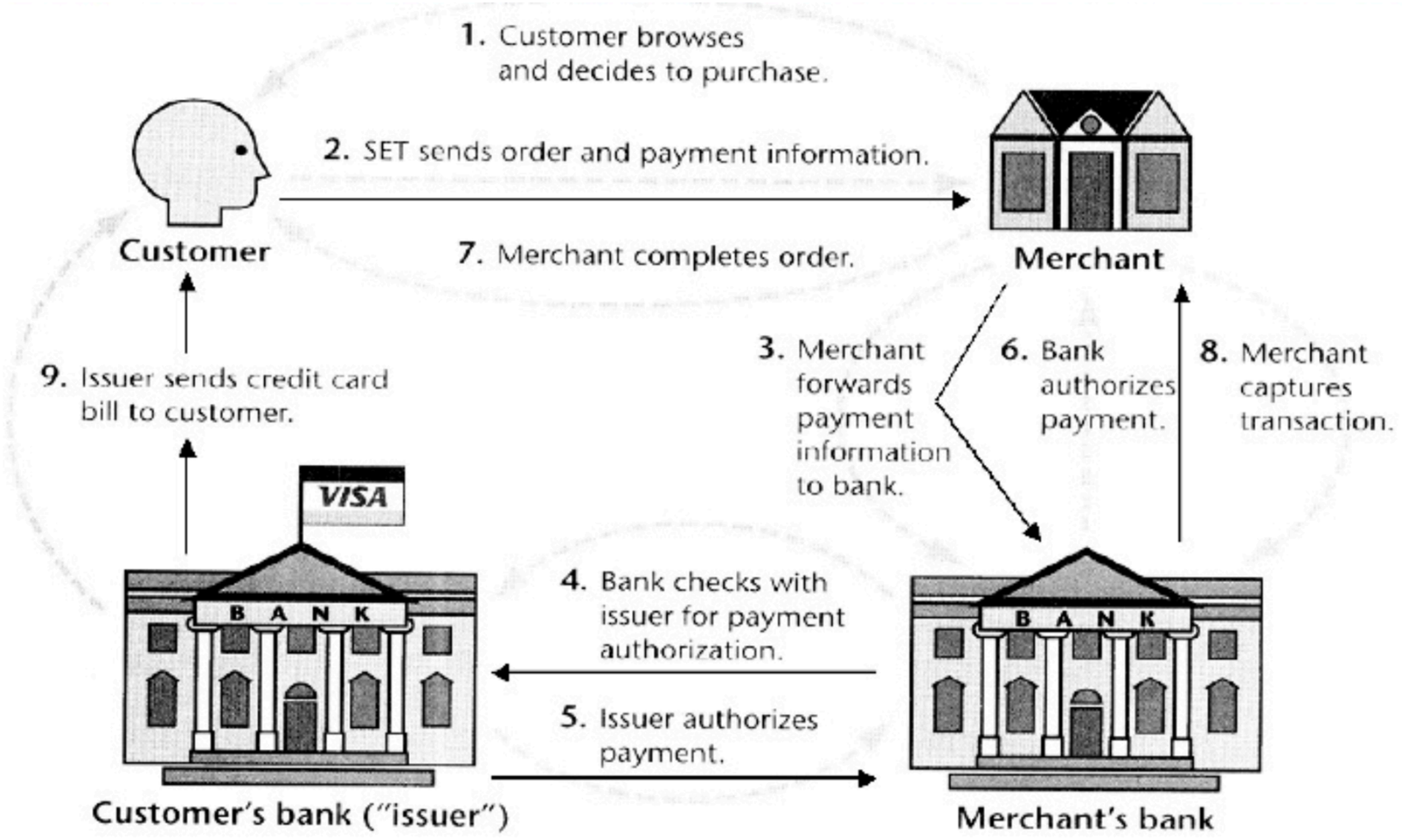
- Deploying e-Cash systems required a centralized bank
  - Required a trusted server with money issuing powers
  - In 1994, EU regulations made this more challenging
  - 9/11 and beyond saw closures of *non-anonymous* currencies (e-Gold and Liberty Reserve)

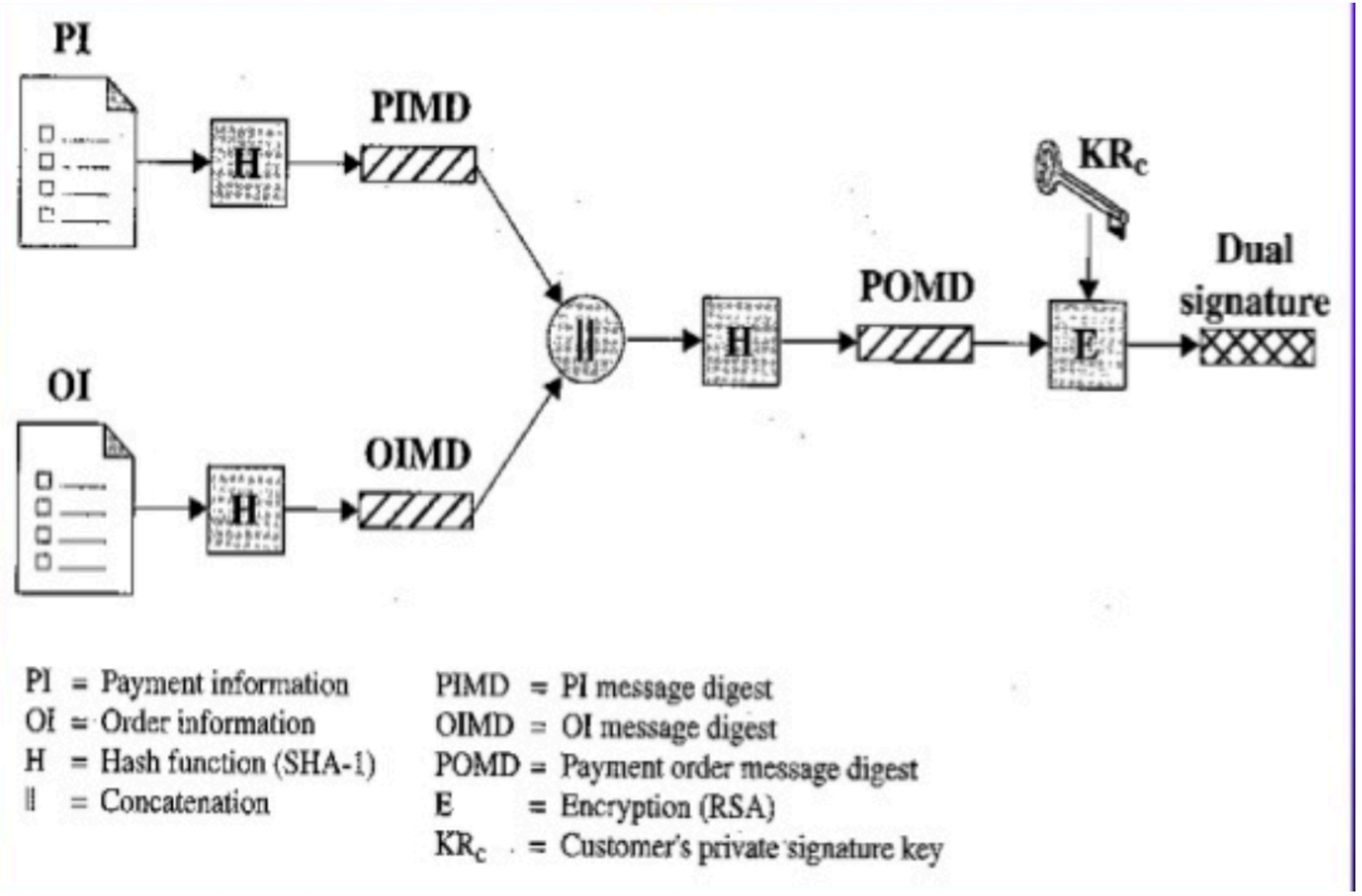
Why did e-Cash fail? (2)

- Were these technical or policy failures? Maybe both.
- The e-Cash model was centralized and relied on a vulnerable interface with the banking system
  - Privacy was (eventually) off the table for regulators
  - Any solution would have to work around those (manufactured) technical problems

1996: SET

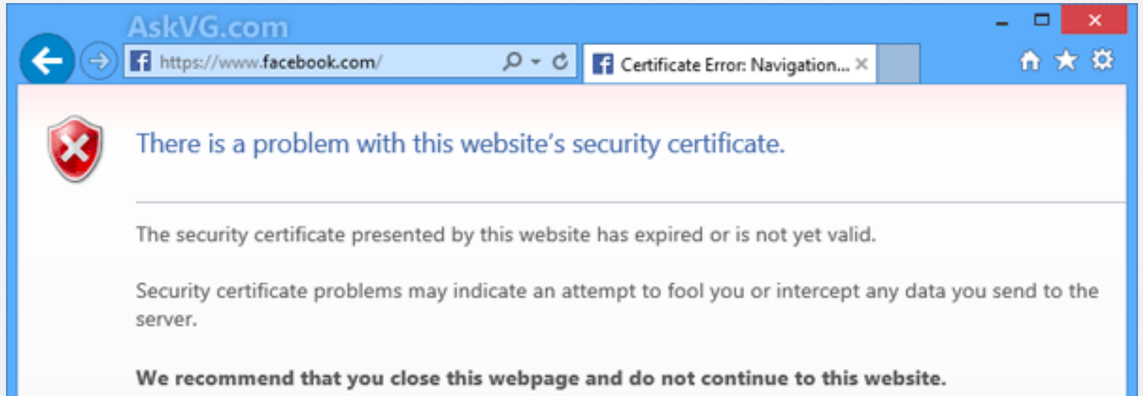
- Developed by Visa and MasterCard
  - Cryptographic architecture based on certificates
  - Assurance, authenticity and confidentiality


1. Customer browses and decides to purchase.
2. SET sends order and payment information.
Customer
7. Merchant completes order.
Merchant
3. Merchant forwards payment information to bank.
6. Bank authorizes payment.
8. Merchant captures transaction.
9. Issuer sends credit card bill to customer.
VISA
B A N K
4. Bank checks with issuer for payment authorization.
5. Issuer authorizes payment.
B A N K
Customer's bank ("issuer")
Merchant's bank


PI
H
PIMD
KRc
Dual
signature
POMD
OI
H
OIMD
H
E
PI = Payment information
OI = Order information
H = Hash function (SHA-1)
|| = Concatenation
PIMD = PI message digest
OIMD = OI message digest
POMD = Payment order message digest
E = Encryption (RSA)
KRc = Customer's private signature key

Why SET failed

- Required end-user certificates
- All the problems of key management PLUS
  all of the problems of identity verification
- Binding keys to user identities seems to trouble users



Liberty Reserve / e-Gold

- A few (centralized) systems tried to build "cash like" payments
  - Liberty Reserve: used a centralized database to issue a "stablecoin" (currency tied 1:1 to the US dollar)
  - e-Gold: similar idea, but tied to gold
  - Both became very popular in the early 2000s

Liberty Reserve / e-Gold

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JUSTICE NEWS

Department of Justice

Office of Public Affairs

FOR IMMEDIATE RELEASE — Friday, January 29, 2016

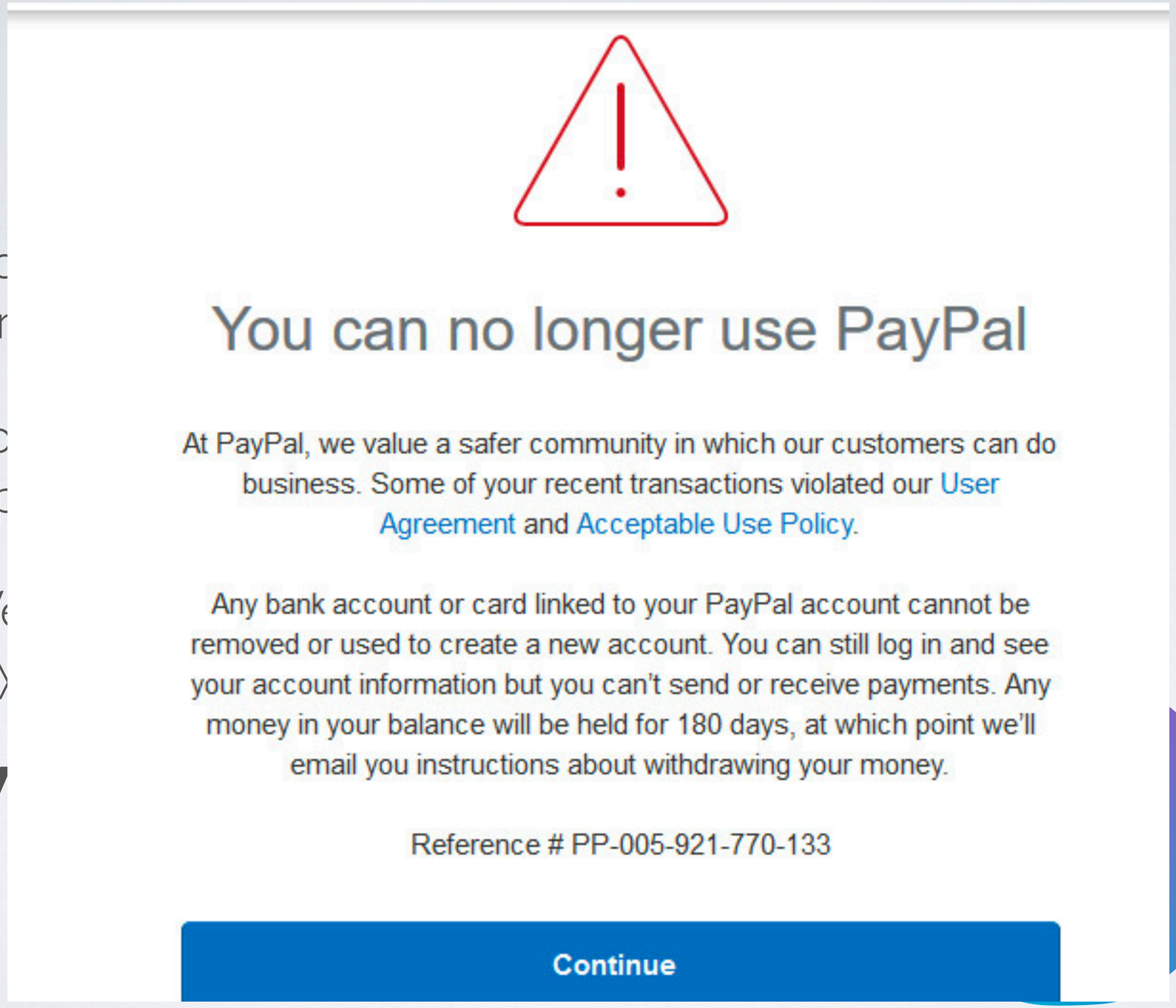
Founder of Liberty Reserve Pleads Guilty to Laundering More Than $250 Million through His Digital Currency Business

The founder of Liberty Reserve, a virtual currency once used by cybercriminals around the world to launder the proceeds of their illegal activity, pleaded guilty today to running a massive money laundering enterprise, announced Assistant Attorney General Leslie R. Caldwell of the Justice Department's Criminal Division and U.S. Attorney Preet Bharara of the Southern

Conclusions (1980s-2007)

- Most cryptographic solutions too complex, or had "undesirable" features (privacy)
- Commercial solutions (existing credit cards, SET) failed to support the case of person->person transfers
- Web browsers didn't support fancy crypto anyway.
- **We got PayPal**

- Mo
  "ur
- Co
  sup
- We
  any
- **W**



Conclusions (1980s-2007)

- Mos ns were too complex, or had und y)
- Cor ting credit cards, SET) failed to supp ->person transfers
- We ort fancy crypto anyw
- **We**

Conclusions (1980s-2007)

- Mos ns
  und y)
- Cor tin
  supp ->
- We ort
  anyw
- **We**

The decentralized era
2008-2019

Nakamoto, 2008

- **Start with the basic intuition of e-Gold**
  - I.e., create a currency ledger on the Internet
  - Then remove the centralized components:
    - No centralized database that can be shut down
    - No backing currency/settlement

Nakamoto, 2008

- Replace the server with a **decentralized** ledger
- Use a new **distributed consensus** algorithm to allow many volunteer computers to maintain a consistent ledger

Decentralizing a ledger

- What problems arise here?

Nakamoto, 2008

- Use a new consensus technique to construct the ledger
  - Uses a new data structure ("blockchain") to store and cryptographically authenticate transaction history between nodes
  - Use a new technique to determine which parties get to add new transactions, with network influence weighted by computational power ("proof of work")

Nakamoto, 2008

- Eliminate the need for real-world currency interface, by creating a new currency entirely (Bitcoin)
- Eliminate the need for explicit identities and authorizations, by using public-key cryptography to authenticate and control currency ownership

Nakamoto, 2008

- Eliminate the need for real-world currency interface, by creating a new currency entirely (Bitcoin)
- Eliminate the need for explicit identities and authorizations, by using public-key cryptography to authenticate and control currency ownership
- **Everything else is straightforward crypto and <u>excellent</u> engineering**

Lessons of Bitcoin

- Getting the consensus algorithm right makes all the difference

Lessons of Bitcoin

- Getting the consensus algorithm right makes all the difference

> [B]lockchain-style consensus indeed achieves certain robustness propert
> in the presence of sporadic participation and node churn that none of the
> classical style protocols can attain.

- Pass, Shi 2018 (also '16, '17, Daian, Pass, Shi '16)

Lessons of Bitcoin

- Using the right consensus algorithm really makes a difference
- **Eliminating the need for key/identity management significantly simplifies the currency problem**

Lessons of Bitcoin

- Using the right consensus algorithm really makes a difference
- Eliminating the need for key/identity management significantly simplifies the currency problem
- **Human beings are weird**

Lessons of Bitcoin

- U ce
- E
  s
- H

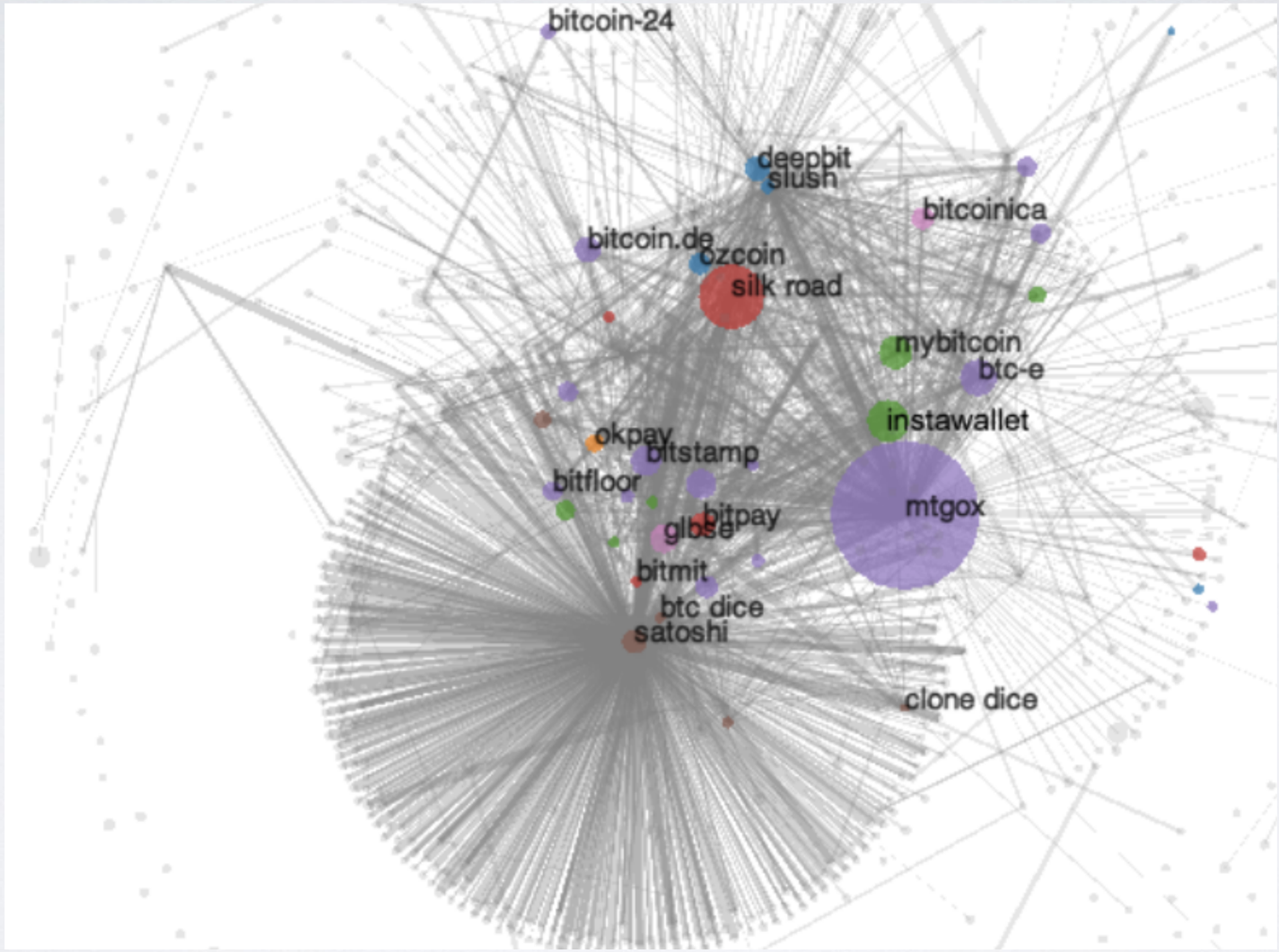
This is simultaneously trivial <u>and</u> the most unexpected lesson of the entire cryptocurrency experiment:

People will assign significant value to **meaningless electronic tokens** — *<u>if</u>* you convince them that the tokens are **secure** and have a **predictable supply.**

Limitations of Bitcoin

- Privacy limitations
- Functionality limitations
- Scalability & Sustainability limitations

Bitcoin & Privacy



Source: MPJLMVS13

Zerocoin/Zcash

WARNING

THIS IS DEVELOPMENT SOFTWARE. WE DON'T CERTIFY IT FOR PRODUCTION USE. WE ARE RELEASING THIS DEV VERSION FOR THE COMMUNITY TO EXAMINE, TEST AND (PROBABLY) BREAK. IF YOU SEE SOMETHING, SAY SOMETHING! IN THE COMING WEEKS WE WILL LIKELY MAKE CHANGES TO THE WIRE PROTOCOL THAT COULD BREAK CLIENT COMPATIBILITY. SEE HOW TO CONTRIBUTE FOR A LIST OF WAYS YOU CAN HELP US.

WARNING WARNING

NO, SERIOUSLY. THE ABOVE WARNING IS NOT JUST BOILERPLATE. THIS REALLY IS DEVELOPMENT CODE AND WE'RE STILL ACTIVELY LOOKING FOR THE THINGS WE'VE INEVITABLY DONE WRONG. PLEASE DON'T BE SURPRISED IF YOU FIND OUT WE MISSED SOMETHING FUNDAMENTAL. WE WILL BE TESTING AND IMPROVING IT OVER THE COMING WEEKS.

WARNING WARNING WARNING

WE'RE NOT JOKING. DON'T MAKE US PULL AN ADAM LANGLEY AND TAKE AWAY THE MAKEFILE.

From payments to state

- Of course once you have a ledger…
  - Each Bitcoin transaction can be considered a function f() consuming some previous state and producing a state update
  - Obviously this generalizes nicely to more complex programs and stored data

From payments to state

```
1  contract MetaCoin {
2    mapping (address => uint) balances;
3
4    function MetaCoin() {
5      balances[tx.origin] = 10000;
6    }
7
8    function sendCoin(address receiver, uint amount) returns(bool sufficient) {
9      if (balances[msg.sender] < amount) return false;
10     balances[msg.sender] -= amount;
11     balances[receiver] += amount;
12     return true;
13   }
14
15   function getBalance(address addr) returns(uint) {
16     return balances[addr];
17   }
18 }
19
```


DeFi
DECENTRALIZED
FINANCE

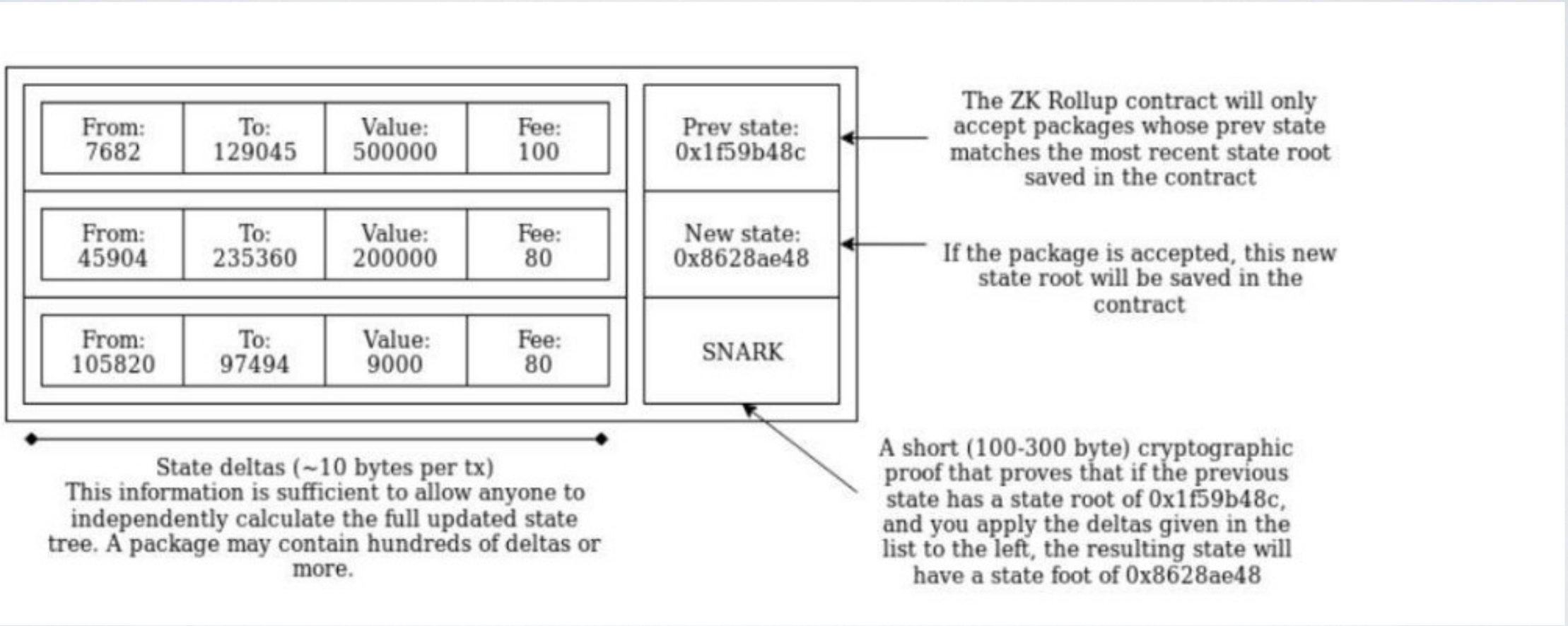
What we'll talk about in this class

- Scaling blockchains to large numbers of transactions
  - Rollups, sidechains, channels, bridges
- Newer types of consensus network (e.g., Avalanche, BFT)
- Privacy
- Other advanced applications (not related to currency)
- Decentralized Finance,
- Identity…

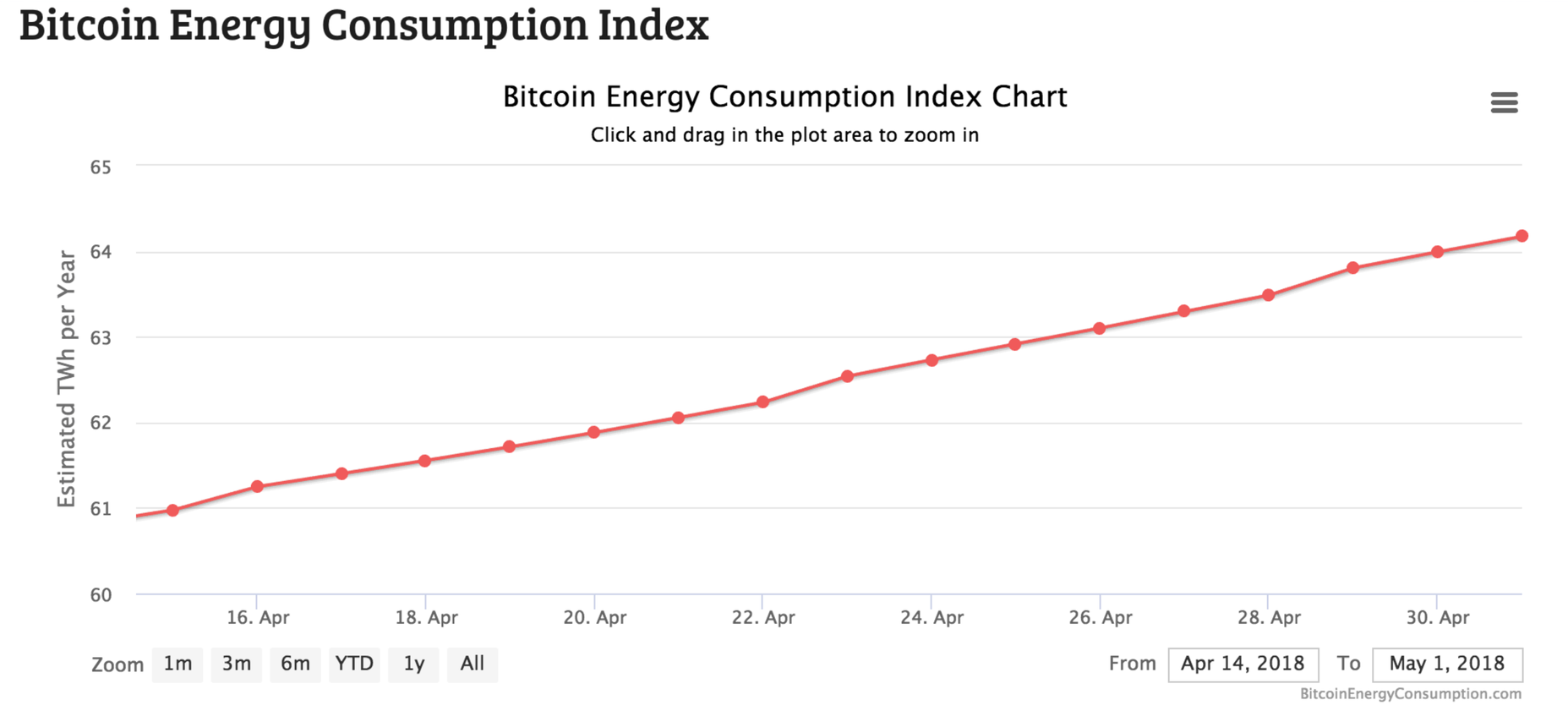
Scaling

- Current Bitcoin/Ethereum transaction rate is ~7TX/s
- Compare with Visa at 10,000-40,000+ TX.s globally
- This gets worse as transaction complexity increases
- Problems are storage/throughput/validation bandwidth

ZK and Optimistic Rollup



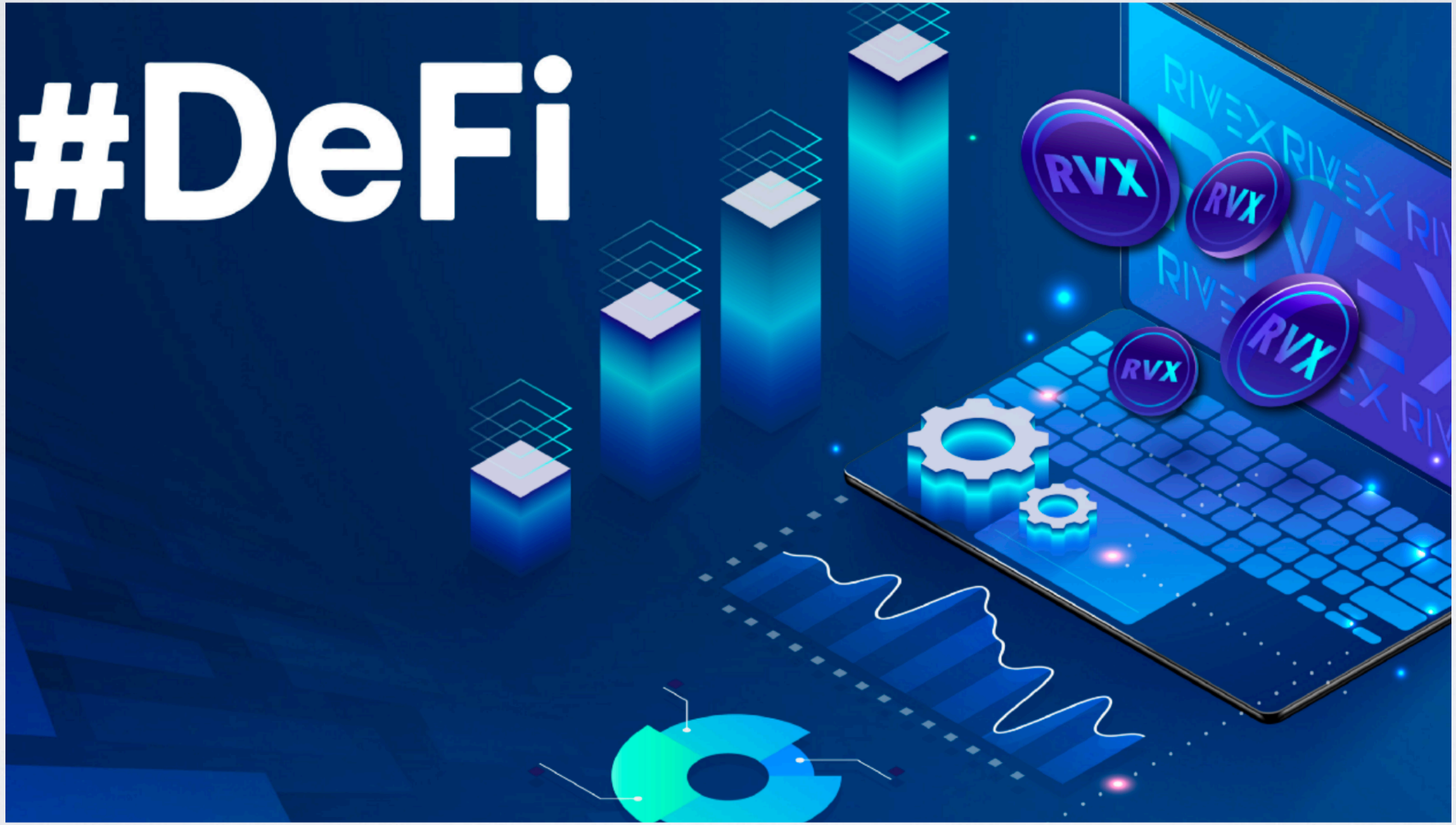
Replacing PoW



Proof of Stake

- Old PoW design is obviously unsustainable
- Most common solution (in permissionless) chains is Proof of Stake"
- Rough summary: enumerate all stakeholders of the coin, scaled by their stake — and then sample one to construct the next block
- Ethereum recently shifted to PoS

DeFi



Moving forward

- Weds: Crypto background
- Next week: consensus networks, Bitcoin
- Do the reading!