Bitcoin, Blockchain, and Cryptocurrencies

MGT 4074 Fintech & Crypto Tokens, Fall 2025

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Roadmap

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Brazil Abandons Blockchain for CBDC

Forbes:

> *Brazil's Central Bank is abandoning the blockchain component of Drex, its ambitious central bank digital currency project.*

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> *The project's original vision was a two-tiered structure. The first monetary layer was to be an environment exclusively for transactions among authorized participants - specifically regulated financial institutions running nodes on the Central Bank-controlled network. The second would be tokenized bank deposits issued by regulated institutions to end customers.*

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TL;DR: Brazil has decided not to record transactions of the "Digital Real" onto a blockchain. Instead, it will utilize a central database.

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  - Digital signature schemes
  - Merkle Trees

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A Philosophical Question...

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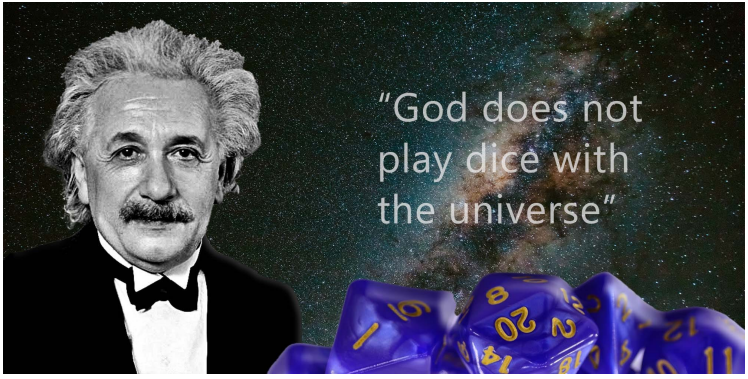

- If you think everything is predetermined, and we fully figure out the laws of physics, doesn't that mean we can predict the future?
- Anyone heard of the "Three Body Problem"?

Chaos

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- Hash functions are **chaotic**: deterministic but unpredictable
  - **Deterministic**: The hash of a number never changes!
  - **Unpredictable**: The hashes of two nearby numbers are *very* far away, and there is *no pattern* to how far

A Chaotic Process

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Why does Cloudflare use lava lamps to help with encryption?

Randomness is extremely important for secure encryption. Each new key that a computer uses to encrypt data must be truly random, so that an attacker won't be able to figure out the key and decrypt the data. However, computers are designed to provide predictable, logical outputs based on a given input. They aren't designed to produce the random data needed for creating unpredictable encryption keys.

To produce the unpredictable, chaotic data necessary for strong encryption, a computer must have a source of random data. The "real world" turns out to be a great source for randomness, because events in the physical world are unpredictable.

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  - Convert text to binary numbers, 1101010...
  - Flip the 4th, 13th, 18th from 1 to 0, or 0 to 1...
  - Make 5th, 17th, and 12th number vote on whether 3rd is 0 or 1...
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- Tl;dr, record your kid doing random stuff, and repeat it a lot of times

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A cryptographic hash function is a mapping $H : M \to D$ from a set M of possible messages of any length to a set D of digests, for example the set of strings of 0s and 1s of a fixed length, such as 256. See Ramzan (2012).

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In **digital signature schemes** (as we will see), a "digest" is a **signed message**.

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Answer: No, hash functions must be hard to invert.

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  - Bitcoins are mined by brute-forcing hashes to find xs that produce $H(x)$ with leading zeroes.

Modular Arithmetic

Powers of 3	3^1	3^2	3^3	3^4	3^5	3^6	3^7	3^8	3^9
Value	3	9	27	81	243	729	2187	6561	19683
Closest multiple of 7	0	7	21	77	238	728	2184	6559	19677
Remainder div. 7	3	2	6	4	5	1	3	2	6

- We use $x \mod y$ to mean, "remainder of x when divided by y", like:

$$81 \mod 7 = 4$$

- In python, $x \mod y$ is just $x \,\%\, y$
- In R, it's $x \,\%\%\, y$

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  - But, using the public key, can't generate new valid signatures

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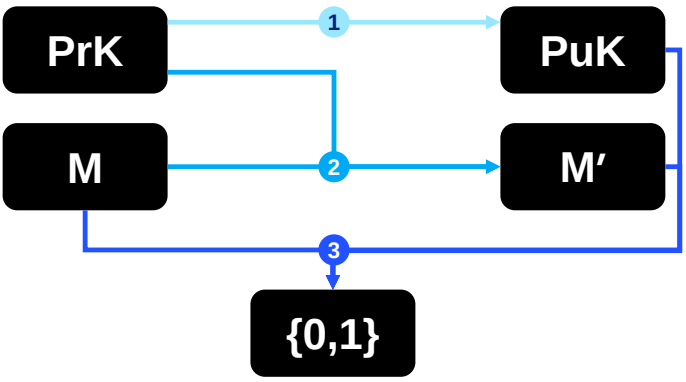
In Bitcoin, these "messages" encode a list of transfers of blocks from one owner to another!

Digital Signature Schemes, Visually



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A: If deposits flow out of banks and into stablecoins, we will lose the liquidity-transforming, loan-supplying function of banks!

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So where does this leave us?

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> But it also means that issuing stablecoins is not as great a business as I once thought. It *was*, when there were only a few stablecoins and the stablecoins acquired their network effects naturally. But in the long run, to be a competitive stablecoin, you might have to pay most or all of your interest income to crypto exchanges, and the exchanges might have to pass most or all of it back to the customers. "You hold people's dollars for them, you collect interest, and you don't give them any of it" really is a good business model, but it's too good to last.

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Uses of Merkle Trees

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Merkle Trees are used in many applications to solve problems such as:

- Maintaining integrity of files stored on Dropbox.com, or *file outsourcing*
- Proving a transaction between Alice and Bob occurred, or *set membership*
- Transmitting files over unreliable channels, or *anti-entropy*

Construciton of Merkle Trees

Start with, say, 8 files $(f_1 ... f_8)$, and a hash function $H(.)$

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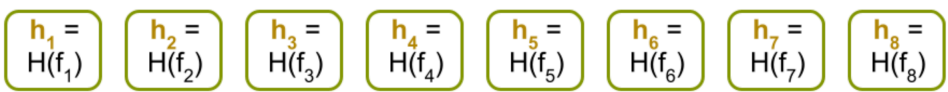
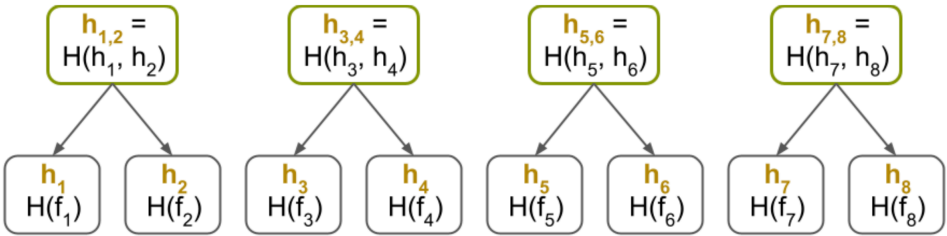
Start by hashing each file $H(f_i)$:



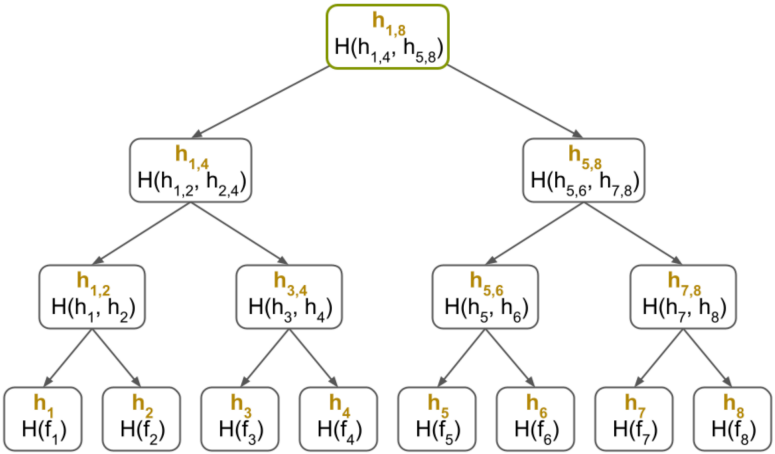
Construction of Merkle Trees

Then, create the second layer of the tree by hashing adjacent nodes together (this can be as simple as concatenating them!)



Construction of Merkle Trees

Continue until you have created an entire "tree":



Construction of Merkle Trees

Question: Why is this tree upside-down?

Construction of Merkle Trees

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Answer: Because Computer Scientists have never gone outside, a necessary prerequisite to see a real tree

Verification with Merkle Trees

Upload your files $(f_1 ... f_8)$ **and** your Merkle Tree to Dropbox, storing only the **Merkle Root** $h_{1,8}$ locally.

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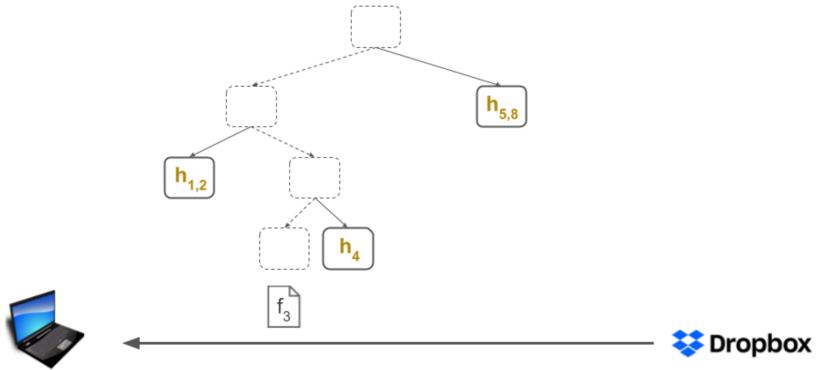
Later, ask for the file you want, say f_3, but make sure to also ask for the **Merkle Proof**: the hashes needed to compute $h_{1,8}$ from the desired **Merkle Leaf** (f_3)

Verification with Merkle Trees

The **Merkle Proof** lets you verify that you downloaded the real, original f_3:



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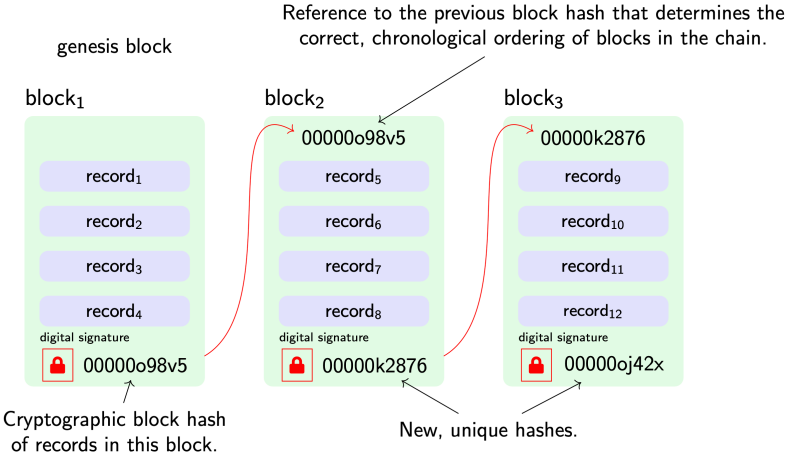
For other (analogous) uses of Merkle Trees including Transaction Verification and Transmitting files robustly over error-prone communication channels, see Tomescu (2020)

Roadmap

What is a Blockchain?

A **Blockchain** is a list of records that are linked together by hash functions



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Say that I, JPH, own and operate a private server which records a Blockchain. I don't know the users' private keys, but I control everything that is written on the blockchain. Can I:

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- Selectively cancel three messages ago, but not the last two?
  - No: the hashes of the last two messages would be wrong if the middle hash is missing.

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Centralized Blockchains are in fact widely-used:

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- Coinbase Base
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Can we take away even more power from the admin? Can we make a set of rules to agree on a shared history of transactions without needing to trust anybody?

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- Bitcoin solves this through **proof of work**

Hash Puzzles

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  2. Proves that you did something hard to do
- With puzzle solution in hand, you become the admin!
- **Incentives:** solving the puzzle gives you some BTC as a block reward
- **Consensus:** everyone works on the longest chain

How to Prevent Doublespending?

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- Can't just selectively delete the transaction from history (why?)
  - Hashes verify integrity of history!
- But...could go back in time, then create a parallel universe (a fork in the chain) where I never spent the money
  - This would be called a doublespend

Turning Back Time...

- Anyone can try, since anyone can try to mine and become admin
- When would I succeed?

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- Anyone can try, since anyone can try to mine and become admin
- When would I succeed?
  - Because everyone uses the **longest chain**, I must be able to hash faster than **everyone else combined**
  - Control 51% of the computing power in the Bitcoin ecosystem!
- For more details, see Stanford CS251 slides

In the News: Google's Agent Payment Protocol

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How it works: Establishing trust via mandates and verifiable credentials

AP2 builds trust by using Mandates—tamper-proof, cryptographically-signed digital contracts that serve as verifiable proof of a user's instructions. These mandates are signed by verifiable credentials (VCs) and act as the foundational evidence for every transaction.

Mandates address the two primary ways a user will shop with an agent:

- **Real-time purchases (human present)**: When you ask an agent, "Find me new white running shoes," your request is captured in an initial **Intent Mandate**. This provides the auditable context for the entire interaction in a transaction process. After the agent presents a cart with the shoes you want, your approval signs a **Cart Mandate**. This is a critical step that creates a secure, unchangeable record of the exact items and price, ensuring what you see is what you pay for.
- **Delegated tasks (human not present)**: When you delegate a task like, "Buy concert tickets the moment they go on sale," you sign a detailed **Intent Mandate** upfront. This mandate specifies the rules of engagement—price limits, timing, and other conditions. It serves as verifiable, pre-authorized proof that can allow the agent to automatically generate a **Cart Mandate** on your behalf once your precise conditions are met.

In both scenarios, this chain of evidence culminates in securely linking your payment method to the verified contents of the Cart Mandate. This complete sequence—from intent, to cart, to payment—creates a non-repudiable audit trail that answers the critical questions of authorization and authenticity, providing a clear foundation for accountability.

The Money Pot Game

- Two options:
  1. Get $1 for sure
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  1. Get $1 for sure
  2. Fight for a $10 pot, which is equally divided between everyone who picks this option
- Which do you pick?

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- Game theory language: call these congestion games, or wars of attrition, or tragedy of the commons

BTC mining

- Suppose mining a block pays 0.001 BTC
- Suppose mining block costs $60 in electricity
  - If BTC price $> \$60k$, everyone mines; blocks produced quickly
  - If BTC price $< \$60k$, nobody mines; tx's aren't included and the blockchain stops working!
- The fact that mining rate depends on BTC vs electricity price is not desirable...
- Solution: use difficulty adjustment to maintain constant block production rate

BTC Difficulty Adjustment

- Blocks should be produced every 10 minutes
- Every 2016 blocks (approx 14 days), Bitcoin considers average block production rate, and...
  - Increases/decreases hash problem difficulty, if block production is too fast/slow
- What determines how fast blocks are produced, fixing hash rate?

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- What determines how many people mine?
  - How profitable mining is, that is, how high BTC price is, vs electricity price

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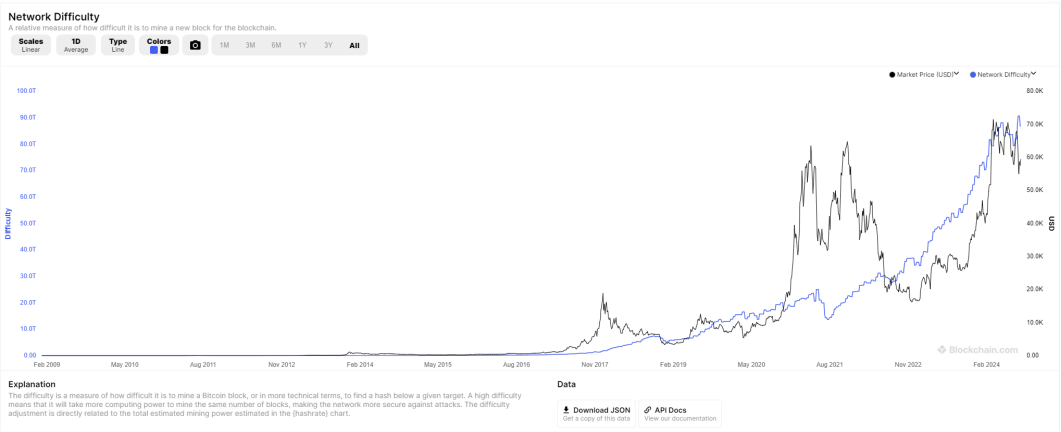
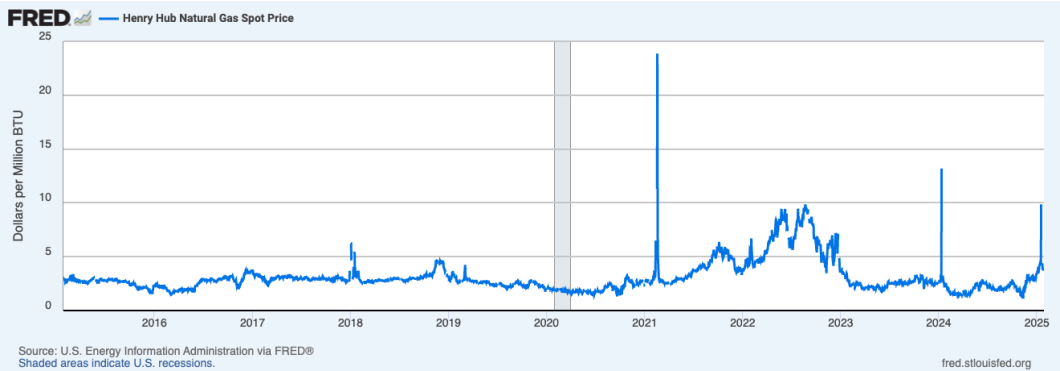
Prediction: difficulty should increase with BTC price

Difficulty vs BTC price



Source: Blockchain.com

Energy Prices...



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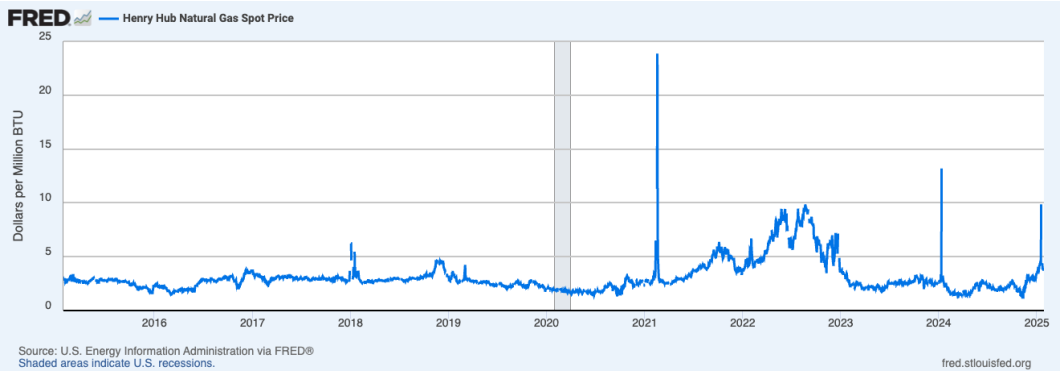
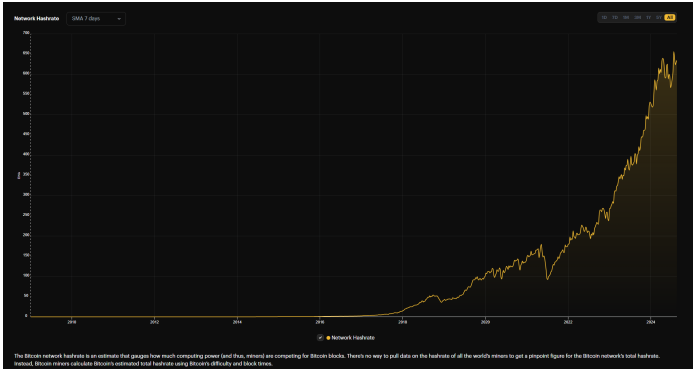


Source: FRED

A **BTU** is a "British Thermal Unit", the energy required to heat a pound of water by 1 degree Fahrenheit (about one match)

Technological Improvement



- 842 Exahashes/s = 842 billion billion hashes a second!
- Each living person in the world could shake each other living person's hand 10 times, every second!
- $\sim 1\%$ of global energy consumption...

Source: Hashrate Index

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- Will this decrease as technology improves?
  - No! Problem difficulty will just adjust...
- What if BTC price falls?

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- Also implies there will only ever be 21 million BTC in existence!
  - By approximately 2140, the block reward will drop to less than the smallest unit of bitcoin ($1/10^8$) and become equal to zero.
  - Difficulty adjustment ensures that block production rate is approximately constant

Why 21 Million?

Satoshi: "My choice for the number of coins and distribution schedule was an educated guess. It was a difficult choice, because once the network is going it's locked in and we're stuck with it. I wanted to pick something that would make prices similar to existing currencies, but without knowing the future, that's very hard. I ended up picking something in the middle. If Bitcoin remains a small niche, it'll be worth less per unit than existing currencies. If you imagine it being used for some fraction of world commerce, then there's only going to be 21 million coins for the whole world, so it would be worth much more per unit. Values are 64-bit integers with 8 decimal places, so 1 coin is represented internally as 100000000. There's plenty of granularity if typical prices become small. For example, if 0.001 is worth 1 Euro, then it might be easier to change where the decimal point is displayed, so if you had 1 Bitcoin it's now displayed as 1000, and 0.001 is displayed as 1."

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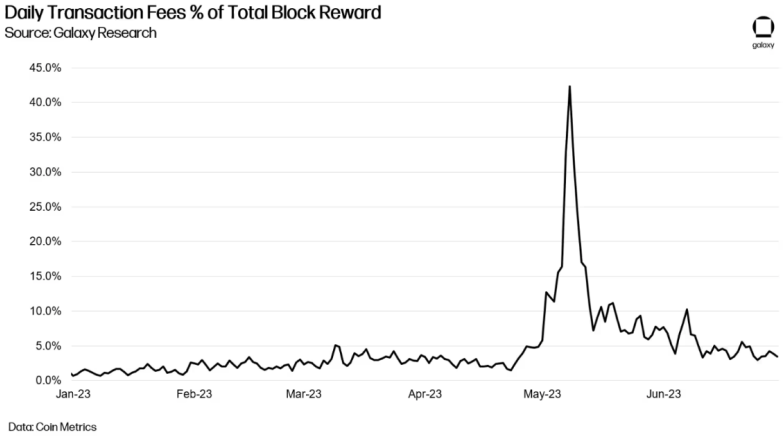
- Miners prioritize including transactions that offer higher fee rates
- As of 2/4/25, the going rate to complete your transaction within 30 minutes is 3 sat/vB, or $\$0.42$ for an average transaction
- A **"mempool"** is a pool of transactions waiting to be added to the bitcoin blockchain

Explore mempools at https://mempool.space/

Transaction Fees as % of Block Revenue



Source: Galaxy

Incentives

- A centralized authority can "censor", i.e. not include tx's
- Decentralization and competition "ensure" performance
  - If you don't include my tx, the next miner will
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- More or less works for just transacting
- Incentives not that strong: tx fees $< 10\%$ of mining revenues
  - But, it's free $$!

Further Reading on Mining Industry

- Galaxy digital 2023 and 2024
- Cool paper on mining pools

Roadmap

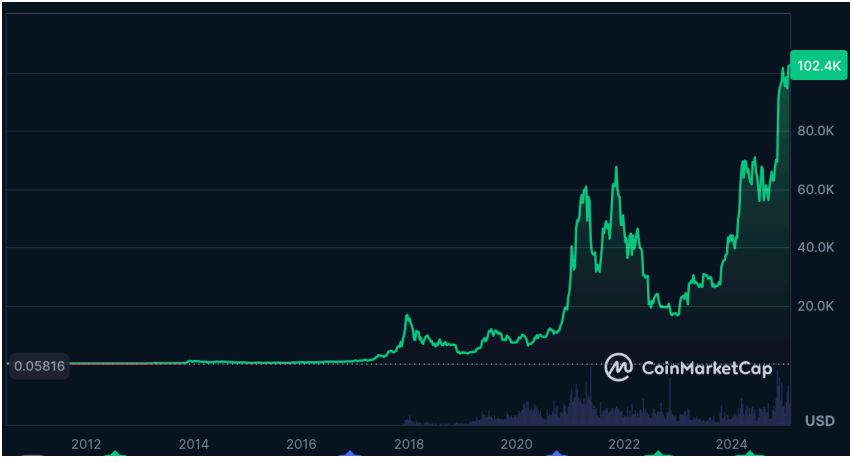
Satoshi Nakamoto

- Started sending emails about Bitcoin August 2008
- Oct 2008: Bitcoin white paper, code released
- January 9: first block mined!
  - "The Times 03/Jan/2009 Chancellor on brink of second bailout for banks"
- May 22, 2010: Laszlo Hanyecz bought two Papa John's pizzas for 10,000 BTC, now worth $600mil USD!
- Quickly became popular among black markets, Silk Road...
- Founder Ross Ulbricht was recently pardoned by Trump

Prizes for a Starcraft Tournament in 2011

Prizes:
1st Place: *$500*
2nd Place: *$250*
3rd Place: *$150*
4th Place: *$100*
5th-8th Place: *25 BitCoins*

Bitcoin Prices



Source: CoinMarketCap

Each BTC Block is a Merkle Tree of Transactions!

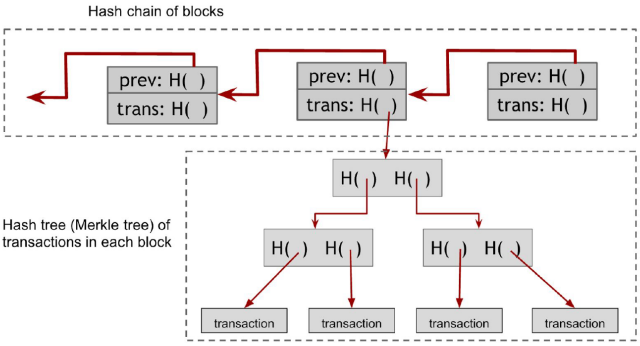


Figure 3.8. The Bitcoin block chain contains two different hash structures. The first is a hash chain of blocks that links the different blocks to one another. The second is internal to each block and is a Merkle Tree of transactions within the blocks.

- Valid block headers' hashes start with a big number of 0's (mining puzzle)

Source: NBFMG, fig. 3.8

Mining, in Practice

- Miners connected to each other in a network
- If you find a valid block, tell all other miners about it
  - They'll then mine the next block, based on yours
- If you solved the hash puzzle, why can't I just steal your solution?

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- Why wouldn't I try to re-mine your block?
  - Consensus: if everyone else uses "longest chain", I do better by accepting your win, and trying to mine the next block

The Power of Consensus

- Notice that all properties depend on everyone "following the rules"...
  - If your block:
    - Doesn't hash to enough 0's, or
    - Steals $$, or
    - Includes invalid tx's, etc.
  - Others won't build on it, so others won't build on others not building on it,
  - So you won't get mining reward
- At some level, maybe the simplicity of the rules, plus the decentralization of mining, provides security?
  - By default, miners will pick the simplest possible path

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- What if I try to spend twice?
  - One tx is "invalid": doesn't obey the rules, since old tx output already spent
  - Remember, though; everything is ultimately due to consensus among miners, that "longest block of valid chains" is the legitimate blockchain

Fees and Times

- Fees: a few cents to a few USD
  - Doesn't depend on tx size
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  - Doesn't depend on tx size
- Time: roughly 1hr
  - Most services wait a few blocks (why?)
  - Tx's deeper down the blockchain are more "final" (harder to "doublespend")
- Long confirmation times a little awkward for "merchant" tx's

User Experience

- In practice, private keys held using "wallet" software or hardware
  - Software: Exodus, Electrum, MetaMask...
  - Hardware: Ledger, Trezor...
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  - I use MetaMask
- In theory, no credit risk – you're holding your own BTC!
  - As long as internet + Bitcoin exists, you can use your BTC!

Don't Lose Your Keys...

As It Happens

This man owns $321M in bitcoin — but he can't access it because he lost his password

Stefan Thomas has 2 guesses left before he's locked out of his fortune forever

CBC Radio · Posted: Jan 15, 2021 5:02 PM CST | Last Updated: January 15, 2021

Stefan Thomas, the founder and CEO of micropayment streaming service Coil, has $321 million worth of bitcoins he can't access. (Submitted by Stefan Thomas)

284 comments

Read Story Transcript

Custodial Ownership

- Many don't care about decentralization, censorship-proofness...
  - But want to buy in case prices go up
- More and more ways to buy BTC
  - Crypto exchanges: Coinbase, Binance...
  - Classic institutions: Paypal, Robinhood...
- Recent ETF approvals makes it easier to buy BTC
- New SEC commissioner Paul Atkins has signaled positivity towards legitimizing crypto investments

Mentions are not endorsements!

"Buy the Market"

The CAPM says buy the market – and BTC's market cap is now approx 2% S&P 500!

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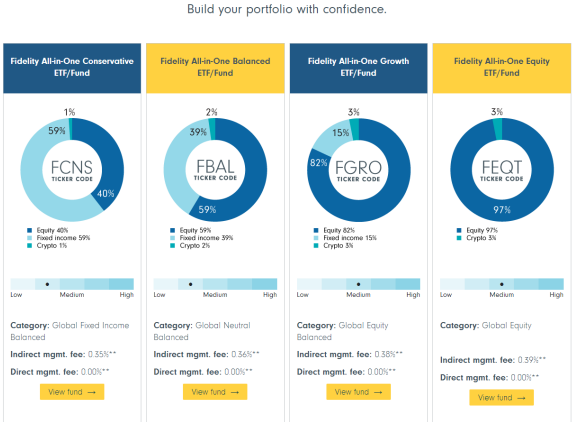

Source: Fidelity Canada

The "Market Cap" Illusion

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  - Investors are willing to substitute frictionlessly between stocks if one is temporarily undervalued
- Reports of $TRUMP being worth $10 billion+ assume unit price would survive a large selloff (a bad assumption in my opinion)