Modern Cryptography Concepts: Hype or Hope

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- What problem is being solved, intuition behind how to solve it, whether it's practical
- I gave a much longer version to colleagues
  - With many more topics
  - I had them vote on the topics they found most interesting…so blame them for the selection of topics

Topics

- I'm going to cover the ones in red in the next slide
- The ones in black were less popular with my test audience

Topics

- How to share a secret
- Zero Knowledge Proofs
- Non-interactive ZKP
- Blind signatures, blind decryption
- Oblivious transfer
- Group signatures, ring signatures
- Bit commitment, coin flip
- Making an unfair coin fair
- Circuit model
- Random oracle model
- Identity based encryption
- Secure multiparty computation (VERY brief) just what problem is being solved)
- Homomorphic encryption (again, VERY brief)
- Bitcoin/blockchain (not so much crypto, but there is SO much hype)

Sharing a Secret

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- Problem: You want to make n backups of a secret S
  - You want to retrieve S in case you forget it
  - But you're afraid some of the backups might get broken into, and you don't want S stolen

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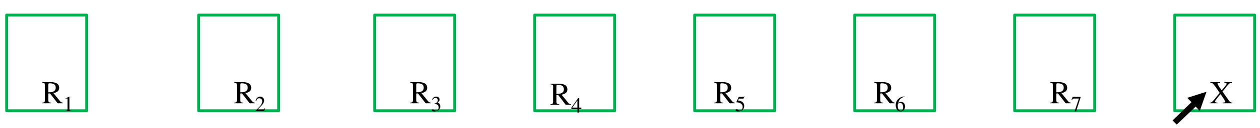
- Problem: You want to make n backups of a secret S
  - You want to retrieve S in case you forget it
  - But you're afraid some of the backups might get broken into, and you don't want S stolen
- Break a secret S into n "shares", such that retrieval of at least k of the shares reveals S, and retrieval of fewer than k reveals nothing

Sharing a Secret S

- N locations, quorum =1
  - Trivial…just store S in each location

Sharing a Secret

- n locations, quorum =n
  - Also easy
  - Store n-1 random #'s in n-1 places, and XOR of S and all the random numbers in the nth place

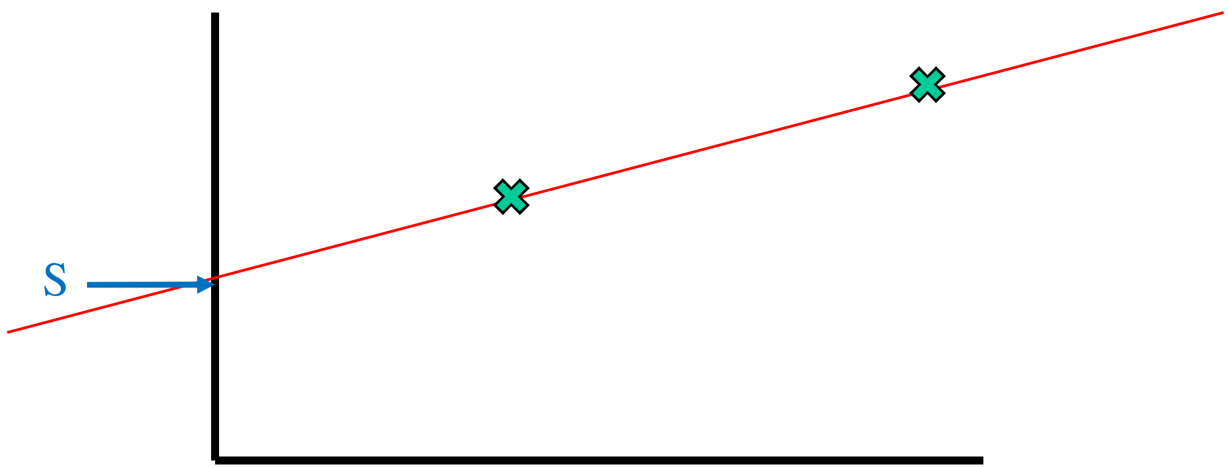


$X = S \oplus R_1 \oplus R_2, \ldots \oplus R_7$

What about $1 < k < n$?

Secret Sharing with k=2

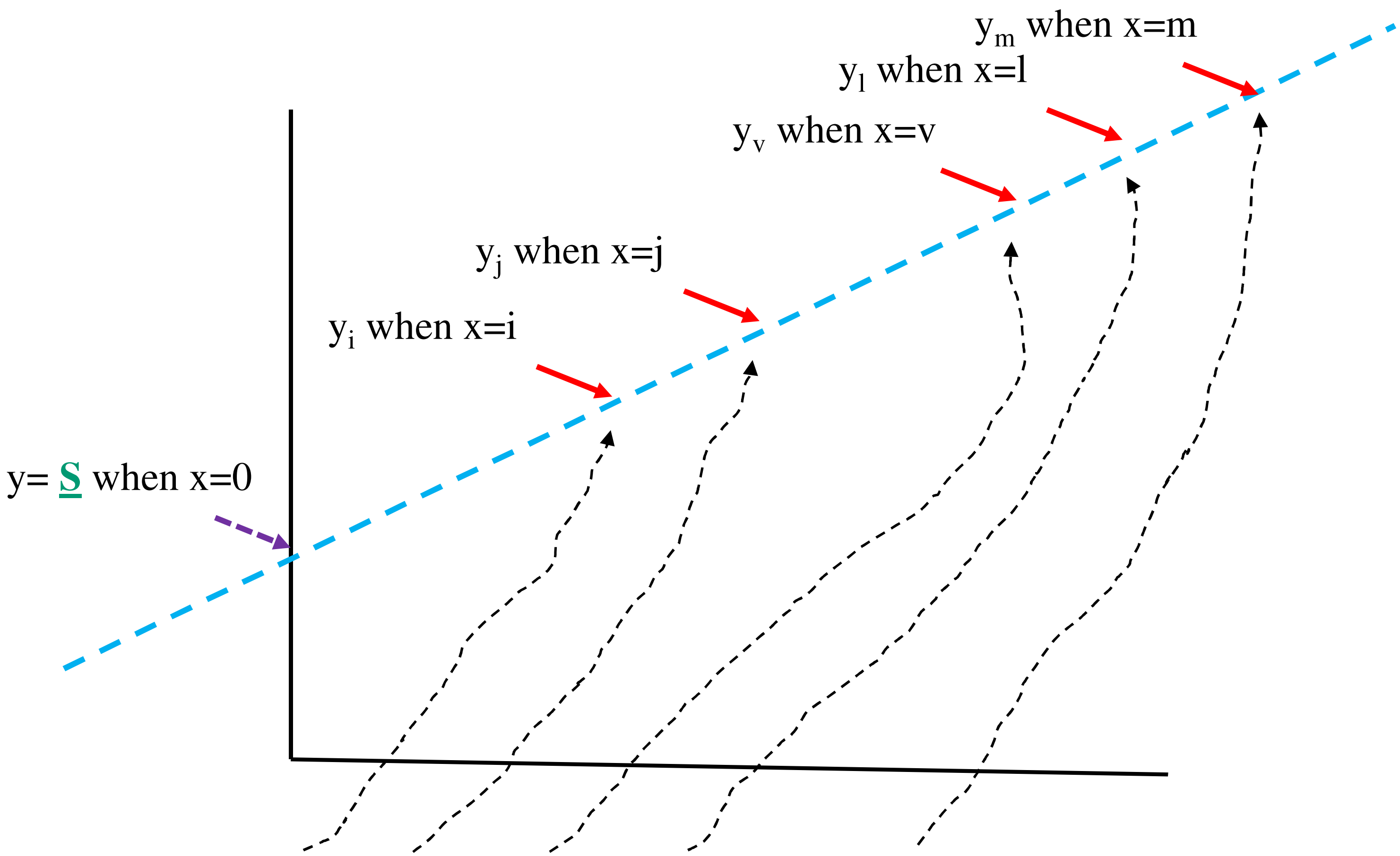
- Choose a line. Any two points reveal the line, any one point gives no information
- Let S be where it crosses the Y axis



Secret Sharing with k=2

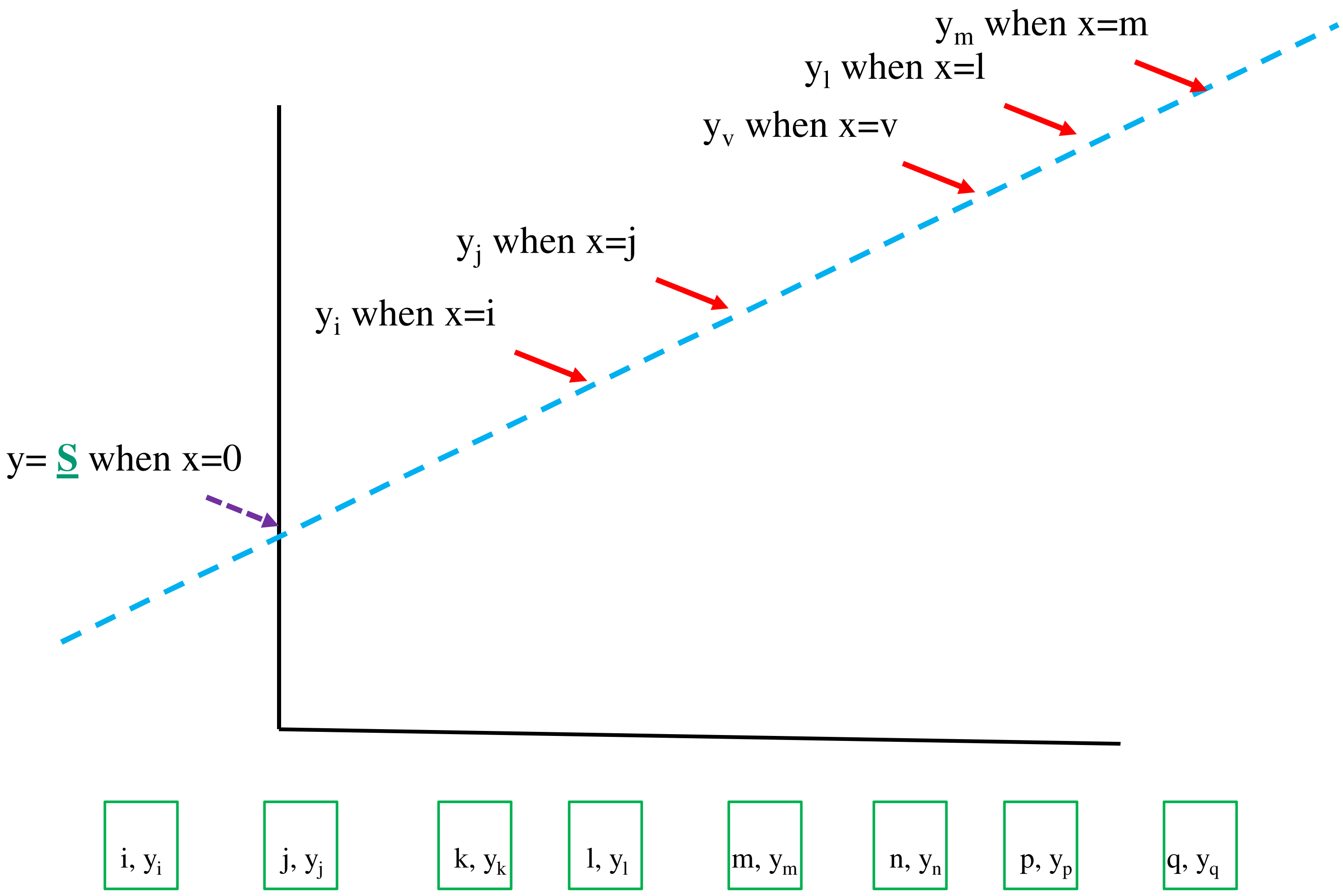
- Do this as follows:
  - Choose random number b
  - Line equation is $y = bx + S$
  - S = value of the line at $x=0$

Secret Sharing of S with k=2



Shares are (i, y_i), (j, y_j), (v, y_v), (l, y_l), and (m, y_m)
Knowing any two of those, you can calculate the line, and solve for S

Secret Sharing of S with k=2



Secret Sharing with 2 < k < n

- Create an equation of order k-1
- Each share is the value of y at some point
- Given any k points, the equation can be solved and S found
- The math:
  - Choose k-1 random numbers $b_1, b_2, \ldots b_{k-1}$
  - Graph is $y = S + b_1x + b_2x^2 + \cdots b_{k-2}x^{k-2} + b_{k-1}x^{k-1}$
  - Secret S is value of y at x=0

Notes on secret sharing

- Real numbers are annoying
  - Even integers are kind of annoying (since they have unbounded size)
  - Solution: do arithmetic mod some prime $p > S$
- A share is an (x, y) pair, where x and y are integers mod p
  - But you can have fixed x-values for each participant
    - Participant 1 is given the value of y at 1
    - Participant 2 is given the value of y at 2
    - Etc.

Summary of secret sharing

- Not only mathematically cool, but very useful and practical

Bit Commitment

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  - They can only talk over the phone (restraining orders?)
  - They have to decide who gets to keep the house
  - They will flip a coin

How to Flip a Coin

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- Two obvious protocols
  - First obvious protocol
    - Alice flips the coin
    - Bob calls “heads” or “tails”
    - Alice declares who won the house

How to Flip a Coin

- Two obvious protocols
  - First obvious protocol
    - Alice flips the coin
    - Bob calls “heads” or “tails”
    - Alice declares who won the house
  - Second obvious protocol
    - Alice flips the coin
    - Bob decides which he wants (“heads” or “tails”, but does not reveal his choice to Alice)
    - Alice tells Bob whether it was heads or tails
    - Bob declares whether he won or lost
- Obviously neither of these works (Alice can cheat in the first one, Bob can cheat in the 2^{nd} one)

Review hashes

- Properties of cryptographic hash h
  - Infeasible to find two numbers x, y that hash to the same value
    - (x, y, such that h(x) = h(y))
  - Infeasible, given a hash, to find a number that hashes to that value
    - (given H, find x with h(x)=H)

The Solution

Bob

Choose random # R
with bottom bit=0 for Tails
with bottom bit=1 for Heads
Sends h(R)

Alice

Flips coin

h(R) →

← Reveal whether flip was "heads" or "tails"

R →

Circuit Model

Why talk about circuit model?

- It’s necessary for understanding secure multiparty computation, and homomorphic encryption

Circuit Model

- Any function of fixed size input and output can be built with a circuit with just two operations
  - XOR ($\oplus$) (addition)
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- Any function of fixed size input and output can be built with a circuit with just two operations
  - XOR ($\oplus$) (addition)
  - AND (&) (multiplication)
- This will be useful for proving it's possible to do homomorphic encryption or secure multiparty computation
- Both of these involve doing computation on data
- If you turn your program into a circuit, then all you have to do is show how to do XOR and AND

Programs as circuits

- You have to expand the circuit for each branch
- Can't do infinite loops
- Imagine a program that searches a database to retrieve an item with a particular value. With a "real program" you could do binary search, but with a circuit:
  - You have to know the maximum size of the database
  - Your circuit-program has to be written out, and each potential branch must be executed for each item in the maximum sized database

But think about how inefficient this is!

- About a million times slower to do a circuit than a "normal" program,
- Plus, whenever you might have done a branch, you have to execute all possible branches
  - Anything that chooses from a large set must execute on every item

Secure Multiparty Computation

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  - *n* participants each have an input
  - Desire to compute a function of all the inputs
  - Where each participant's input stays secret

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  - n participants each have an input
  - Desire to compute a function of all the inputs
  - Where each participant's input stays secret
- Example: An auction
  - Who has the highest bid?
  - Nobody wants their bid revealed to others

Obvious Solution

- A trusted 3rd party who receives all the inputs, computes the answer, and then tells everyone the answer
  - "the highest bid was X"
  - "Joe, you are committed to paying X"

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- However, cryptographers want to not depend on a trusted 3rd party
- Several proposed solutions (all very expensive!)
- One is actually deployed in the yearly Danish sugar beet auction

Outline of one solution

- Each participant P_j does secret-sharing of its own input I_j, into n k-shares (quorum k+1)
  – A k-share is a point on the graph of a degree k polynomial
  – Shares of participant J's input, I_j are I_{j1}, I_{j2}, I_{j3}, … I_{jn}
- Participant j gives
  – I_{j1} to participant P_1
  – I_{j2} to participant P_2
  – etc

Each participant will now know

- n things: a k-share of each of the n inputs
- Participant 3, for instance, will know
  - I_{13}, I_{23}, I_{33}, I_{43}, … I_{n3}

Note

- If k+1 participants conspired, they could calculate all the inputs
- So the assumption is that this won't happen

Outline of one solution

- Turn the program into a circuit with operations
  - addition
  - multiplication
- Each participant operates on their own share of the inputs
- At the end of the computation, each participant will have a k-share of the answer

Adding two inputs

- If the program says to compute $I_5 + I_7$, each participant adds its share of I_5 to its share of I_7
  - For instance, participant m computes $I_{5m} + I_{7m}$
  - Result $(I_{5m} + I_{7m})$ is participant m's k-share of $I_5 + I_7$
  - Because what's being computed is shares of the sum of the polynomials for I_5 and I_7
  - That's really cool!!!

What about multiplying two inputs?

- Suppose instead the program says to multiply: I_5 * I_7
- Just multiply your share of I_5 to your share of I_7
- Now everyone has a share of I_5 * I_7 but unfortunately it's a 2k share (a degree 2k polynomial)!
  - Because the polynomial for I_5 is being multiplied by the polynomial for I_7
  - Meaning quorum is now 2k+1
- And you're dead if the polynomial degree is ever bigger than n

Suppose there were a trusted 3rd party Z

- Then everyone could send Z their 2k-shares of $I_5 * I_7$
- Z could calculate $I_5 * I_7$
- And calculate n k-shares of $I_5 * I_7$
- And send one k-share to each member

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- But if we have a trusted 3rd party we don't need any of this complicated stuff!!

However….

- The computation the trusted 3rd party needs to do to create k-shares out of the 2k-shares only involves additions ("linear operations")
- And those can be done in a distributed way, on k-shares of the 2k-shares

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- The computation the trusted 3rd party needs to do to create k-shares out of the 2k-shares only involves additions ("linear operations")
- And those can be done in a distributed way, on k-shares of the 2k-shares
- Very expensively, of course
  - Both in computation and network bandwidth
  - Because after each multiply, everyone has to distribute k-shares of their 2-k share, so everyone can participate in reducing it, and then distributing k-shares

Summary of Secure Multiparty Computation

- (my opinion)
  - Not a very important problem
  - And sufficiently expensive it's impractical (despite Danish sugar beet auction)
- But lots of published papers

Homomorphic Encryption

Homomorphic Encryption

- Encrypt your data
- Do operations on the encrypted data
- The answer is the encrypted answer

Homomorphic Encryption

- Sounds really appealing
  - Store encrypted data in a public cloud you don't really trust
  - Efficiency: Instead of downloading all your data and decrypting it locally (more trusted environment), do operations in the cloud without the cloud knowing the data decryption key

Fully homomorphic (FHE)

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  - And the result will be the encrypted answer

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- Means you can do any computation on encrypted data without knowing the key
  - And the result will be the encrypted answer
- Don't get too excited: It's completely impractical
  - Encrypted data and computation are about 5 or 6 (decimal) orders of magnitude less efficient than doing computation on plaintext
  - Plus of course converting the algorithm to a circuit makes things even worse

What about “partially homomorphic”

- Sure…examples
  - Equality Preserving
    - Good security practice uses an “IV” for each encrypted item, so that the same plaintext will encrypt differently each time

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    - Good security practice uses an “IV” for each encrypted item, so that the same plaintext will encrypt differently each time
    - But if you want to test for equality, skip the IV
      - Then you can test for equality (the same plaintext will always have the same ciphertext)
  - Order-preserving Encryption
    - A cute idea (next slide)
- These leak information obviously

Order-Preserving Encryption

- To encrypt n items, sorted from smallest to largest:
  - Encrypt each one (say using AES), to produce a 128-bit result
  - Create, say, a 256-bit result by putting the (sorted) item number in the high order part of the result

Order-Preserving Encryption

plaintext	**Order-preserving Encryption**	
79	000001x^&*bd	
215	000002qj&*kl	
218	0000034j^%$c	
979	000004n$FOjw	
7933	000005!Jilr7r	

Order-Preserving Encryption

- Can get fancier if you need to be able to add new things
  - Start with first item, put a medium number for high order part
  - To insert an item, choose a high-order part midway between already-inserted items
  - Worst case: if the items are already sorted

Order-Preserving Encryption (where you can add items later)

plaintext	Order-preserving Encryption	
79	000373x^&*bd	
215	005762qj&*kl	
218	0066914j^%$c	
979	073118n$FOjw	
7933	091326!Jilr7r	

Partially Homomorphic, minimizing information leakage

- Let's say you want only authorized people to be able to test for equality
- Do equality-preserving encryption, but then encrypt one more time, with a key available only to people authorized to test for equality

Order-Preserving Encryption

plaintext	**Order-preserving Encryption**	**Encrypt with key K, known if authorized to see ordering**
79	000001x^&*bd	{000001x^&*bd}K = 49*&^%ac
215	000002qj&*kl	{000002qj&*kl}K = S7*$#xje
218	0000034j^%$c	{0000034j^%$c}K = &8:lp#xu
979	000004n$FOjw	{000004n$FOjw}K = z]9&#x87
7933	000005!Jilr7r	{000005!Jilr7r}K = Ju7*7v33

Back to Fully Homomorphic Encryption

Turn your program into a circuit

- Remember, any computation can be built with a circuit with just two operations
  - XOR ($\oplus$) (multiplication)
  - AND (&) (addition)
- Then figure out a homomorphic scheme that can do both operations

One homomorphic operation

- Unpadded RSA, multiplication
- Public key is (e,n), private key is (d,n)
- Encryption of x is x^e mod n
- Want x * y
- Multiply encrypted versions:
  - (x^e mod n) * (y^e mod n) = $(xy)^e$ mod n
- Answer is encrypted x*y

Fully Homomorphic

- All the known schemes involve “noisy numbers”
- Intuition
  - Encrypted number is “near” a legal value
  - If the encrypted number was *exactly* a legal value, the scheme wouldn’t be secure
  - Adding or multiplying numbers increases the noise
  - If the noise gets too much, it can’t decrypt properly

- So there were schemes that allowed doing a few operations on the encrypted data, but then the noise got too great

Breakthrough: “Bootstrapping”

- Craig Gentry made this breakthrough
- It is possible to “refresh” the encrypted data to the original noise level
  - Encrypt, then homomorphically decrypt the data
- Really really slow

Summary of Fully Homomorphic Encryption

- Lots of papers
- Absolutely impractical in terms of computation and data expansion

Bitcoin/Blockchain

What is Blockchain?

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  - “When I use a word, it means just what I choose it to mean”

    Humpty Dumpty, in Alice in Wonderland’s Through the Looking Glass

What is Blockchain?

- It's a word
  - "When I use a word, it means just what I choose it to mean"

    Humpty Dumpty, in Alice in Wonderland's Through the Looking Glass
- Extreme confusion because people are using the term "blockchain" for lots of things

Hype

- Articles about how “it” (whatever “it” is) is being considered for all sorts of problems
  - IoT
  - Alternative to PKI for managing identities
  - Real estate transactions
  - Protecting our nuclear technology (really!)
    - “Even the US Military is looking at blockchain technology to secure nuclear weapons"

Bitcoin's Blockchain

- The design of the blockchain technology as invented for Bitcoin requires (a lot of) monetary compensation to a community of "miners"

Bitcoin

Bitcoin

- Paper in 2008, by Satoshi Nakamoto (presumably a pseudonym)
- Released as open source software soon after
- The community agrees on modifications, so details of Bitcoin might change
- Really no spec…just the code.
- As we'll see, there could be (and has been) a problem if different implementations deployed, with subtle incompatibilities

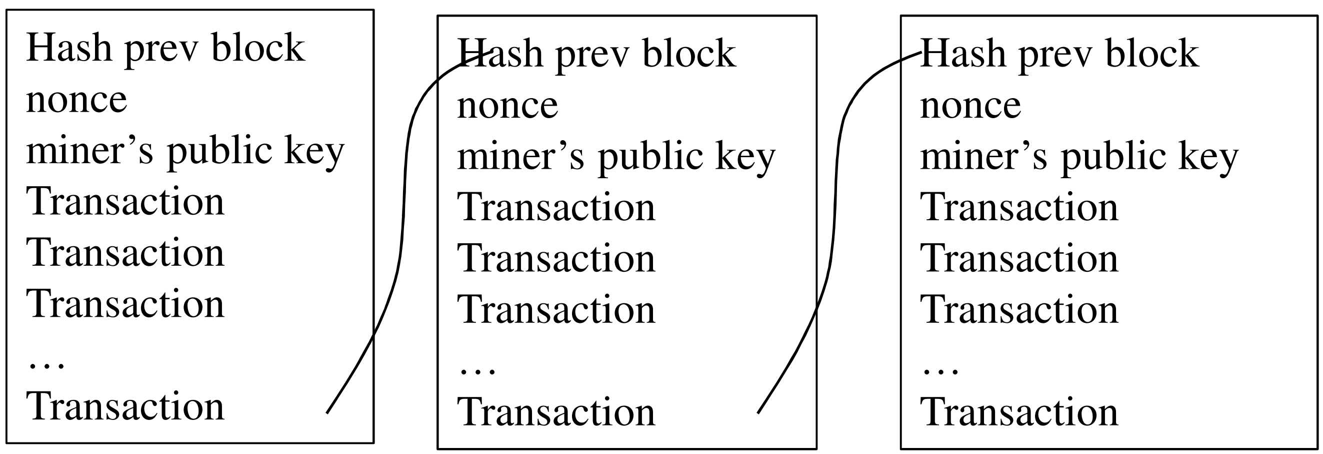
Bitcoin Design Goals

- Don’t trust known institutions
- Instead, trust is given to a large community of anonymous “miners”
- Anyone can be a miner (just download the software, or buy a specialized Bitcoin-mining rig)
- Miners are rewarded based on doing (a lot!!!) of computation
- Assumption: the set of honest miners will have more compute power than any set of dishonest miners

Bitcoin

- Public Ledger
  - Every transaction recorded and world-readable
    - “payer” and “payee” in a transaction are public keys, and you can use a different public key for each transaction
      - Public key X pays public key Y some amount

Format of Ledger: Blockchain



The Ledger

From transaction x8, X pays A 74.92 (hash=x15)
From transaction x11, Z pays B 38.22 (hash=x16)
From transaction x15, A pays C 74.21 (hash=x17)
From transaction x4, Q pays D 855.21 (hash=x18)
From transaction x17, C pays D 74.03 (hash=x19)
From transaction x18, D pays E 25.11, and F 830 (hash=x20)
etc.

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etc.

Difference between received quantity and paid quantity is a transaction fee (a "tip" to miner who creates this block)

The Ledger – multiple outputs

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etc.

Note: Multiple outputs

- Lets you give yourself change
- Or you can split the amount among different entities

Anonymity

- Not really anonymous
- Entire world knows sequence of public keys
  – Merchant likely to know who belongs to the public key that paid him (he has to ship the merchandise, for instance)
  – Other instances where who owns a public key might be known
  – And then analyzing transaction sequence A pays B pays C can give information

Valid Transactions

- Suppose A pays B output of transaction with hash x
- How to tell if the transaction is valid?
  - Transaction (A pays B) must be validly signed by A
  - Need to find transaction with hash x, to make sure A owns that amount (A was the payee)
    - Presumably, can do some pre-processing so a hash=x can be found more efficiently than linear search
  - Need to search every transaction since, to make sure A hasn't paid that transaction to someone else
    - Again, an implementation can optimize this by keeping track of unspent transactions

No central authority

- Central thing (like a bank) would make definitive ledger easy and efficient
- But Bitcoin is completely distributed, no pre-ordained trusted things
- Where do Bitcoins come from?
- How is the ledger agreed-upon?

Blockchain

- The blockchain is a set of blocks, and is the format of the ledger of all transactions
- A block is a set of new, valid transactions to add to the blockchain
  - Whose cryptographic hash is very very very hard to compute
- Bitcoin tries to cause a block to be added by the community of miners about every 10 minutes
- If blocks are found too quickly on average, hash difficulty is increased. If too slow, hash difficulty is decreased

Cryptographic Hashes

- A good hash is like a random number
  - As if, for every input, a random number were generated
- Probability that 1^{st} bit = 0 for random input is 50%
- Probability that top 10 bits = 0 for random input is $1/2^{10}$
- The maximum winning hash value in Bitcoin is modified to make finding blocks easier or harder
- Currently the hash has to have 70 leading zeroes!

How to Find a Block with Hash with 70 leading zeroes

- Insert a bunch of valid pending transactions
- Choose a random number for the "nonce"
- Compute the hash
- If the hash doesn't have 70 leading 0's (probability of $1 - 1/2^{70}$ that it won't), choose a different random number
- Repeat (about 2^{70} times)

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- Repeat (about 2^{70} times)
- If you're lucky enough to be the first to find a next block with a small enough hash value, you get rewarded with some Bitcoins

Miner Reward

- If you are the first to find a valid next block, your reward:
  - Some number of Bitcoins (currently, 12.5), plus any transaction fees

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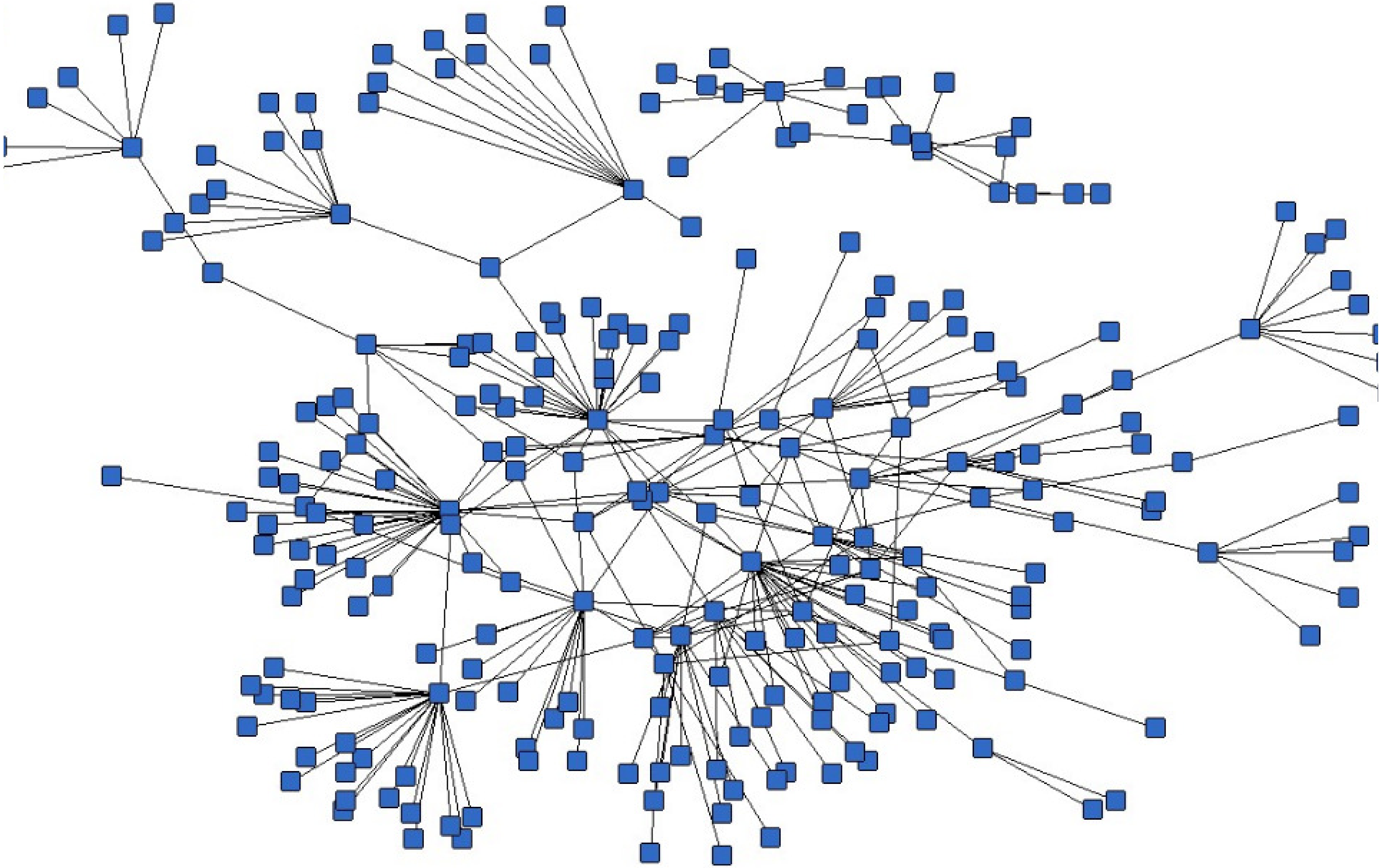
- Remember, anyone can be a miner
- So "trust" is given because someone is willing to do that much worthless computation
- Assumption: there will be a lot of honest miners, and no dishonest miner (or collection of them) will be able to dominate the compute resources

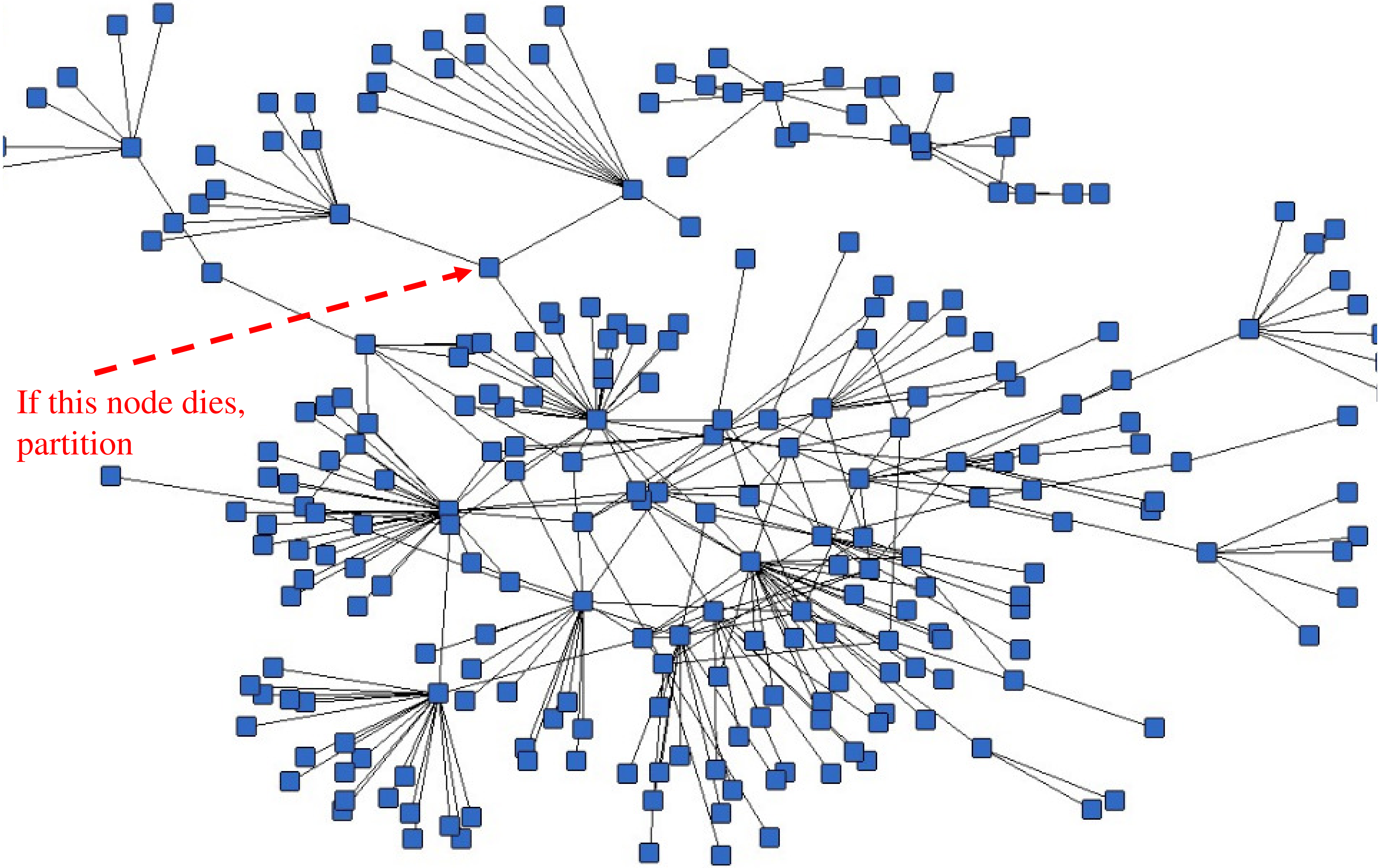
Suppose a set of miners had most of the compute resources

- They could undo transactions and create an alternate history
- Including double-spending their own money, after the payee thought it was safely paid
- Basically, they could bring down the whole Bitcoin concept

Broadcast

- This technology is also expensive in network bandwidth
  - A transaction has to be broadcast to, at least, most of the miners
  - When a miner finds a hash to create a new block, that block needs to be broadcast to most of the miners
  - If your transaction was not included in the winning block, hopefully it will be in a later block
  - Basically, a gossip protocol: your node somehow knows some others, they tell others, etc.




If this node dies,
partition

Blockchain forks

- It’s possible for multiple miners to semi-simultaneously find a hash
- Which means the blockchain will fork
- If a miner sees multiple ones, it works on the longest valid one (most blocks, and all contained transactions valid)
- So hopefully the network will converge on a single chain

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  - Note: 6 blocks is about an hour!

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- So hopefully the network will converge on a single chain
- This can take several blocks, so the advice is not to consider your transaction complete until it's in block n, and the chain is n+6
  - Note: 6 blocks is about an hour!
- Until your transaction where A paid you is safely recorded, A can double spend, and cheat you

Blockchain forks

- If Internet were partitioned, or gossip network partitioned, miners on each side would happily be adding blocks to the blockchain
- When the partitions rejoined, whichever side had the longest blockchain would win…everything beyond where they forked, in the losing blockchain, is no longer in the ledger
  - any Bitcoins mined aren't there any more
  - any transactions in the losing fork are no longer in the ledger
  - any payers in transactions in losing fork can re-spend

Really bad forks

- March 2013: a new version of Bitcoin software had some "harmless" tweaks, like making the code more efficient
- But there was a block that couldn't be processed by the previous version
- So, permanent fork!
- Eventually people noticed (hours and many blocks later), and downgraded to the older version
- But what if lots of different implementations, and no way of contacting all the miners?

Finite Total Bitcoins

- Initially the reward for finding the winning hash of a block was 50 Bitcoins
- Then it was halved to 25. Recently (July 2016), halved again to 12.5
- Every 4 years (or so), the reward (# of Bitcoins) halved
- Eventually, (about 2140) the reward will be zero
  - but it will be negligible long before that
  - miner still gets transaction fees
- As of Dec 2015, about 71% of Bitcoins have been mined

Transaction Fees

- Bitcoin claims it has lower transaction fees than, say, credit cards
- And today that's true…most transactions do not include a transaction fee, and yet they get swept into the blockchain
- But if too many transactions per time to fit into the block, miners will only include transactions with highest transaction fee
- Blocks are finite size. Each transaction is work for the miner (to ensure transaction valid, and more bytes in block means more hashing work)
- And as reward depends on fees rather than mined coins, transaction fees will escalate – currently with mining reward, miner gets about $5.85 reward per transaction in block (today, transaction fees only account for about 3% of reward)
- Note: The open source client has some algorithm for fees

Interesting statistics

- https://blockchain.info/stats
- http://www.coindesk.com/data/bitcoin/

Full vs Lightweight Nodes

- Imagine if your smartphone needed to store the entire blockchain!
- As well as search through the whole blockchain to see if the payer really owns the money he’s paying you
- So instead, a (lightweight) client node is configured with contact information for a few trusted full nodes, which will check transactions

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- So instead, a (lightweight) client node is configured with contact information for a few trusted full nodes, which will check transactions
- Note the irony: Supposedly nothing needs to be trusted, but clients have to trust the configured full nodes

How much energy?

- Assumptions
  - If mining very lucrative, more miners will join
  - If cost of electricity is more than reward, miners will drop out
  - So, amount spent on electricity will be a little less than reward

How much energy?

- Hard to know exactly – depends on a lot of things, but let's try
  - Miner reward over the last year has been about a million dollars a day
  - Reports are that miner reward barely covers the cost of electricity
  - At 10 cents per Kilowatt-hour, this is about enough electricity for 200,000 American homes
  - Or about ½ a nuclear power plant

But

- Psychology: if you buy a mining rig, you want to use it, even if paying more for electricity than you're reaping
- You may not know how much the Bitcoin mining is costing you
- There are countries where electricity is highly subsidized, so mining there is way cheaper
- You may be stealing the electricity, so you might not care
  - Bots, invalid public cloud accounts
  - Harder to win against specialized mining machines, but hey, if the electricity is "free"

How much storage?

- About 85 GB, up about 40 GB since last year
  - On each full node (about 5000 nodes currently)
- Can grow at most 50GB per year, with fixed size blocks and 10 minutes/block
- But they're talking about increasing block size
- https://blockchain.info/charts/blocks-size
- And this is stored at every full node

It’s hard to protect your Bitcoins

- If you lose your wallet, all your money is gone
- If your computer is broken into, your money can be stolen and spent by someone else
- With banks, there is some legal protection of user money
  - I assume…what if you don’t protect your password? Do you get stolen money back?
  - It’s probably somewhat possible to trace where money went, but maybe foreign banks provide cover

Why I'm not a fan

- Enormously wasteful of energy, bandwidth, storage
  - Imagine if it were more popular, and used for more things!
- Transaction fees will eventually need to be really large
- Fragile, especially if any diversity in implementations (permanent forks)
- Trust model (nation state or mining pool could have too much compute and double-spend, refuse to record transactions they don't like, etc.)
- Difficult for user to protect money
- Does coffee shop have to make you wait for an hour to make sure that they'll get paid?
- Permanent record of every transaction
- Limited # of transactions per unit time (blocks are finite size, one block every fixed amount of time)

What do people think are the good things about Bitcoin/blockchain?

- “Distributed ledger”
  - I claim distributed databases are known technology
- “No central authority”
  - I claim you can have several trusted authorities, with a transaction being valid only if more than half have signed…much more efficient, and sensible than thousands of anonymous miners
- “No greedy banks taking 3% transaction fees”
  - I claim Bitcoin transaction fees will be even worse
- “Immutable, permanent record”
  - Can do that with signatures, and storage in multiple places
- “Proof that event x occurred at some time”
  - Can use public trusted time-stamping services

Confusion

- People are calling all sorts of things "blockchain"
- They might be totally reasonable technology…but they aren't "revolutionary new technology", and they aren't Bitcoin's blockchain

Thank you!