Class logistics

1. Website for weeks 1-5:
   https://people.cs.uchicago.edu/~davidcash/23280-winter-19/
   (Or: https://david.cash forwards to my page, then click link)

2. Get on Piazza if you were not added automatically

3. Request access to Canvas if you were not added automatically

4. Assignment 1 will be out tonight and due in one week
Lecture 2 Outline

1. Cryptographic Hash Functions
   - Blockchains
   - Proofs of Work

2. Putting DCash “on the blockchain”, with an authority

3. The idea of decentralization

4. Decentralized DCash with an Angel

5. Decentralized DCash via proofs-of-work
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Hash Functions

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```
1  2  3  ...  n
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<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>...</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
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- Simple hash functions work, like $h(x) = x \mod n$ (or slightly more complicated)
- Collisions happen: $x \neq x'$ but $h(x) = h(x')$, and must be handled by table.
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- ... are much more resilient to adversarial inputs
Aside: Huge, Astronomical, and Depressingly Large

<table>
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<th># Steps</th>
<th>Who can do that many?</th>
</tr>
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<tbody>
<tr>
<td>$2^{30}$</td>
<td>Your laptop (one day)</td>
</tr>
<tr>
<td>$2^{56}$</td>
<td>Strong computer with GPUs</td>
</tr>
<tr>
<td>$2^{80}$</td>
<td>All computers on Bitcoin network in a few days</td>
</tr>
<tr>
<td>$2^{128}$</td>
<td>US Gov in ??? years, or very large quantum computer*</td>
</tr>
<tr>
<td>$2^{256}$</td>
<td>Nobody ever?</td>
</tr>
<tr>
<td>$2^{1024}$</td>
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*Not directly comparable but this is an estimate of equivalent power. Quantum computers are most effective against public-key crypto like digital signatures, but they also speed up attacks on hash functions.*
A cryptographic hash function $H$ is **collision-resistant** if no feasible attack can find inputs $x, x'$ such that $x \neq x'$ but $H(x) = H(x')$. 
Security of Cryptographic Hash Functions

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- This means $H$ is *committing*: Suppose you predict the closing prices of the S&P 500 tomorrow, and let $x$ be your predictions. You publish $y = H(x)$.
- After the market closes, you can only reveal the $x$ you chose. Finding another $x$ to change your prediction amounts to finding a collision.
Real Cryptographic Hash Functions Get Broken

Most crypto (encryption, digital signatures, etc) only gets broken very rarely. But hash functions are harder to build and do get broken.
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\[
\text{MD5(d131dd02c5e6eec4693d9a0698aff95c 2fcab58712467eab4004583eb8fb7f89} \\
\text{55ad340609f4b30283e488832571415a 085125e8f7cdc99fd91dbdf280373c5b} \\
\text{d8823e3156348f5bae6dadc436c919c6 dd53e2b487da03fd02396306d248cda0} \\
\text{e99f33420f577ee8ce54b67080a80d1e c69821bcb6a8839396f9652b6ff72a70} \\
\]

\[
= \text{MD5(} \\
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\text{55ad340609f4b30283e488832571415a 085125e8f7cdc99fd91dbd7280373c5b} \\
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You can ignore the alphabet soup of hash function names. Bitcoin uses SHA256.

Xiaoyun Wang (Tsinghua University), 2004
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Definition: A *block* is a data structure with two fields: Hash and Data.
Hash Functions and Blocks

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![Diagram of a block with Hash and Data fields]

**Definition:** If the hash field of a block is $H(x)$, where $x$ is the another block, we say that the block *points to* $x$ and we indicate this in a diagram as:

![Diagram showing a block pointing to another block]
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- **Note:** Input to H should include *both* fields of previous block (hash and data)

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**Definition:** A *blockchain* is linear sequence of blocks that point to each other.
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Given the last block, it's easy to add a block to a blockchain. Just evaluating $H$ on the last block and put the result in your new block's hash field.
Blockchains Integrity

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Theorem that can be formalized proved: Changing/deleting/adding a block without changing the final hash requires finding a collision in $H$ (which we believe is infeasible).
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Hash Security Beyond Collision Resistance

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- Probability $1/2$ that it starts with at least one zero, $1/4$ that it starts with at least two zeros, $1/8$ for three, $1/16$ for four, etc
- Once $z \approx 80$ this probability very small by computer standards
- In probability jargon: Number of starting zeros is geometric with parameter $1/2$. 
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- Canonical algorithm evaluates hash $2^z$ times *on average*
- $z=20$ is quick to solve, $z=70$ is solvable only by powerful computers
Proofs-of-Work for Anti-Spam (Not used, sadly)

$POW = \text{Proof of Work}$

Sender

Email server
Proofs-of-Work for Anti-Spam (Not used, sadly)

POW = Proof of Work

Sender → Email server
Proofs-of-Work for Anti-Spam (Not used, sadly)

POW = Proof of Work

Sender

Please solve POW $x$ to send

Email server
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POW = Proof of Work

Please solve POW \times x to send

Email server

Sender
Proofs-of-Work for Anti-Spam (Not used, sadly)

POW = Proof of Work

Sender → Please solve POW · x to send → Email server

Spammer → c → Email server
Proofs-of-Work for Anti-Spam (Not used, sadly)

POW = Proof of Work

Sender

Email server

Spammer

Email server

Please solve POW $x$ to send $c$
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POW = Proof of Work

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Email server

Spammer

Please solve POWs $x_1, x_2, x_3...$ to send

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Email server

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- Evaluating POW takes time/money/compute hardware for good and bad parties
- Set hardness parameter $z$ so that:
  1. Normal senders can solve one puzzle quickly, without noticing the work
  2. It is unprofitable for spammers to solve millions of puzzles
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Recalling DCash

**Initialization**: Ben, Emily, and David all generate keys for digital signatures

- David’s verification key: $\text{PK}_{\text{david}} = 5e7843...$
- Ben’s verification key: $\text{PK}_{\text{ben}} = 88f01e...$
- Emily’s verification key: $\text{PK}_{\text{emily}} = 16823a...$

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- To determine if a transaction is valid, we must rerun entire history of ledger
DCash 2.0 (a.k.a. Scroogecoin, Text section 1.5)

- Move from “account-based ledger” to “transaction-based ledger”
DCash 2.0 (a.k.a. Scroogecoin, Text section 1.5)

- Move from “account-based ledger” to “transaction-based ledger”
- Store transactions in a blockchain managed by a semi-trusted authority
DCash 2.0 (a.k.a. Scroogecoin, Text section 1.5)

- Move from “account-based ledger” to “transaction-based ledger”
- Store transactions in a blockchain managed by a semi-trusted authority

**Authority’s responsibilities:**
1. Publish blockchain contents publicly.
2. Create coins and assign them to owners (public keys) at will.
3. Receive transactions notifications and commit them to the blockchain.
DCash 2.0 Blocks, Transactions, and Coins

- One transaction per block

$$\begin{array}{|c|}
\hline
\text{<hash>} \\
\hline
\text{<transaction ID>} \\
\hline
\text{<transaction data>} \\
\hline
\end{array}$$

Just a counter from first block
(can be implicit and not actually written down).
DCash 2.0 Blocks, Transactions, and Coins

- One transaction per block
- Each transaction *consumes* some coins and *creates* new coins
DCash 2.0 Blocks, Transactions, and Coins

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- Each transaction *consumes* some coins and *creates* new coins
- Each coin is created and consumed once. A created coin is *unspent* until it is consumed

![Diagram of a transaction]

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DCash 2.0 Blocks, Transactions, and Coins

- One transaction per block
- Each transaction *consumes* some coins and *creates* new coins
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```
<hash>

<transaction ID>

<transaction data>
```

Just a counter from first block (can be implicit and not actually written down).

- Two types of transactions: CreateCoins and PayCoins
First Type of Transaction: CreateCoins

- CreateCoins transactions... create coins.
- Authority decides when to create coins and who gets them.

<table>
<thead>
<tr>
<th>transID: 73</th>
<th>type: Create</th>
</tr>
</thead>
<tbody>
<tr>
<td>no coins consumed</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>num</th>
<th>value</th>
<th>receipt</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>3.2</td>
<td>0x782...</td>
</tr>
<tr>
<td>1</td>
<td>1.4</td>
<td>0x34e...</td>
</tr>
<tr>
<td>2</td>
<td>7.1</td>
<td>0x551...</td>
</tr>
</tbody>
</table>

H(prev)

david’s signature
First Type of Transaction: CreateCoins

- CreateCoins transactions… create coins.
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</tr>
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</tr>
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</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>david's signature</td>
</tr>
</tbody>
</table>

- Every coin has a **coinID** consisting of **transID** and an index starting at zero.
- **coinIDs** are unique and never reused
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<table>
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<th>coinID 73(0)</th>
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<th>value</th>
<th>receipt</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0x782</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
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<th>coinID 73(1)</th>
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<th>value</th>
<th>receipt</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.4</td>
<td>0x34e</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>coinID 73(2)</th>
<th>num</th>
<th>value</th>
<th>receipt</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>7.1</td>
<td>0x551</td>
<td></td>
</tr>
</tbody>
</table>

david’s signature

- Every coin has a coinID consisting of transID and an index starting at zero.
- coinIDs are unique and never reused.
- Coins can have different values.
Second Type of Transaction: PayCoins

- PayCoins transactions consume some number of coins and create new coins owned by (potentially) different keys
- Payers must sign transaction

<table>
<thead>
<tr>
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<tbody>
<tr>
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<td>2.0</td>
<td>0x782...</td>
</tr>
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<td>1</td>
<td>0.4</td>
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</tr>
<tr>
<td>2</td>
<td>7.7</td>
<td>0x551...</td>
</tr>
</tbody>
</table>

consumed coinIDs: 68(1),42(0),72(3)

transID: 74  type:Pay
Second Type of Transaction: PayCoins

• PayCoins transactions consume some number of coins and create new coins owned by (potentially) different keys
• Payers must sign transaction

• Consumed coins should sum to value as created coins

<table>
<thead>
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payers’ signatures

H(prev)

…
Second Type of Transaction: PayCoins

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```plaintext
<table>
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<th>value</th>
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<td>0x551...</td>
</tr>
</tbody>
</table>
```

- Consumed coins should sum to value as created coins
- Intuitively, consumed coins $68(1), 42(0), 72(3)$ are destroyed (melted down) and coins $74(0), 74(1), 74(2)$ are newly created with possibly different owners.
Second Type of Transaction: PayCoins

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Consumed coins should sum to value as created coins.

Intuitively, consumed coins $68(1), 42(0), 72(3)$ are destroyed (melted down) and coins $74(0), 74(1), 74(2)$ are newly created with possibly different owners.

This is “transaction oriented”: Each transaction says where its funds came from.
Valid transactions in DCash 2.0

• CreateCoins transactions are valid if the authority signed them and the hash matches the previous block

• PayCoins transactions are valid if:
  1. Consumed coins were indeed created previously
  2. Consumed coins have not been consumed in a previous block
  3. Consumed coins sum to same value as created coins
  4. Signatures from payers are all valid
  5. Hash matches previous block
Quickly validating PayCoins Transactions

1. Step backwards and check if consumed coins were spent since transaction 42
2. Look up consumed coins, sum up their values, compare to output sum
3. Check sigs (using public keys of owners of consumed coin)

- This is easier than with our original ledger: We don’t have to compute how much value each account has.
Tricks with PayCoins Transactions

• Can consume a coin, pay someone, and pay yourself the change.
• Can split coins by paying yourself twice in one transaction.
• Easy to extend DCash 2.0 to allow multiple transactions in a block.
(Semi-) Trust in the DCash Authority

<table>
<thead>
<tr>
<th>No prev</th>
<th>H(prev)= 8912...</th>
<th>H(prev)= 443e...</th>
<th>H(prev)= 7621...</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;transdata&gt;</td>
<td>&lt;transdata&gt;</td>
<td>&lt;transdata&gt;</td>
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</tr>
</tbody>
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  *No, this requires forging a signature.*
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  *No, this requires modifying the blockchain and will be detected by users.*
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**But the authority can:**
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1. Create as many coins as it likes.
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But the authority can:
  
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**But the authority can:**

1. Create as many coins as it likes.
2. Refuse transactions, locking people out or extorting them.
3. Walk away from the entire affair, rendering all coins worthless.
Lecture 2 Outline

1. Cryptographic Hash Functions
   - Blockchains
   - Proofs of Work

2. Putting DCash “on the blockchain”, with an authority

3. The idea of decentralization

4. Decentralized DCash with an Angel

5. Decentralized DCash via proofs-of-work
Decentralized Technologies vs Centralized
Decentralized Technologies vs Centralized

Decentralized
1. The Internet
2. Email
3. The Web
4. Git
Decentralized Technologies vs Centralized

**Decentralized**
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**Centralized**
1. AOL
2. Facebook
3. Piazza
4. DNS
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- Easy to join, no “permission” required
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**Note:** A system may run on thousands of different computers yet still be centralized and controlled by one organization.
Decentralization as Studied in Computer Science

- Computer scientists have studied decentralized systems since the 1970’s.
- The news was mostly bad: In many models it is impossible to distribute decisions.
- The relevant problem for us is called *distributed consensus*.

---

**Impossibility of Distributed Consensus with One Faulty Process**

MICHAEL J. FISCHER  
Yale University, New Haven, Connecticut  
NANCY A. LYNCH  
Massachusetts Institute of Technology, Cambridge, Massachusetts  
AND  
MICHAEL S. PATERSON  
University of Warwick, Coventry, England

Abstract. The consensus problem involves an asynchronous system of processes, some of which may be unreliable. The problem is for the reliable processes to agree on a binary value. In this paper, it is shown that every protocol for this problem has the possibility of nontermination, even with only one faulty process. By way of contrast, solutions are known for the synchronous case, the “Byzantine Generals” problem.
Distributed Consensus

- Several nodes communicate asynchronously
- Every node is either honest or malicious
- Honest nodes supply input values and follow specified protocol
Distributed Consensus

- Several nodes communicate asynchronously
- Every node is either honest or malicious
- Honest nodes supply input values and follow specified protocol

Distributed consensus problem:
At start: All honest nodes have input value
At end: Protocol terminates and
  1. All honest nodes agree on same value
  2. The agreed-on value originated from an honest node.
Distributed Consensus of Blockchain State
Distributed Consensus of Blockchain State

- Nodes connected to network broadcast transaction information
Distributed Consensus of Blockchain State

- Nodes connected to network broadcast transaction information
- Specified protocol says how to decide on the state of blockchain, but some nodes are malicious and don’t follow protocol.
Distributed Consensus of Blockchain State

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- Each honest node will have a view of the blockchain.
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Identities and Sybil Attacks

- In Bitcoin, identities are not assigned by an authority. Anyone can create a node any time.
Identities and Sybil Attacks

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- It’s easy for an adversary to create *tons* of nodes. This is called a *Sybil attack*.
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**Lesson:** Without an authority to vet nodes, we can’t count on malicious nodes being in the minority.
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**Lesson:** Without an authority to vet nodes, we can’t count on malicious nodes being in the minority.

**Goal:** Have all honest nodes agree on one of their views of the blockchain.
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DCash 3.0: Consensus with an angel (text section 2.3)

- In this protocol, time is divided into rounds.
- Every node maintains its own personal “view” of the blockchain.
- We start with an unrealistic model that depends on an imaginary *angel*.
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**Angel’s magic power:** Able to select a random node from the network and announce its identity to everyone. The chosen node can add a block to its personal view. Nobody else can add a block to their view.

**Exception:** Malicious nodes are a hive-mind and share one personal view.
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This protocol doesn’t exist in reality! We will build the angel and personal views using POWs later.
DCash 3.0: Consensus with an angel (text section 2.3)
Consensus protocol with angel:
DCash 3.0: Consensus with an angel (text section 2.3)

Consensus protocol with angel:
1. Transactions are broadcast to everyone
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**Consensus protocol with angel:**
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6. Everyone else accepts the announced view as their own if:
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**Note 1:** When a node is chosen, it can always add a block to its view. It’s up to the other nodes to accept it or not.

**Note 2:** A node may **only** add a block to its view when the angel chooses it.
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Example: Angel picks an honest node

Consensus!
Example: Angel picks an malicious node
Example: Angel picks an malicious node
Example: Angel picks an malicious node
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Example: Angel picks an malicious node

Malicious node tries to delete a block by omitting it from announced view.
Example: Angel picks an malicious node

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Example: Angel picks an malicious node

Consensus! Honest nodes aren't fooled b/c blockchain is not longer.

Malicious node tries to delete a block by omitting it from announced view.
Example: Angel picks an malicious node twice
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Malicious node adds a block to its personal view with a deleted block, but no one else accepts it (as before).
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Malicious node adds a block to its personal view with a deleted block, but no one else accepts it (as before).
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Malicious node adds a block to its personal view with a deleted block, but no one else accepts it (as before).

However, the malicious node adds the block to its view of the chain.
Example: Angel picks an malicious node twice
Example: Angel picks an malicious node twice
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Example: Angel picks an malicious node twice
Example: Angel picks an malicious node twice

Malicious node adds another block to its personal view with a deleted block. Now it has more blocks than other views, so they accept it. 😞
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• Malicious nodes need to grow a longer chain in order to cheat.
• Being picked several times allows them to grow their chain.
• But when honest nodes are picked, the chain grow and others accept it.
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Theorem: Assume the majority of nodes are honest. Once the honest nodes are “ahead” of the malicious nodes, the chance the malicious nodes will ever “catch up” decreases exponentially in the size of the lead.
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**Going forward:** “Confirmations” for a transaction are subsequent blocks that follow the transaction’s block. More confirmations mean the transaction is “more official”.
Problem to solve later: Sybil attacks

**Vulnerable to Sybil attacks**: If there are a ton of malicious nodes, then the probability a malicious node is chosen is high.

Probability that angel picks honest node = \# honest / total
Probability that angel picks malicious node = \# malicious / total
Problem to solve later: Sybil attacks

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\[
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\[
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\]

Create tons of malicious nodes
Problem to solve later: Sybil attacks

**Vulnerable to Sybil attacks**: If there are a ton of malicious nodes, then the probability a malicious node is chosen is high.

Probability that angel picks honest node = \# honest / total
Probability that angel picks malicious node = \# malicious / total

Create tons of malicious nodes  Angel picks malicious leaders
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Create tons of malicious nodes → Angel picks malicious leaders → Get ahead, delete blocks

Malicious nodes can “undo” transactions after buying things.
Lecture 2 Outline

1. Cryptographic Hash Functions
   - Blockchains
   - Proofs of Work

2. Putting DCash “on the blockchain”, with an authority

3. The idea of decentralization

4. Decentralized DCash with an Angel

5. Decentralized DCash via proofs-of-work — Next time.
The End