# Foundations of Blockchain

## Scaling Blockchains: the Lightning Network

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# Scaling Blockchains

# On-chain versus Off-chain

- A payment is on-chain if it is recorded as a transaction on the blockchain;
- Off-chain payments are not visible in the underlying blockchain. Usually, these payments are privately exchanged between the involved parties.

Exchanging payments on-chain requires submitting a transaction and waiting its inclusion in a block. However, blockchains have limited throughput performance:

- Bitcoin: 7 transactions per second (TPS), a block every 10 min;
- Ethereum: 12–15 TPS, a block every 12 s;
- Algorand: 8–12 TPS (but theoretically, up to 7500 TPS), a new block every 3.9 s;
- Different factors can affect these numbers (e.g., block size, fees, consensus).

# Scaling Blockchains (1)

To mitigate the performance bottleneck, many approaches have been proposed:

- **DAG**-based blockchains;
- **Sharding technique**: splits transactions into shards, which are processed in parallel; however, it is hard to achieve consensus across shards;
- **Layer-2 protocols**: process certain transactions outside of the main chain, but the consensus of theses transactions relies on a parent chain;
- **Sidechain** technique: separate (auxiliary) blockchain that processes transactions individually. It has its own consensus algorithm. It interacts with the main chain.

# Scaling Blockchains (2)

- **Heterogeneous structure**: uses different types of block (e.g., *keyblocks* to conduct consensus; *microblocks* to vote for leaders and carry transactions).
- **Hybrid consensus**: 2+ consensus protocols, e.g., to smoothly switch between optimistic conditions (PBFT) and the worst-case conditions (PoW).

Wang et al, “SoK: DAG-based Blockchain Systems”. ACM Comput. Surv. 55(12), art. 261 (2023).

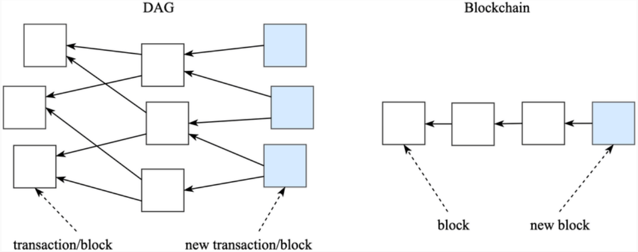
# Scaling Blockchains

## DAG-based Blockchains

# DAG-based Blockchains

Directed Acyclic Graph (DAG)-based Blockchains:

- Blockchains maintain transactions/blocks in one single chain.
  - Concurrent transactions/blocks compete for one valid position each round.
  - Leading to slow confirmation.
- DAG-based blockchains structure transactions/blocks in the form of graph;
- They can improve **performance** by requiring less communication, computation, and storage overhead.



# DAG-based Blockchains

Rough classifications of DAG-based Blockchains:

- Unit Representation:
    1. Requests are immediately handled whenever received;
    2. Requests packaged by powerful parties (e.g., miner, validator) and then disseminated;

# DAG-based Blockchains

Rough classifications of DAG-based Blockchains:

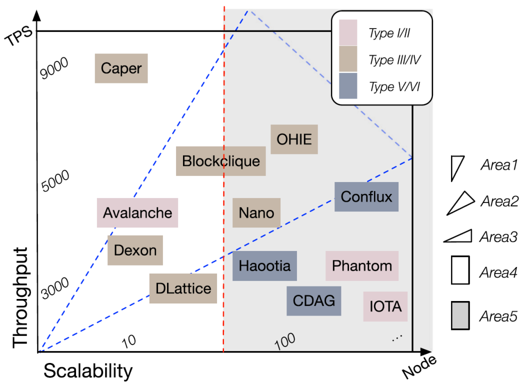
- Unit Representation:
  1. Requests are immediately handled whenever received;
  2. Requests packaged by powerful parties (e.g., miner, validator) and then disseminated;
- Graph Topology:
  1. Divergence: units sparsely spread in unpredictable directions without predetermined orders;
  2. Parallel: units are maintained in the form of multiple (parallel) chains;
  3. Convergence: units are organized in a determined sequence or tend to converge in a determined sequence.

Wang et al., "SoK: DAG-based Blockchain Systems", ACM Comput Surv 55, 12, Art. 261, 2023.

# DAG-based Blockchains

| | *Divergence* | *Parallel* | *Convergence* |
|---|---|---|---|
| $1^{od}$ | IOTA [21], Graphchain [40], Avalanche [45] (*Type I*) | Nano [36], Caper [37], Vite [38], Chainweb [39], Hashgraph [41], DLattice [42], Aleph [43], Jointgraph [46], Lachesis [47–51] (*Type III*) | Byteball [22], Haootia [44] JHdag [26] (*Type V*) |
| $2^{od}$ | Spectre [23], Phantom [56], Meshcash [63] (*Type II*) | Prism [52], Blockmania [53], Blockclique [54], OHIE [57], Sphinx [58, 59], Eunomia [60], DEXON [64], PARSEC [65] (*Type IV*) | GHOST [35], Inclusive [55], CDAG [61], Conflux [62], StreamNet [66] (*Type VI*) |

DAG-based blockchain systems cannot improve the **performance**, **scalability**, **security**, **decentralization**, and **(strict) consistency** at the same time.




BFT-style

PoW variants

# The Lightning Network

# The Lightning Network

- Bitcoin publicly records every transaction in a globally replicated ledger. Every transaction is seen, validated, and stored by every participating node;
- Once blocks are full, excess transactions are left to wait in a queue;
- Competition for fees can increase the cost of each transaction;
- Increase the block size limit implies utilization of more resources and may not completely solve the problem;
- Visa network processes (at peak) 40,000 TPS: Unlikely to scale a blockchain to validate the entire world's transactions in a decentralized way.

# The Lightning Network

- Several efforts proposed to build payment channels aiming at processing the majority of transactions off-chain (e.g., [M+16][M+19][S+22]);
  - HTLC and multi-signatures used to bound layer-2 to layer-1;
  - Different approaches: payment channels, (optimistic and zero-knowledge) rollups;
  - Different abstractions: state channel, payment channel, payment channel hubs;
  - A survey on layer-2 protocols [G+23];
- The Lightning Network (LN) represents the most prominent solution for managing Payment Channel Networks (PCNs) [PD16]:
  - Several alternatives leverage the LN key ideas (e.g., Eclair[1], Raiden[2], Thunder[3]).

[1] https://github.com/ACINQ/eclair
[2] http://raiden.network/
[3] https://github.com/blockchain/thunder

# The Lightning Network

- The Lightning Network (LN) is a second layer technology on top of Bitcoin.
- A matter of trust:
    - Cryptographic systems (like LN) allow to transact with people we do not trust;
    - This is not a trustless operation;
    - We still need trust in the used protocol (and its software implementation) that will result in fair outcomes;
    - Differently from traditional financial systems, cryptographic systems make trusted third parties unnecessary to ensure fair outcomes;

# The Lightning Network

- The LN enables fast, secure, private, trustless, and permissionless payments:
  - **Fast:** Users can route payments to each other for low cost and in real time;
  - **Trustless:** Users who exchange value do not need to wait for block confirmations for payments;
  - **Secure:** Once a payment has completed, it is final and cannot be reversed.
  - **Privacy:** Payments are transmitted between pairs of nodes and are not visible to everyone, resulting in much greater privacy;
    - **Onion routing:** even the nodes involved in routing a payment are only directly aware of their predecessor and successor in the payment route;
  - **Resource-friendly:** Payments do not need to be stored permanently (fewer resources needed; hence, LN is cheaper);
  - **Safety:** LN uses real bitcoin, which is always in the possession and full control of the user.

# The Lightning Network

## Payment Channels

# Payment Channel

- A payment channel is a financial relationship between two nodes;
- It allocates a balance of funds and is managed by a cryptographic protocol;
- The cryptographic protocol consists in a 2-of-2 multisignature address:
  - 2-of-2 multisignature address: both parties hold a share to spend funds;
  - The protocol prevents either channel partner from spending the funds unilaterally (i.e., to cheat);
- The channel partners negotiate a sequence of transactions that spend from this multisignature address;
  - Instead of recording these transactions on the blockchain, *parties hold these transactions unspent*;
  - The latest transaction defines how that balance is divided between the parties;
  - As a new transaction is negotiated, the previous ones are revoked (neither party can regress to a previous state).

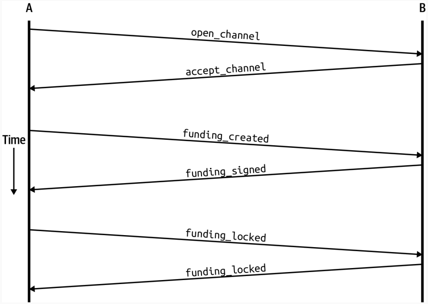
# Payment Channel

- A payment on a payment channel is almost instant;
- If the channel is open, making a payment does not require the confirmation of Bitcoin blocks;
- Payments made in a payment channel are only known to the involved parties;
- Opening and closing channels requires an on-chain transaction:
    - This incurs transaction fees;
    - It is more convenient to keep channels open as long as possible.

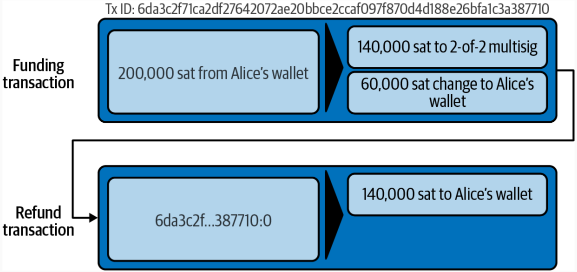
# Funding Transaction

- One of the two channel partners will fund the payment channel by **sending bitcoin** to the 2-of-2 multisignature address;
- This transaction recorded on the Bitcoin blockchain;
  - The locking script (includes): *`2 <PubKey1> <PubKey2> 2 CHECKMULTISIG`*;
  - Later, we will detail the content of the funding transaction;
- The funding transaction is public, but it is not obvious that it is a Lightning payment channel;
  - It is a **P2SH** (Pay-to-Script-Hash), whose address always starts with *3*;
- Channels are typically publicly announced by routing nodes that wish to forward payments (and earn from fees);
- **Private** channels (non-advertised) also exist;
  - e.g., by mobile nodes not participate in routing;

# Funding Transaction




- *open_channel* and *accept_channel* exchange configuration values;
- *funding_create* creates the funding transaction, which is the signed by B; A requires B to sign also the refund transaction;

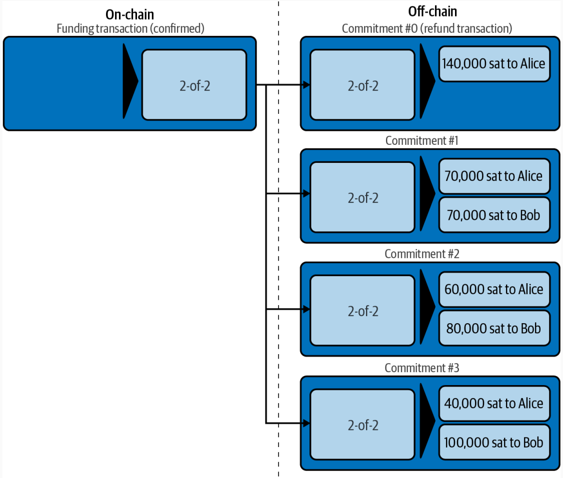



- When the funding transaction is confirmed on the blockchain, the parties exchange *funding_lock*

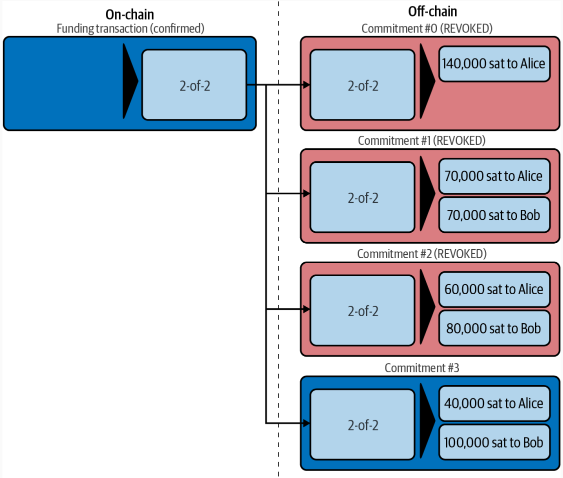
# Commitment Transaction

After the funding transaction, commitment transactions are created each time the channel balance changes;

With a signed commitment transaction, each partner gives the other the ability to get his funds back;



# Commitment Transaction

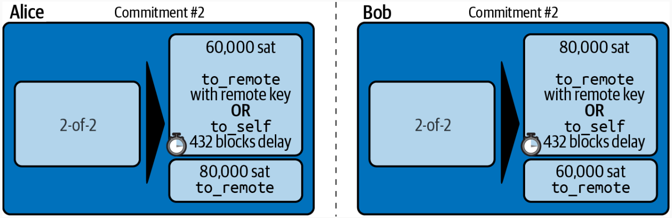



How to prevent publishing a previous commitment transaction?

- Commitment transactions are constructed so that if an old one is transmitted, the cheater can be punished.
- The penalty consists in giving the cheated party an opportunity to **claim the balance** of the cheater.

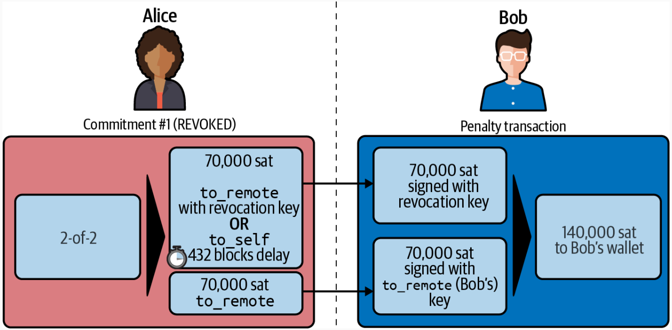
# Commitment Transaction

- The commitment transaction includes:
  - a timelock delay: which prevents the owner from spending it immediately;
  - a revocation secret: which allows the other party to by-passing the timelock.
- The two channel partners hold two different variations of this transaction:



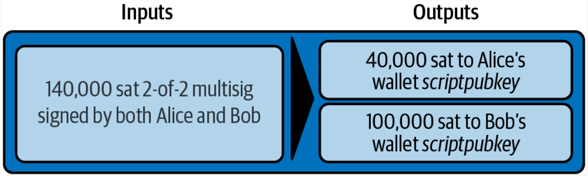
# Commitment Transaction

- With a new commitment transaction, the previous revocation secret is revealed;
- If a party cheats, the other can immediately publish a penalty transaction to get its funds as well as the cheater's funds;



# Closing a Channel

- Channel partners prefer not to close a channel (e.g., future use, avoid fees);
- However, sometimes it is necessary:
  - To reduce the balance held on Lightning channels (e.g., for security reasons);
  - The channel partner becomes unresponsive or not well-connected;
  - The channel partner has breached the protocol (i.e., closing is needed to protect funds);
- A mutual closing occurs by publishing a (co-signed) closing transaction with the last balance of the channel (it has no timelock);
  - Fees are paid by who opened the channel;



# Closing a Channel

- A forced closing occurs by publishing the last **commitment transaction**;
- Forced closing is not recommended unless strictly necessary;
- Forced closing has higher fees:
    - The commitment transaction includes (up to five times) higher fee than the fee estimators suggest at the time the commitment transaction is negotiated;
    - The transaction includes additional outputs (e.g., time-lock, revocation hash);
    - Any pending routing attempts will have to be resolved on-chain;

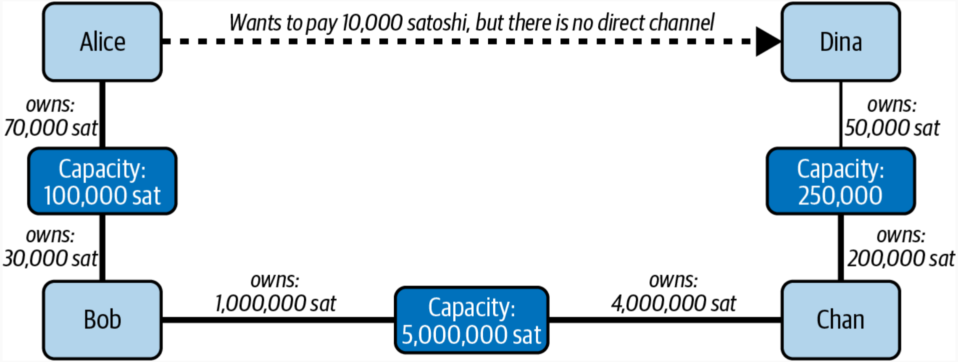
# The Lightning Network

## Payment Channel Network

# Routing

- The LN uses a gossip protocol to distribute public information about channels;
  - Not all information about a channel is propagated, to preserve privacy and scalability;
  - Propagated: capacity, channels partners;
  - Not propagated: balance, precise topology, single payments;
- When several participants have channels, payments can also be **forwarded** from channel to channel;
- The cryptographic protocol protects the entire network of participants:
  - They can forward payments without trusting any of the other participants;

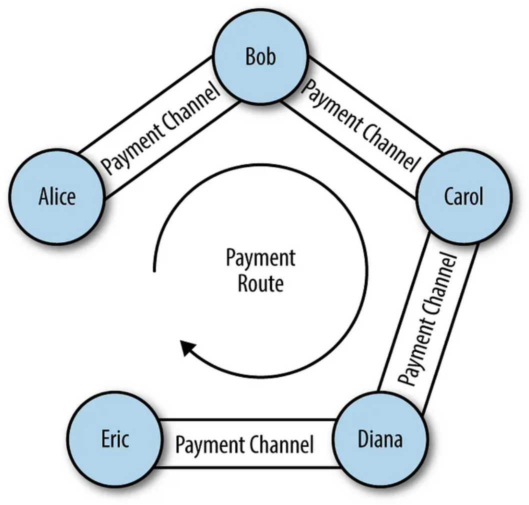
# Payment Channel Network



# Payment Channel Network

- LN defines a fairness protocol, with the following properties:
  - **Trustless operation:** participants do not need to trust each other;
  - **Atomicity:** Either the payment is fully executed or it fails (everyone is refunded);
  - **Multihop:** The security extends end to end for payments routed through multiple payment channels.
  - (Optional) **Multipart Payments:** ability to split payments into multiple parts while maintaining atomicity
- Hash time-locked contract (HTLC):
  - Uses a cryptographic hash algorithm to commit to a randomly generated secret;
  - Conditions a payments to the knowledge of a value;
  - Uses a hash preimage as the secret that unlocks a payment;
  - Returns funds on timelock expiration;
- Alternative: Point Time-Locked Contract (PTLC):
  - Leverages properties of elliptic curves.

# Payment Channel Network



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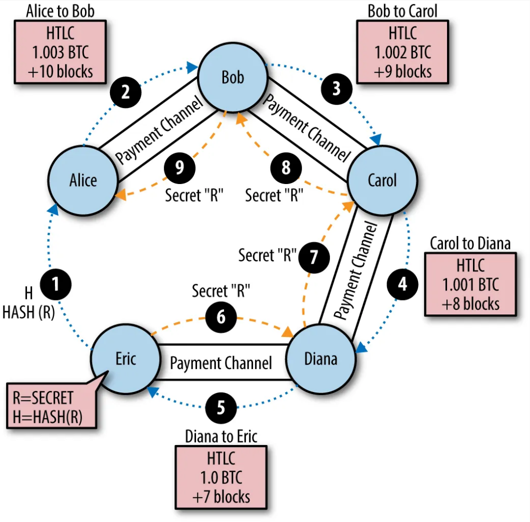

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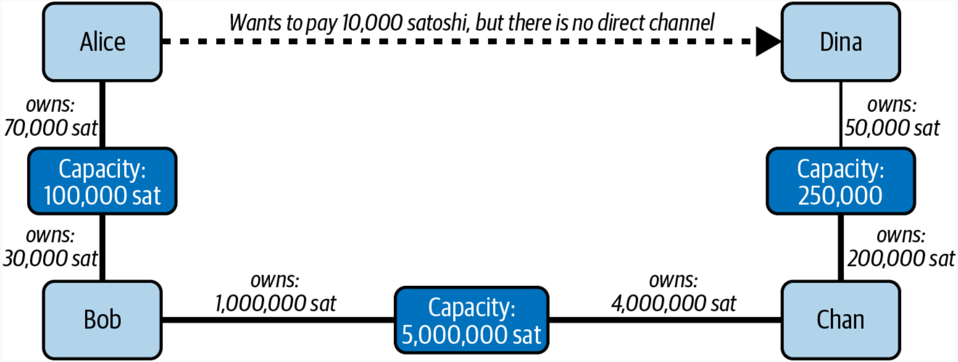

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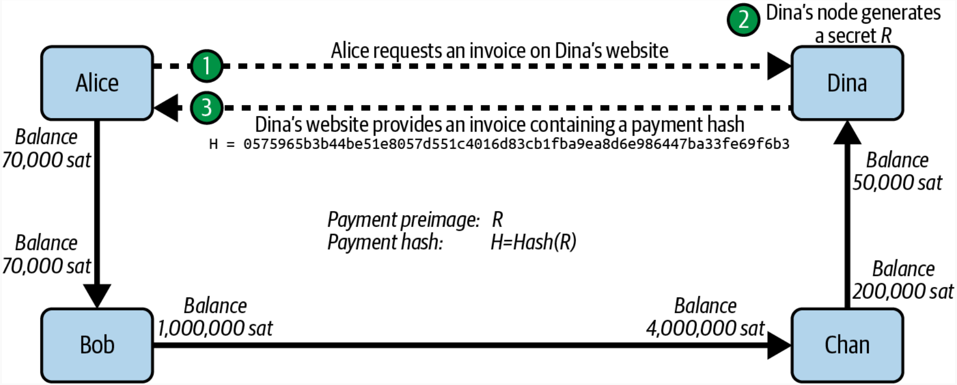

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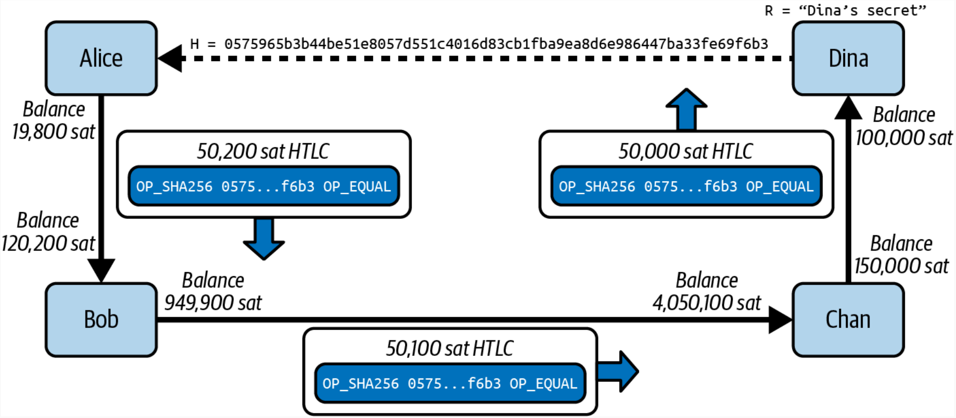

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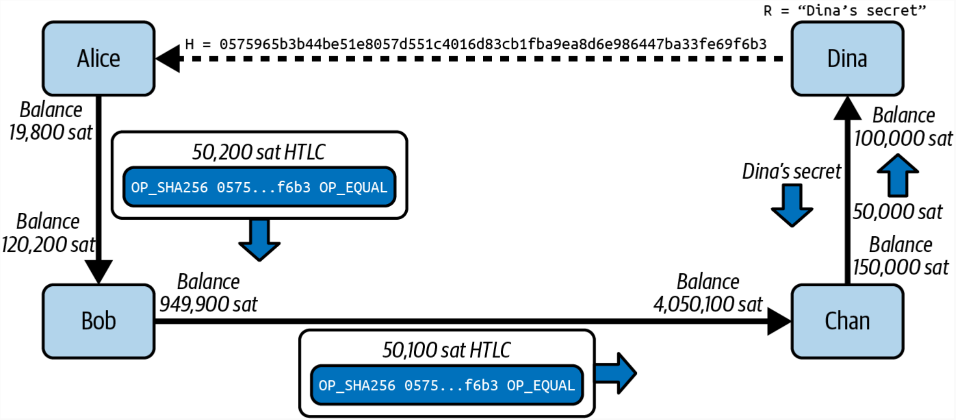

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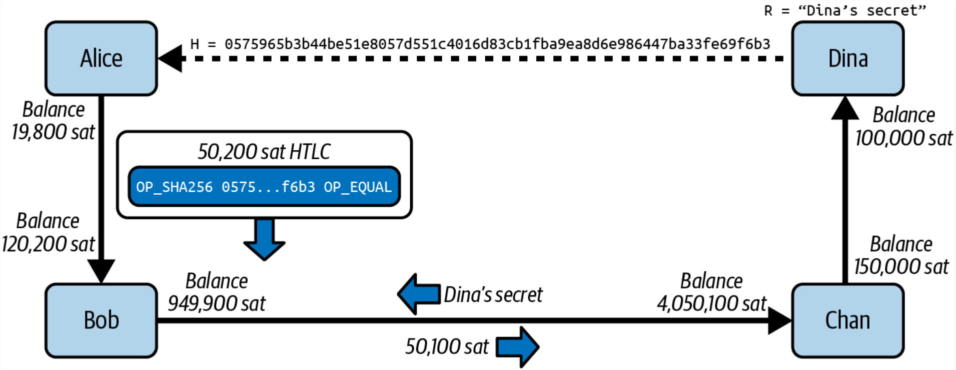

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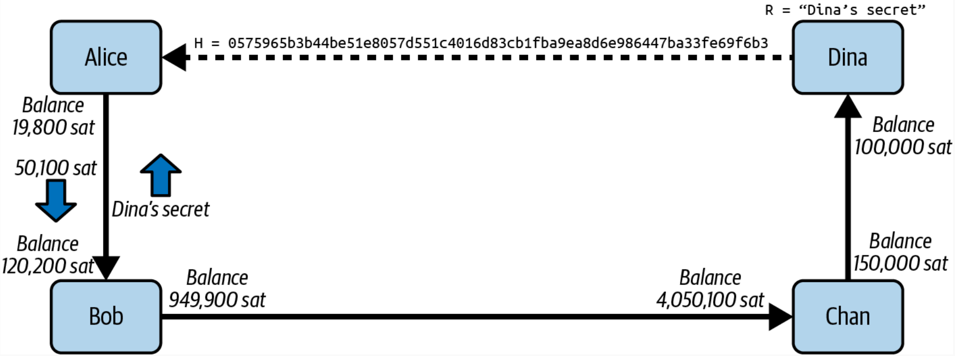


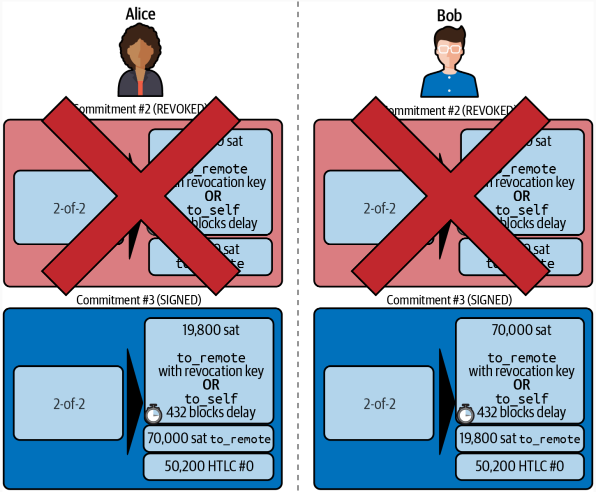
# Payment Channel Network

# Time Lock in HTLCs

- As HTLCs are extended from payer to payee, the time-locked refund clause in each HTLC has a **different time-lock value**;
- To ensure an orderly unwinding of a payment that fails, each hop needs to wait a bit less for their refund.
- For example, Alice sets the refund timelock to a block height of +500 blocks; Bob would then set the timelock to current + 450 blocks; Chan to current + 400 blocks.
- The decrementing timelock prevents race conditions and ensures the HTLC chain is unwound backward, from the destination toward the origin.

# HTLC and Commitment Transaction

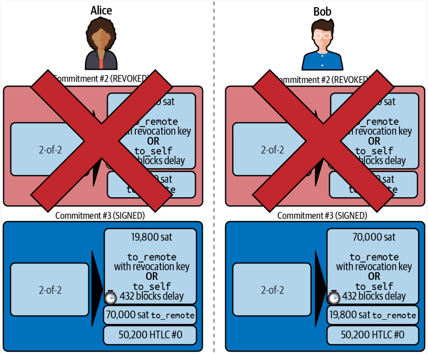
When B receives an HTLC from A, he creates a new commitment transaction with the same two outputs as before and a **new** one representing the HTLC;



# Multiple HTLCs in a Commitment Transaction

- A and B can have many HTLCs across a single channel;
- Each HTLC is added to the transaction as an **additional output**;
- At most 483 (pending) HTLCs are allowed on a channel;
    - This limit is imposed by the maximum Bitcoin transaction size;
- When the HTLC **preimage** is revealed and the payment is executed correctly, both A and B can remove the HTLC from the commitment transactions and update their channel balances.

# Multiple HTLCs in a Commitment Transaction



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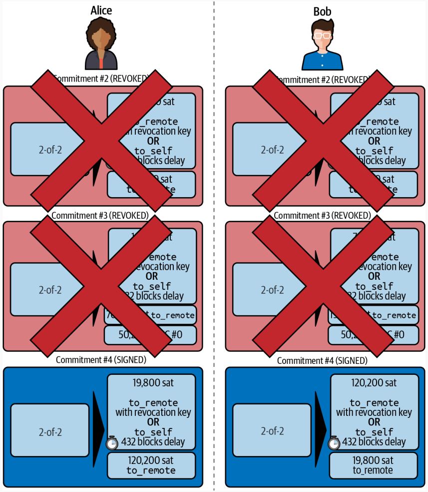

# The Lightning Network

## Routing

# Source-based Path Finding

- The exact channel balances of every channel is unknown;
- Multiple path-finding and routing algorithms can coexist on the LN;
  - Path Finding: the process of finding and choosing a contiguous path made of payment channels that connects sender A to recipient B.
  - Routing: the active process of sending a payment on a path, which involves the cooperation of all the intermediary nodes along that path.
- Source-based path-finding is successful at the current scale of LN;
  - The path-finding strategy currently implemented is to **iteratively try** paths until one is found that has enough liquidity to forward the payment.
  - This does not necessarily result in the path with the lowest fees;
  - The probing is done by the Lightning node or wallet (hence, it is *not directly seen* by the user).

# Path Finding

LN implementations use a very simple path-finding mechanism:

1. Create a **channel graph** from announcements and updates containing the capacity of each channel;
2. Filter the graph, ignoring any channels with insufficient capacity for the amount we want to send;
    - Channels capacity can only be estimated (probabilistic approach);
3. Find paths connecting the sender to the recipient;
4. Order the paths by some weight;
5. Trial-and-error loop: Try each path in order until payment succeeds;
6. Optionally use the HTLC failure returns to update the channel graph, reducing uncertainty;

# Path Finding: Definition of Best Path

- Different criteria for defining the *best* path:
  - e.g., with enough liquidity, with low fees, with short timelocks, compliant to specific policies.
- A payment channel is characterized by:
  - **Capacity**: the aggregate amount of satoshis funded with the funding transaction (max amount of value held in the channel). Announced by the gossip protocol.
  - **Balance**: amount of satoshis held by each channel partner that can be sent to the other channel partner;
  - **Liquidity**: portion of the balance that can actually be sent across the channel in one direction (i.e., balance minus reserve and pending HTLCs);
- Uncertainty of balances: We can use failed HTLCs returned from our payment attempts to update our liquidity estimate and reduce uncertainty.

# Path Finding and Payment Delivery

- Well-known problem: computing the shortest path!
  - **Fee** and **timelock** information are important for successfully routing the payment;
  - The process of calculating fees happens from the recipient to the sender backward;
  - Dijkstra or A* can be used to search for a path, using fees, estimated liquidity, and timelock delta as a cost function for each hop.
- The sender's node starts the trial-and-error loop by constructing the HTLCs, building the onion, and attempting delivery of the payment.
  - A successful result;
  - An error: the payment can be retried via a different path by updating the graph;
  - No response: no retry possible to avoid a double payment.

# Onion Routing

- LN uses an onion routing protocol (SPHINX Mix Format);
- An intermediary node can **only** see on which channel it received an onion and on which channel to forward the onion.
  - Onions can have up to around 26 hops;
  - The onions are small enough to fit into a single TCP/IP packet;
  - The onions are constructed such that they will always have the same length independent of the position of the processing node along the path.
- Onions have an HMAC at each layer so that manipulations of onions are prevented;
  - Onion encrypted using different ephemeral encryption keys for every hop;
- Errors can be sent back to the original sender (using onion routing).

# Onion Routing

| | IP Routing | Onion Routing |
|---|---|---|
| **Type** | Best effort | Source based |
| **Data format** | Open headers | Encrypted headers |
| **Sender / Recipient** | Known to routing nodes | Unknow to routing nodes |
| **Address Space** | logical-hierarchical overlay network | fully decentralized p2p network |
| **Edge weights** | Mostly static (bandwidth) | Highly dynamic (fees, balances) |
| **Topology info propagation** | Network can react to change (e.g., BGP) | Gossip is slow / noisy to propagate all relevant information |
| **DoS Attacks** | Via spoofing can be mitigated by ISPs | Anyone can send/delay onions. Impossible to mitigate! |
| **Path finding** | Collaboratively by the network | Achieved by sender or 3rd party service |

# The Lightning Network

## Concluding Remarks

# Main Differences between LN and Bitcoin

- In LN, the recipient of a payment creates an invoice (address is not enough):
  - An invoice is a payment instruction with a payment hash (hash of a random number), a recipient, an amount, and an optional text description;
  - An invoice can **only be used once**;
- A payment results in a **channel balance update** (no UTXOs consumption);
  - Portions of balance can be sent back and forth within the channel;
  - Payments are immediate and almost completely private;
  - A user can only send as much bitcoin as currently exists on his side of a channel;
- The payment recipient needs to be **online** (synchronous payment).
- Blockchain **confirmations** only matter for opening and closing channels;
- Users pay **fees** for routing payments through channels: a minimum base fee plus a fee rate proportional to the payment value;

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