STRUCTURING MULTI TRANSACTION CONTRACTS IN BITCOIN

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Is Cash Bitcoin's Killer App?

- Ethereum does smart contracts!
  - like the DAO

*Betteridge's Law

Safe Contract Extensions for Bitcoin Contracts

- Tools for complex contracts
- Avoid internal complexity

We Can Have It All

- Transaction level invariants called Covenants can get us there

Contributions

- Extensions to Covenants
- Merkle Compressed Covenants
- Transaction Diagrams
- Multi-Phase Execution Techniques

Covenant Contracts

BACKGROUND KNOWLEDGE

The Naughty Banker

- You ask Bob’s Bank to hold a $100 deposit
  - Bob buys himself some new sneakers with your money

Covenant Contracts

- Contracts that **REQUIRE** creation of a contract of certain form
- Example: Hiring a Banker
  - They have your money but only you can withdraw!

Placeholder Notation

- high level:
  - COV(plain English invariant)
- script:
  - <plain English invariant> OP_COV
- Examples:
  - COV(Bob’s Bank only lets me withdraw)
  - <Bob’s Bank only lets me withdraw> OP_COV

Making Covenants

- Two Major Variant
  - *Invariant by Execution*
    - OP_COV[MES16] “Introspective”
      - Pattern matching
    - *“Computational” ☹ impractical*
  - *Invariant by Construction*
    - Recovered PubKey “Cryptographic”
      - OP_CHECKSIGFROMSTACK + OP_CAT/SUBSTR
      - SIGHASH_MASK-ing
    - MultiSig “Trustful”
      - 1 of N honesty

☹ Grave Concerns ☹

- Fungibility & Privacy
  - Forced Compliance
- Computational Explosion
  - Loops could make Turing Complete

- Open Topic: Expressive & Safe contracts without covenants?
  - Like preventing Turing Completeness…
    - {CSS, MOV, C++ Templates…} are Turing Complete
  - Trivial Bitcoin “covenants”
    - sum(Outputs) <= sum(Inputs), inputs exist, etc…

extensions to

COVENANTS

Tale of Expired Accounts

- Let’s say you have a phone number as 2FA to your bank account
  - When you change your number, you want the 2FA to change too
  - In fact, you want to **not be able** to change your phone before your 2FA points to the new record

Input-Join Covenant

- Two outputs forced to be consumed in one transaction
- Execution or Construction based implementations

✓Minimal Bitcoin Extensions needed

Two Cars Problem

- You need One car at noon
  - You have a Ferrari and a Porsche
  - You want your (really good) friend to borrow one car at noon but not the one that you want
  - “Only after I have chosen should you be able to drive away”

Impossible Input Covenant

- Prove an input creation impossible
  1. Prove an input was already consumed
  2. Construct input from consumed input
  3. 1 & 2 Prove input creation impossible
- “Constructive” without extension, “Introspective” with new OpCodes
  - Consuming output exclusively made in a branch equivalent to chain introspection
  - Must be constructed ahead of time

Bad Airlines

- You're flying from JFK to SFO with a layover in ORD
  - You go JFK → ORD
  - ORD gets snowed in
  - You're stuck in the snow
- How can we ensure JFK→SFO next time?

Intermediate Output Covenant

- <i> OP_IS_IUTXO requires output at index <i> be spent in same block
- Bad for two-phase-commit protocols
  - Except *between* commits
- Complicates block-creation code
  - Child-Pays-For-Parent similar

Bad Airlines (Part 2)

- You book your own transfers, avoiding ORD and other cold airports
  - When you get to the airport you realize the first check-in won’t give you all your tickets, you need to go through security twice

Virtual Output Covenant

- **<s> <i> OP_SIG_VUTXO** requires that output at <i> redeemable with <s>
- **<i> OP_IS_VUTXO** requires some other input script provide proof
  - allows optimizing malleating provers…
- Same goal as OP_IS_IUTXO
  - No multiple transactions
  - No mining complexity
  - Additional Signing complexity
- Could permit shared-stack
  - Through alt-stack?
- Safe “Turing Complete” recursion?
  - $\mathbf{\Delta}_0$, Russell's Post Theorem Trace Witness
  - You can tweet me too…
    “Imma let you finish but VUTXO is the best $\mathbf{\Delta}_0$ – @JeremyRubin”

application

MERKLE COVENANTS

Compressed Contracts

- Summarize useless clause in contract
- Example: Appendix A
  - Provide your Tax Payer ID here ____
  - See Appendix A if no Tax Payer ID

MAST: Merkelized Abstract Syntax Tree

- **O(log(n))** branch elimination compression
- Huffman Codable
- Example:

Compile

if (A) {T} else {F}

to

```
assert(H(code)==(A ? H(T) : H(F)));
eval(code);
```

Bitcoin Implementation (Proposal)

- Put all branches into a tree & run
- Example
  - **if (A){if (B){C} else {D}} else {E}**
  - Merkle Tree of {`**assert(A&&B);C**`, `**assert(A&&~B);D**`, `**assert(~A);E**`}
  - Prove branch in the tree, then run
- One Input inside one Transaction

Properties

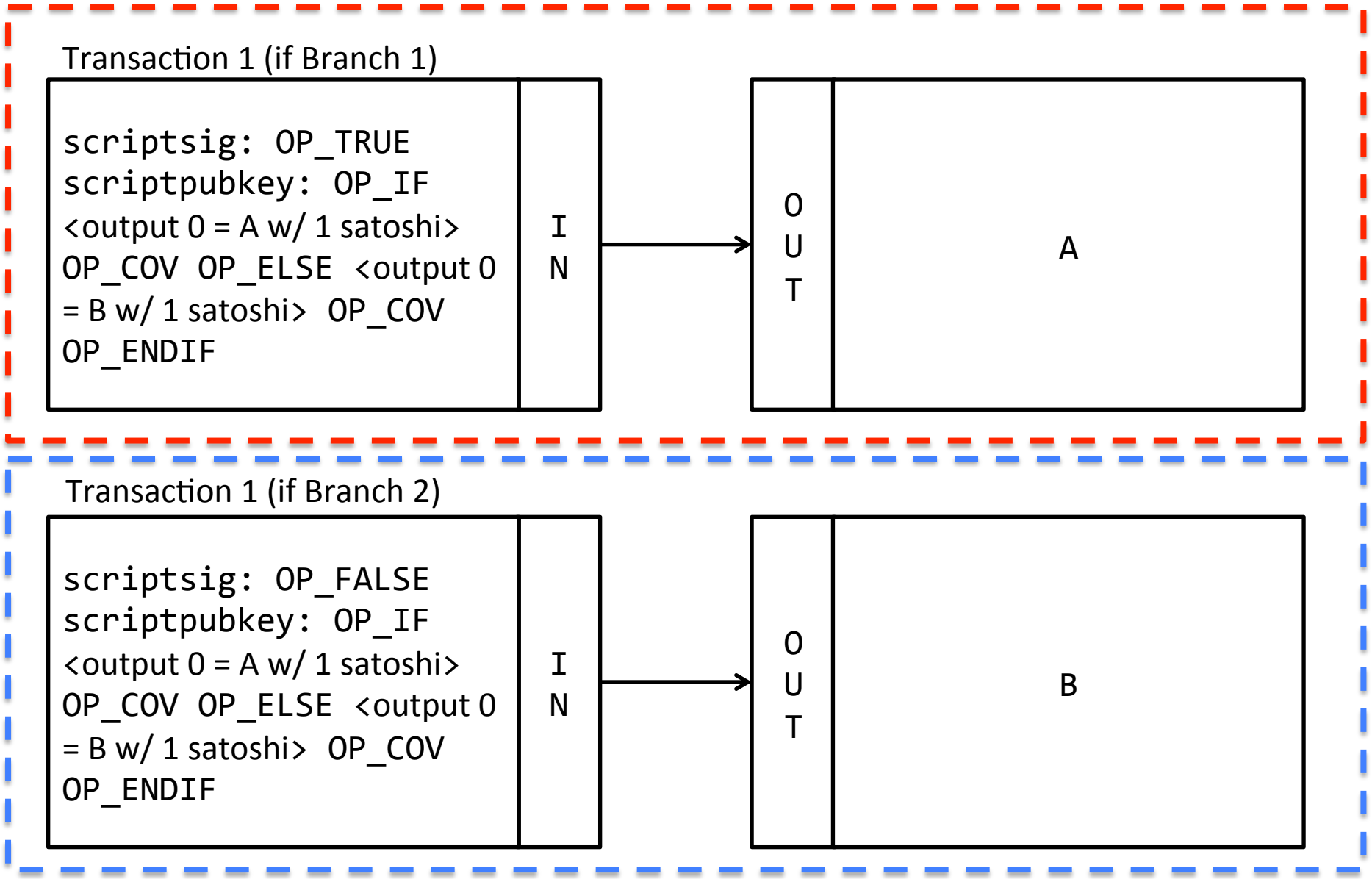
- Atomic Execution
  - **No intermediate state**
- Minimal Hash “Overhead”
  - 1 Hash/Pruned Branch, 1 Parent Hash
- No need to reveal not-taken branch

Conditional Covenant

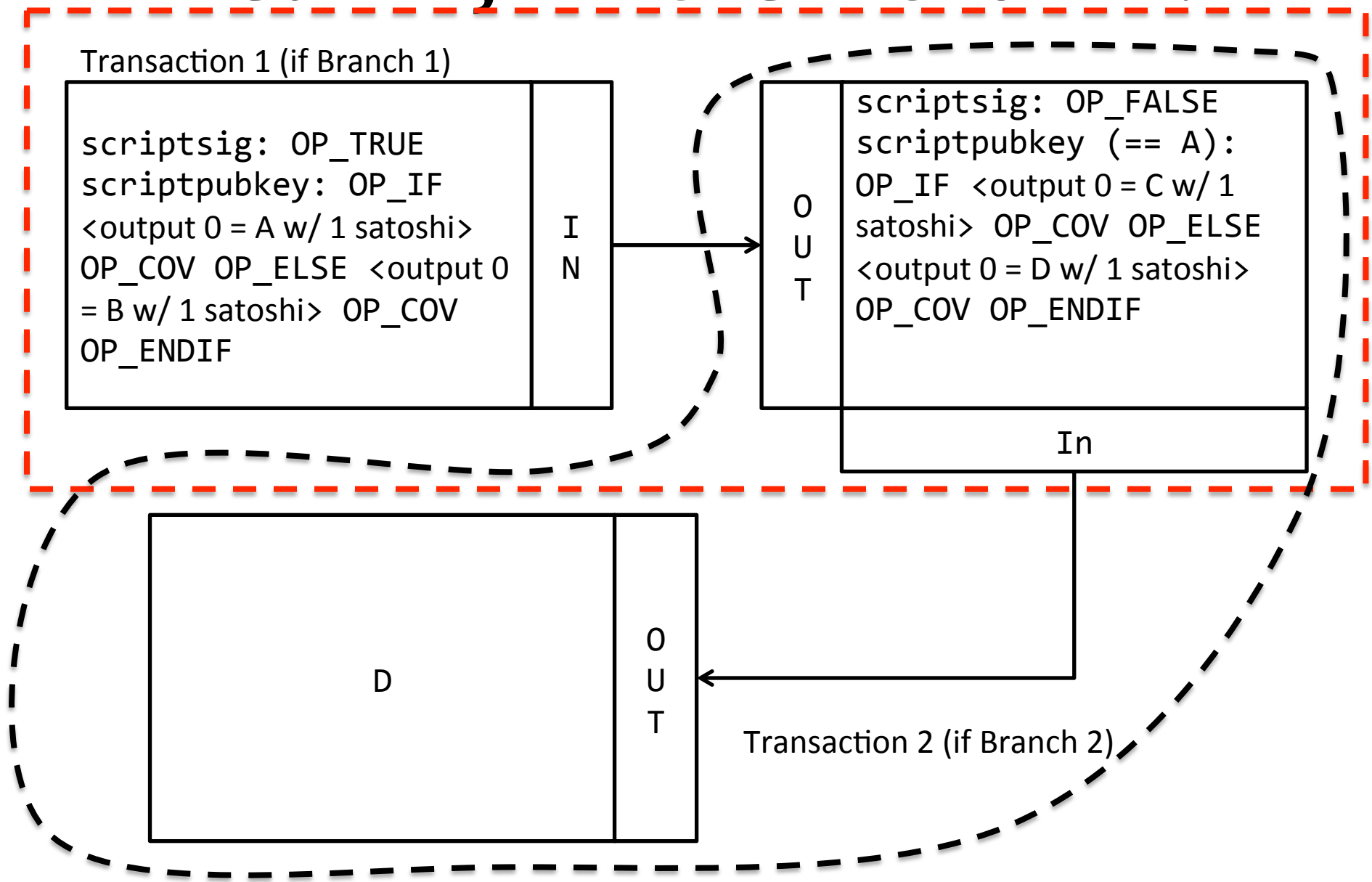
- Make an Output as follows
  - scriptpubkey:

```
OP_IF
    <output 0 = A w/ 1 satoshi> OP_COV
OP_ELSE
    <output 0 = B w/ 1 satoshi> OP_COV
OP_ENDIF
```

Either Red Tx or Blue Tx



Red Tx; Either C or D?



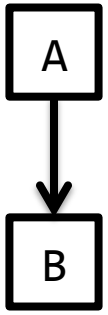
Properties

- Non-Atomic Execution Mode
  - Intermediate states allowed
  - Extra hash per branch
- Atomic Execution Mode
  - Using OP_IS_VUTXO
  - Minimal Hash “Overhead”
    - 1 Hash/Pruned Branch, 1 Parent Hash
- No need to reveal not-taken branch
- Signature Parallelization benefits
- Larger Max Script Size

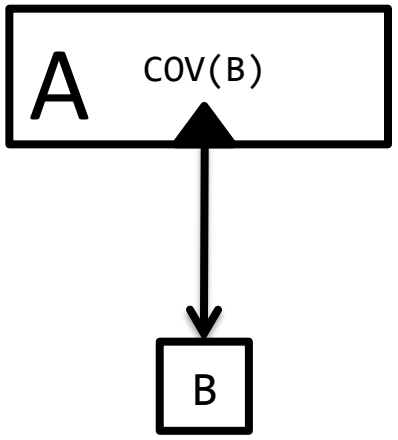
TRANSACTION DIAGRAMS

Primitives: Transaction

input: A
script: “…”
scriptSig: “…”
output: B

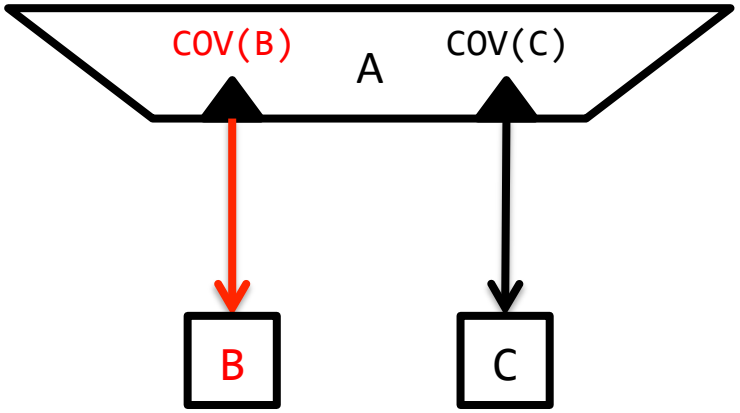


Primitives: Output Covenant



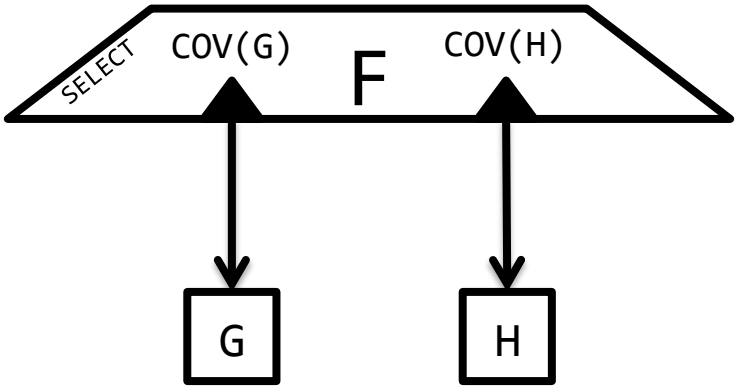
input: A
script: COV(B)
scriptSig: “…”
output: B

Primitives: Conditional Covenant



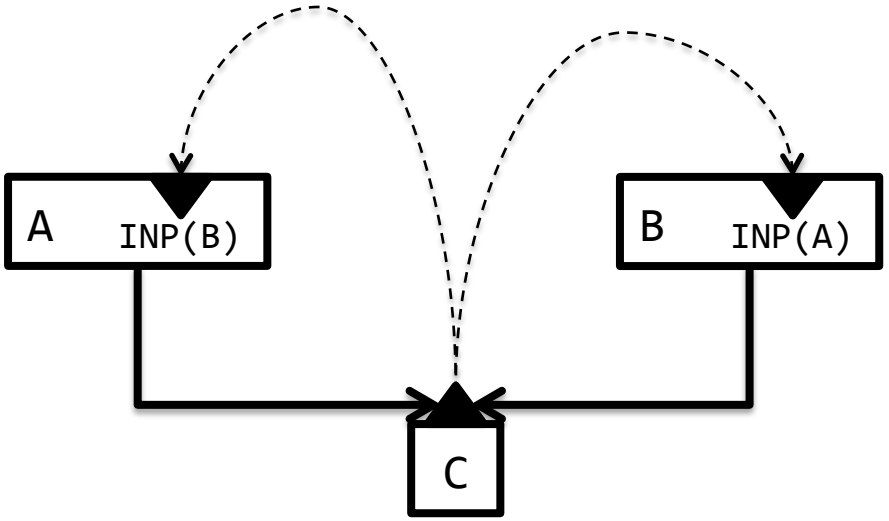

```
input: A
script:
OP_IF
    <output 0 = B> OP_COV
OP_ELSE
    <output 0 = C> OP_COV
OP_ENDIF
scriptSig: OP_TRUE
output: B
```

Primitives:
AND Covenants

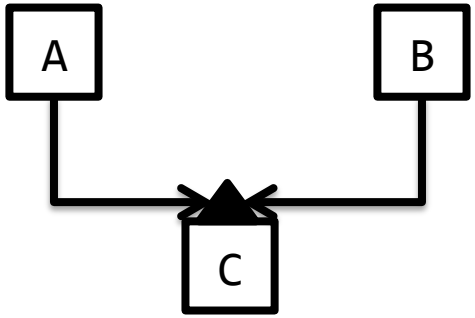



```
input: F
script:
<output 0 = G > OP_COV
<output 1 = H> OP_COV
OP_ENDIF
scriptSig:
outputs: G, H
```

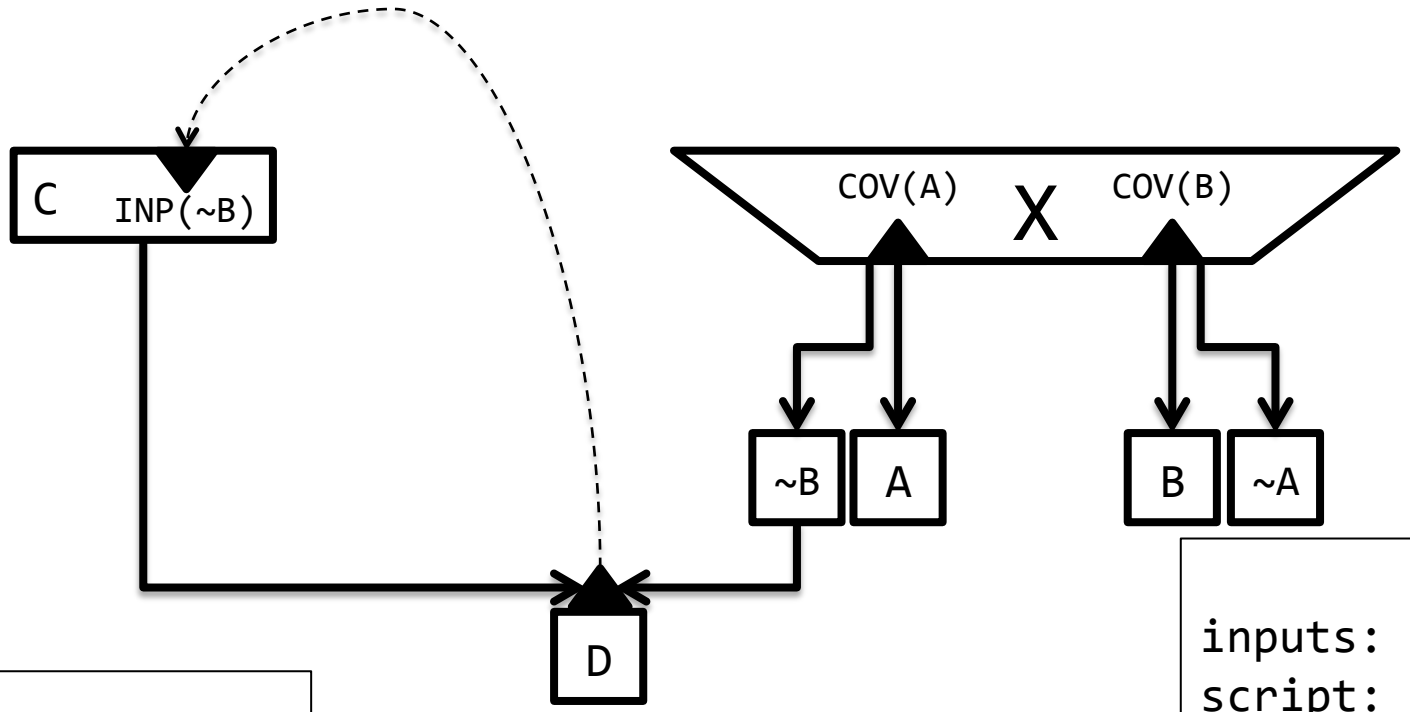
Primitives:
Input Join Covenant



inputs: A, B
script: “…”
scriptSig: “…”
outputs: C



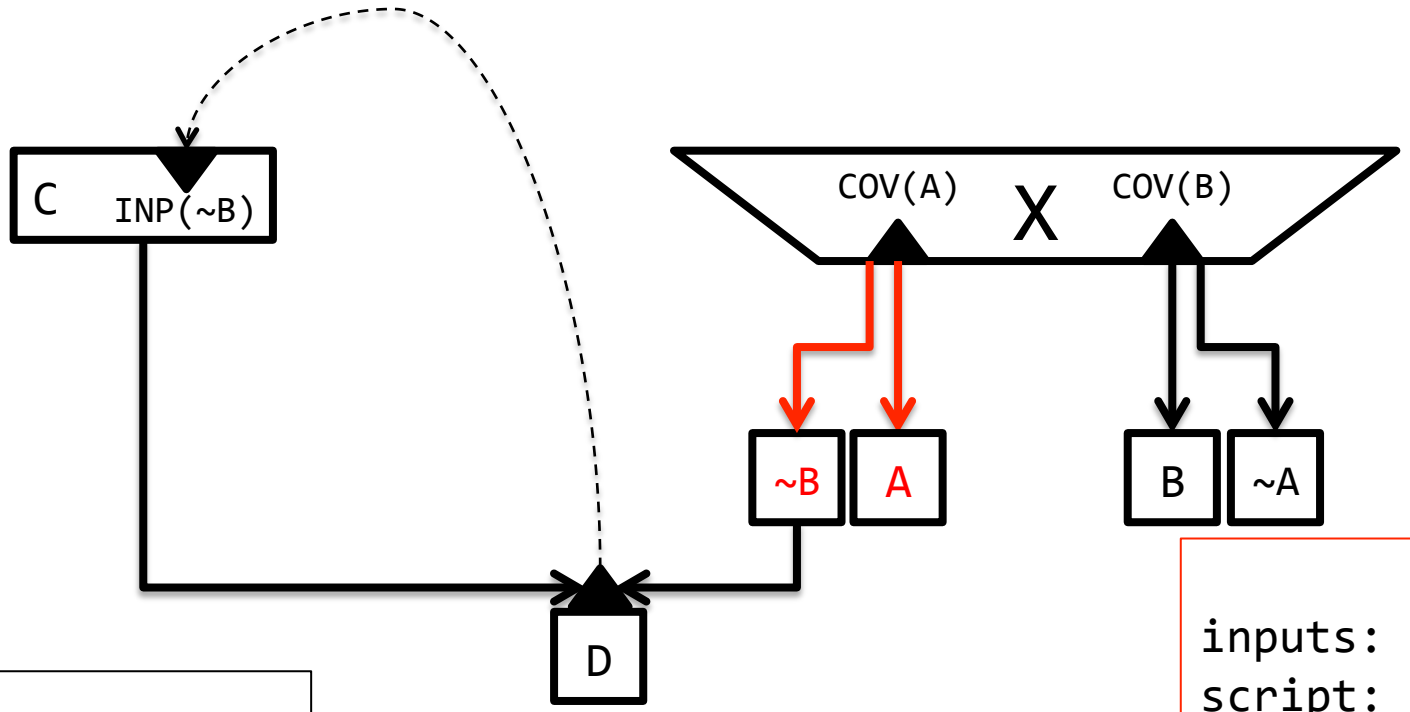
Primitives: Impossible Input Covenant (Constructive)



inputs: C, ~B
script: “…”
scriptSig: “…”
outputs: D

inputs: X
script: OP_IF
<~B, A> OP_ELSE
<B, ~A> OP_ENDI
F OP_COV
scriptSig: “…”
outputs: ~B, A

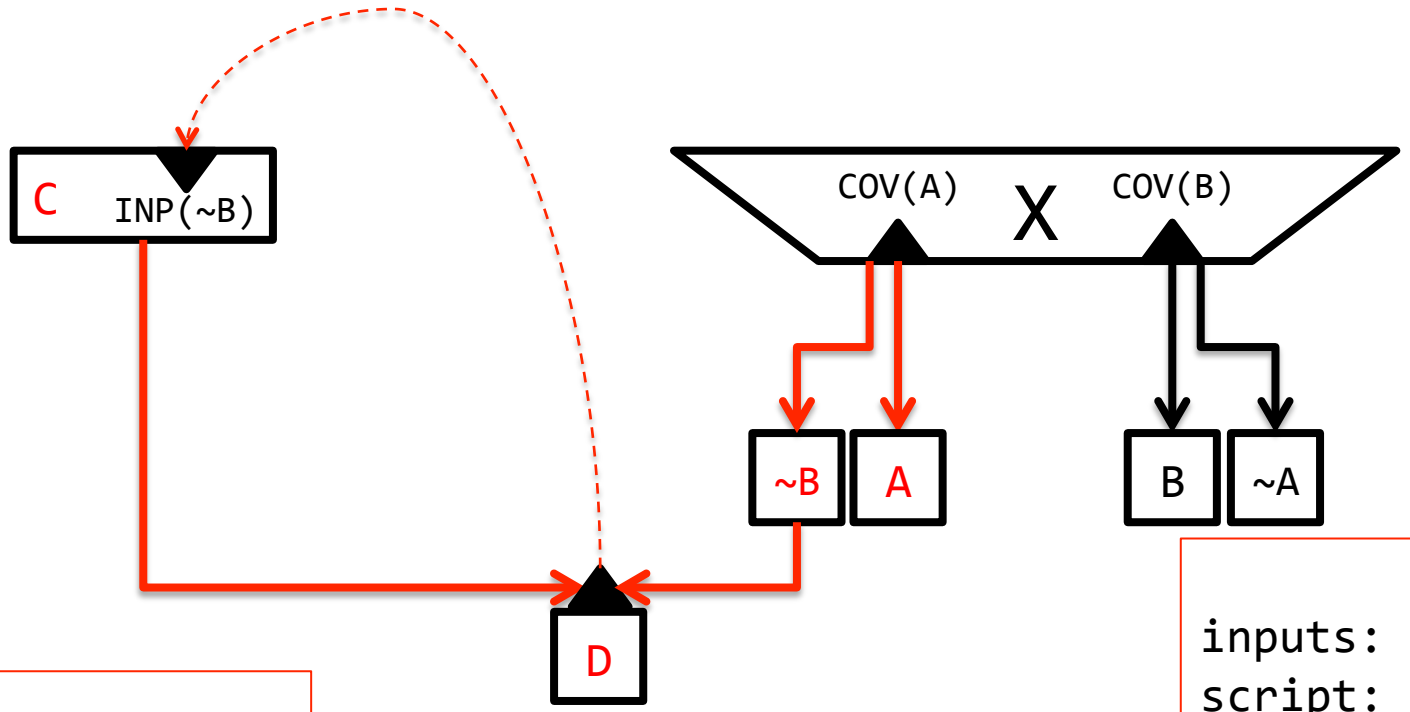
Primitives: Impossible Input Covenant



inputs: C, ~B
script: "…"
scriptSig: "…"
outputs: D

inputs: X
script: OP_IF <~B, A> OP_ELSE <B, ~A> OP_ENDIF OP_COV
scriptSig: "…"
outputs: ~B, A

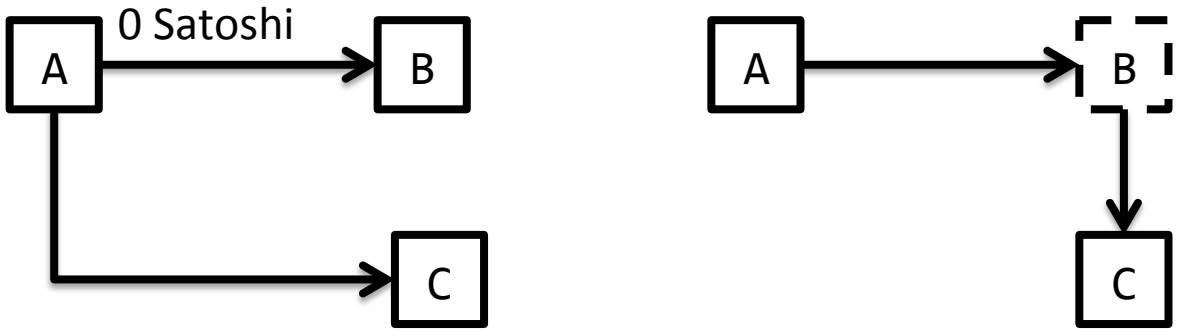
Primitives: Impossible Input Covenant



inputs: C, ~B
script: "…"
scriptSig: "…"
outputs: D

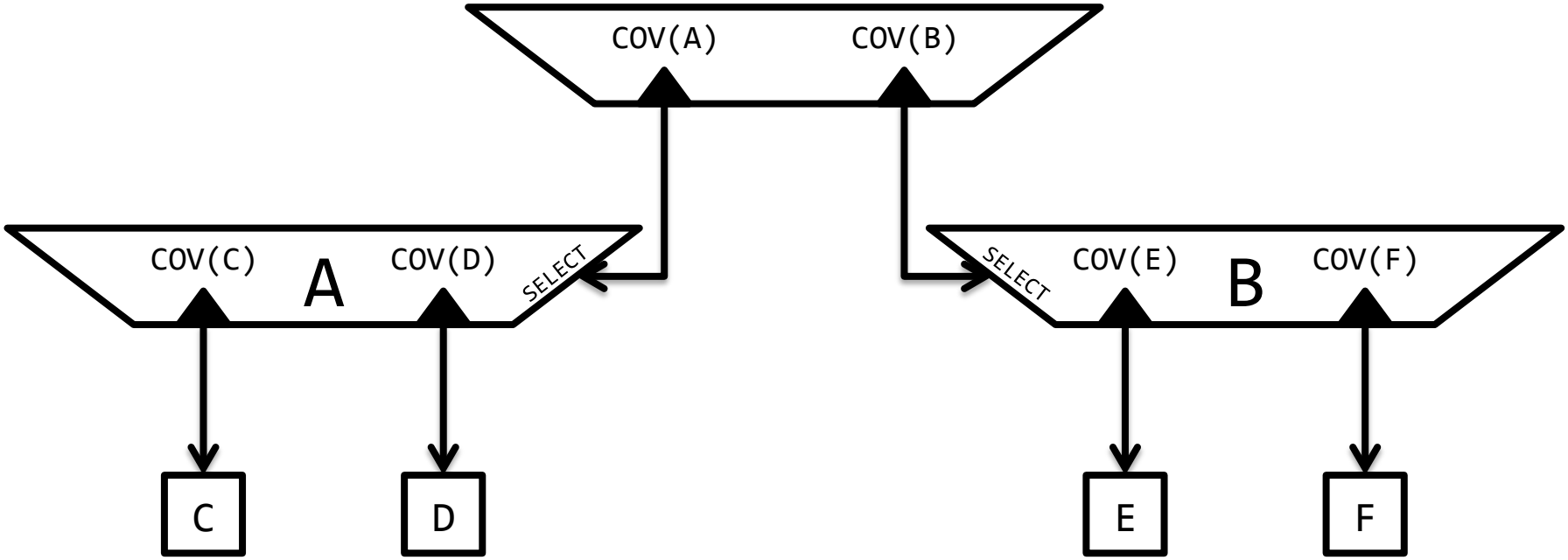
inputs: X
script: OP_IF <~B, A> OP_ELSE <B, ~A> OP_ENDIF OP_COV
scriptSig: "…"
outputs: ~B, A

Primitives: Virtual Output

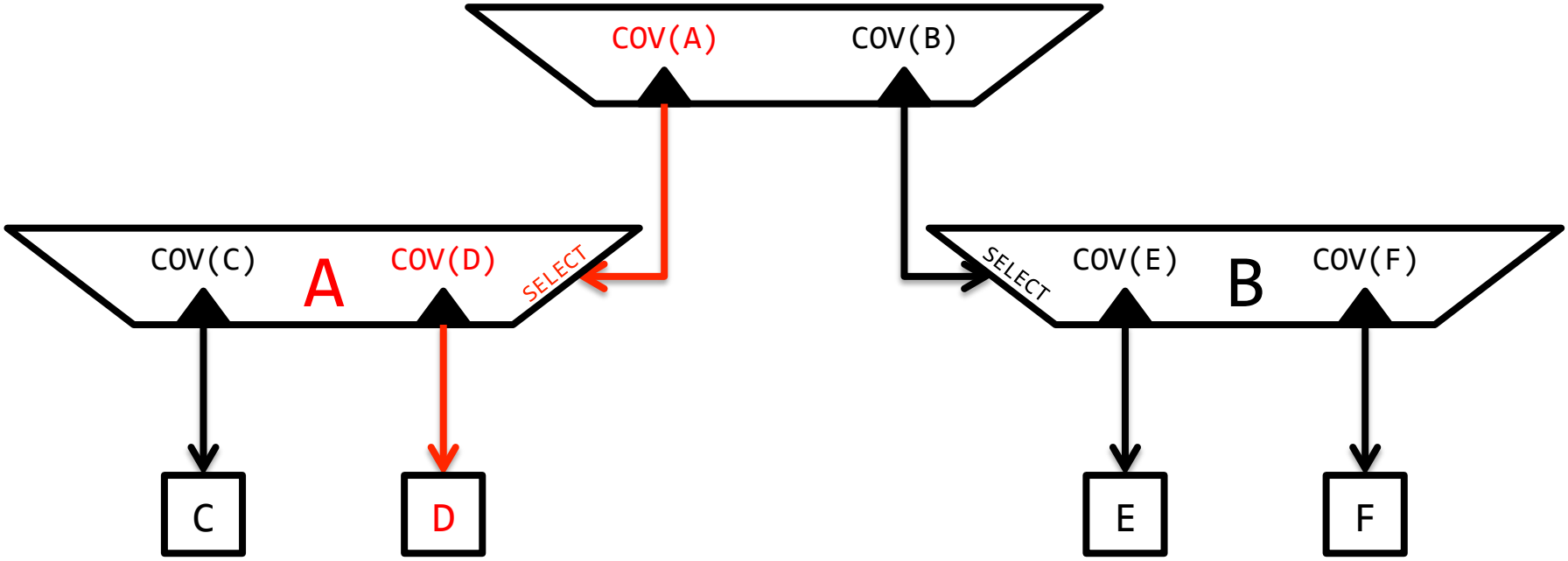


input: A
script: <index(B)> OP_IS_IUTXO
scriptSig: “…”
output: B, C

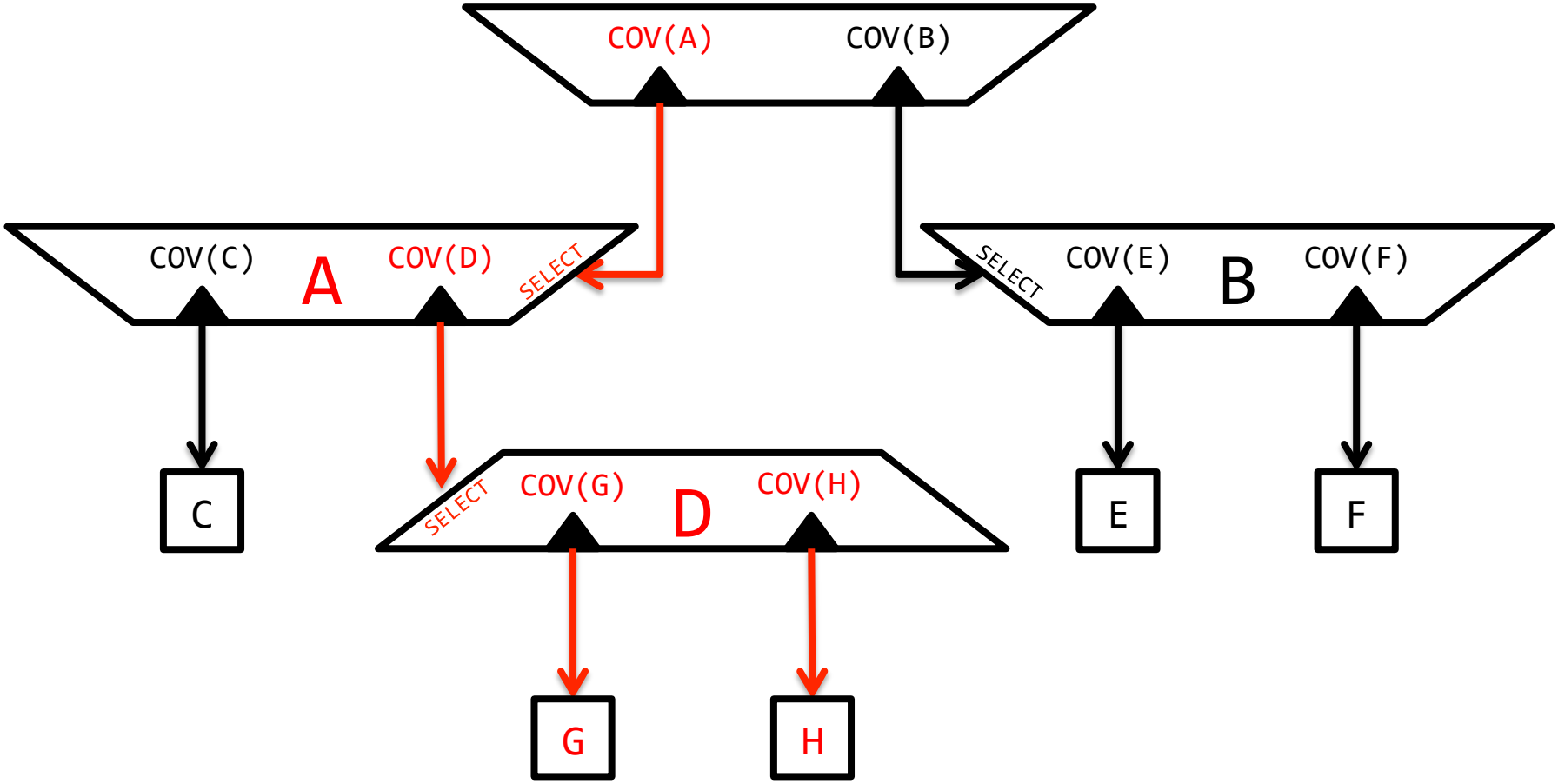
MAST



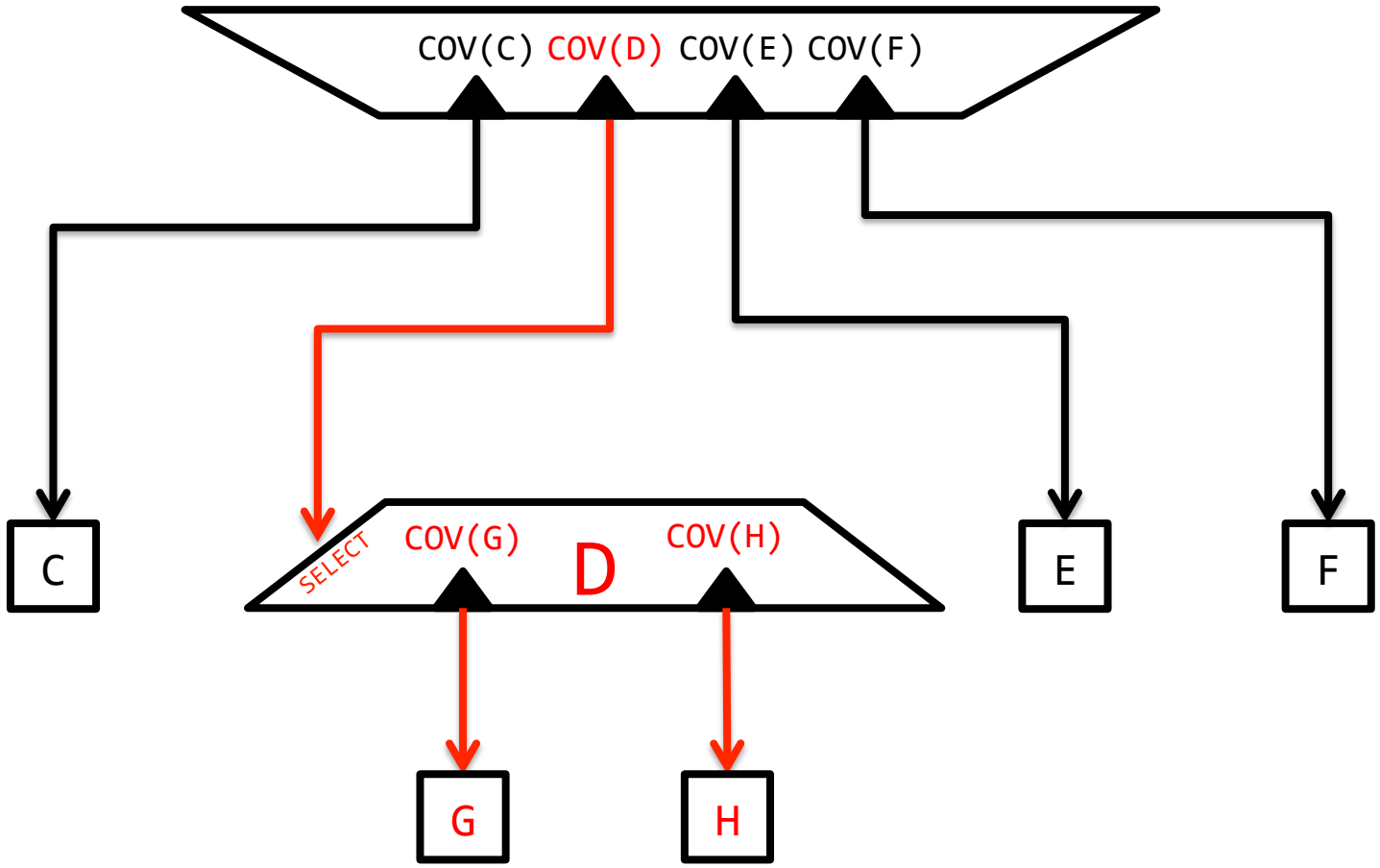
MAST Execution



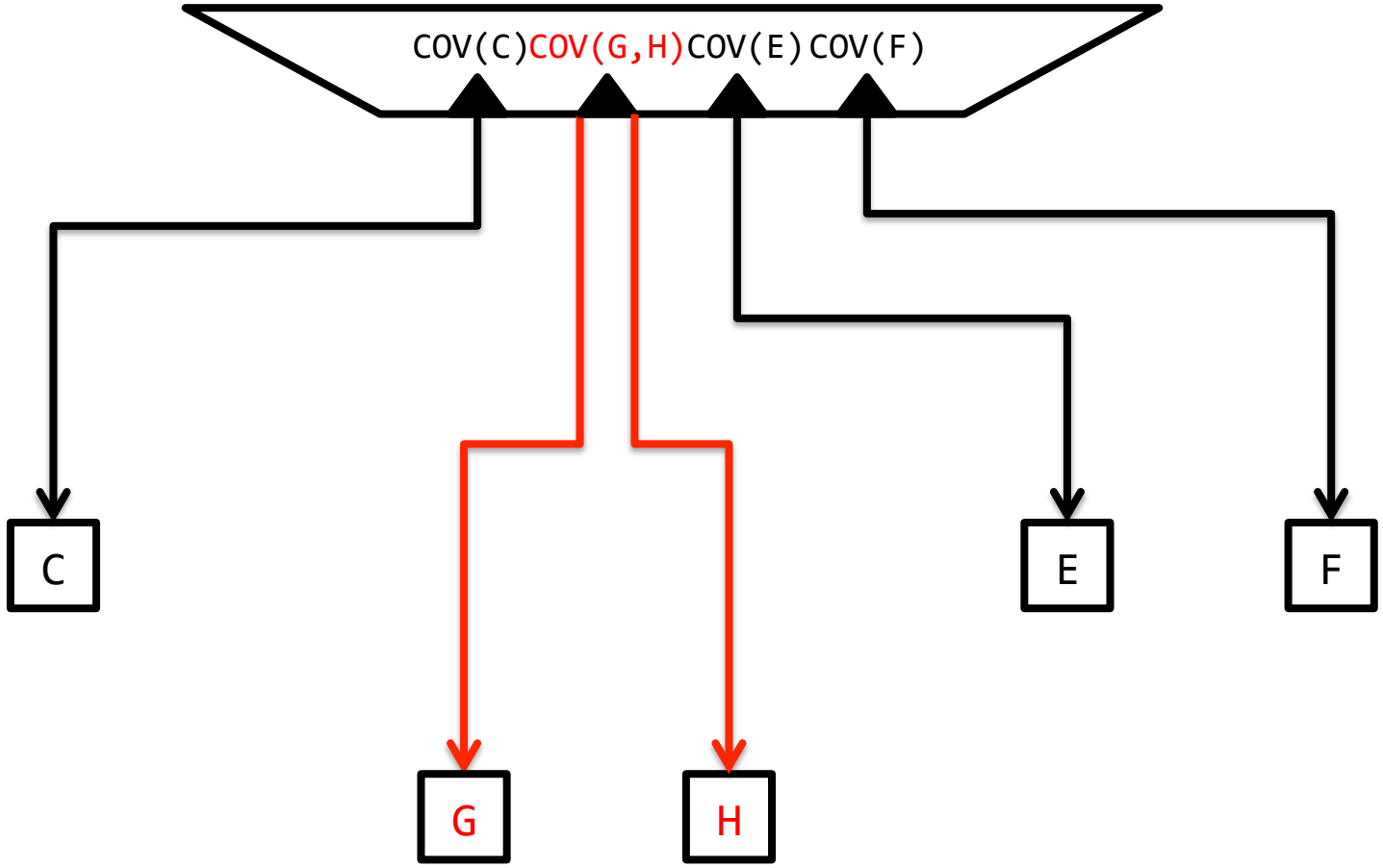
MAST


COV(A)
COV(B)
COV(C)
A
COV(D)
SELECT
SELECT
COV(E)
B
COV(F)
C
SELECT
COV(G)
D
COV(H)
E
F
G
H

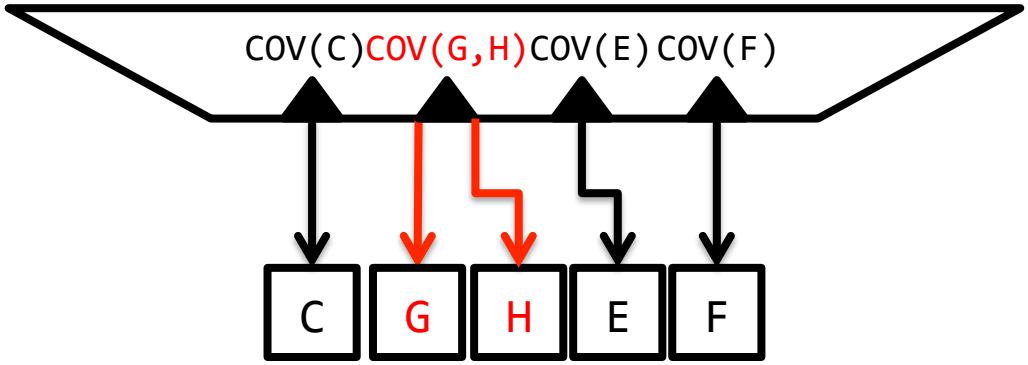
Shorthand



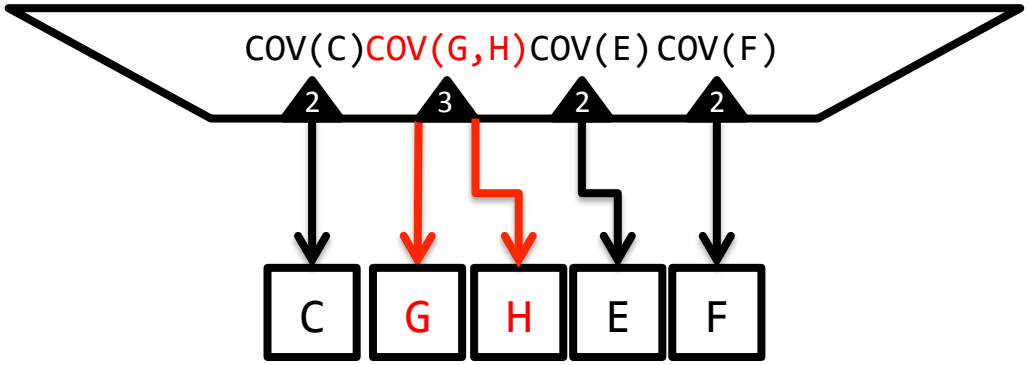
Shorthand



Shorthand



Shorthand with Depth



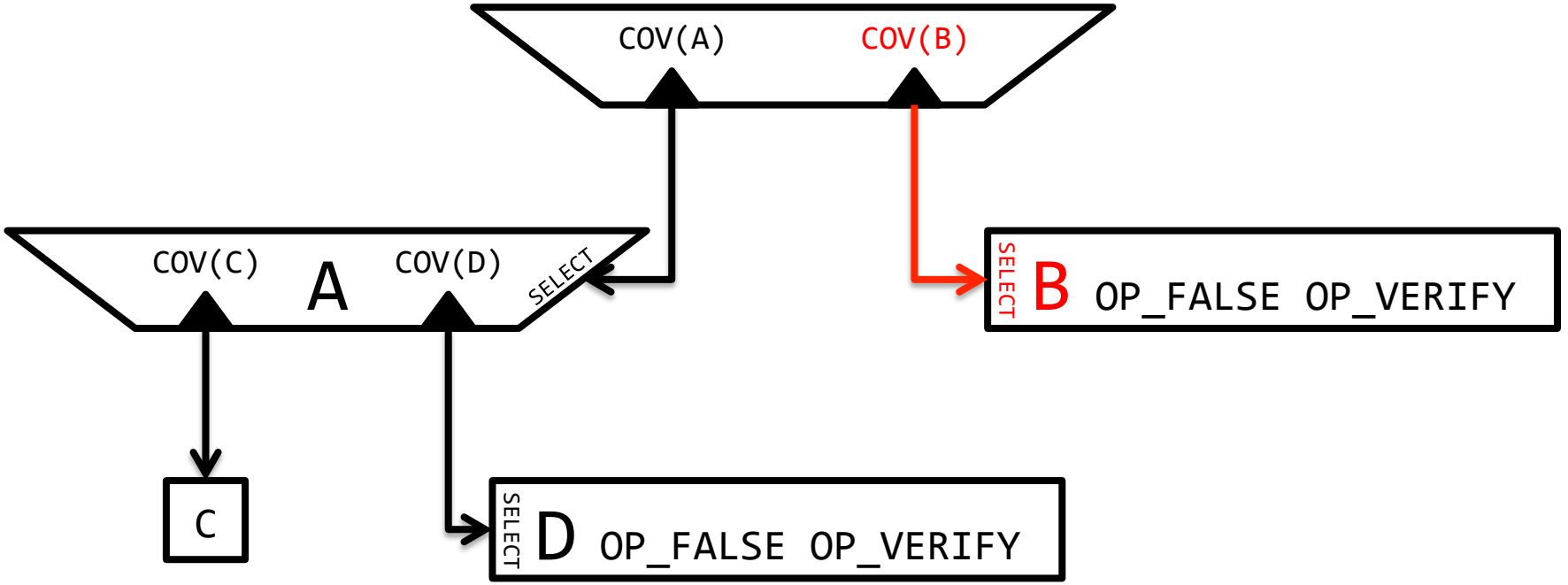
techniques for

MULTI-PHASE EXECUTION

Stuck State

- A multi-transaction contract which is stuck at a certain branch, when other branches could have avoided the stuck state
- Transactions **CANNOT** be rolled back

Stuck State


COV(A)
COV(B)
COV(C)
A
COV(D)
SELECT
SELECT
B OP_FALSE OP_VERIFY
C
SELECT
D OP_FALSE OP_VERIFY

Simply Non-Stuck

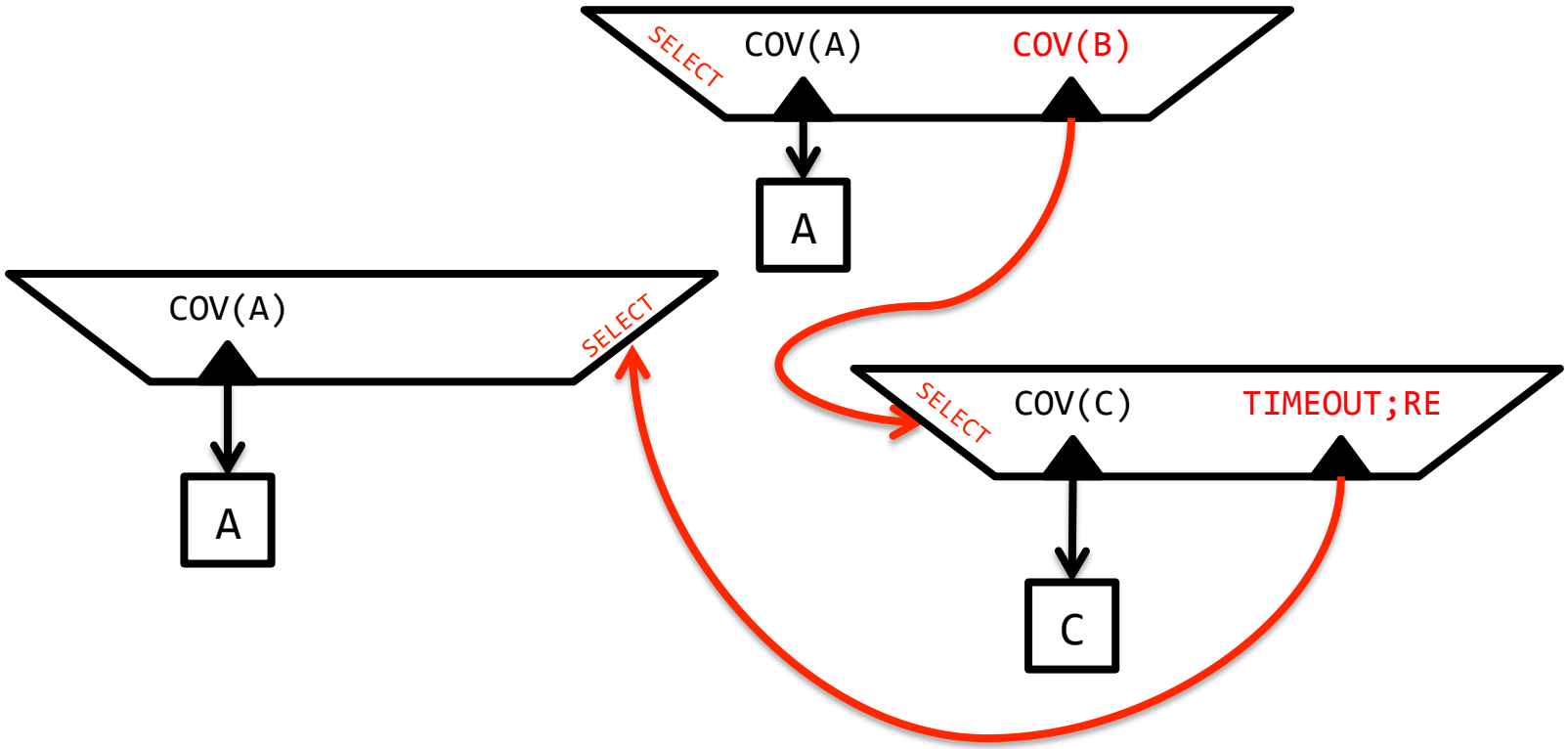
- Avoid contracts that may get stuck
  - Only use virtual/intermediate outputs

- Two-phase commits must be able to get stuck

Taken-Branch-Elimination Rollback

- [If after acceptable delay,] recreate all of a transaction's input scripts without branch taken
- Finite (no looping)
- No New Opcode
- Drawback: Program Size

Taken-Branch-Elimination Rollback



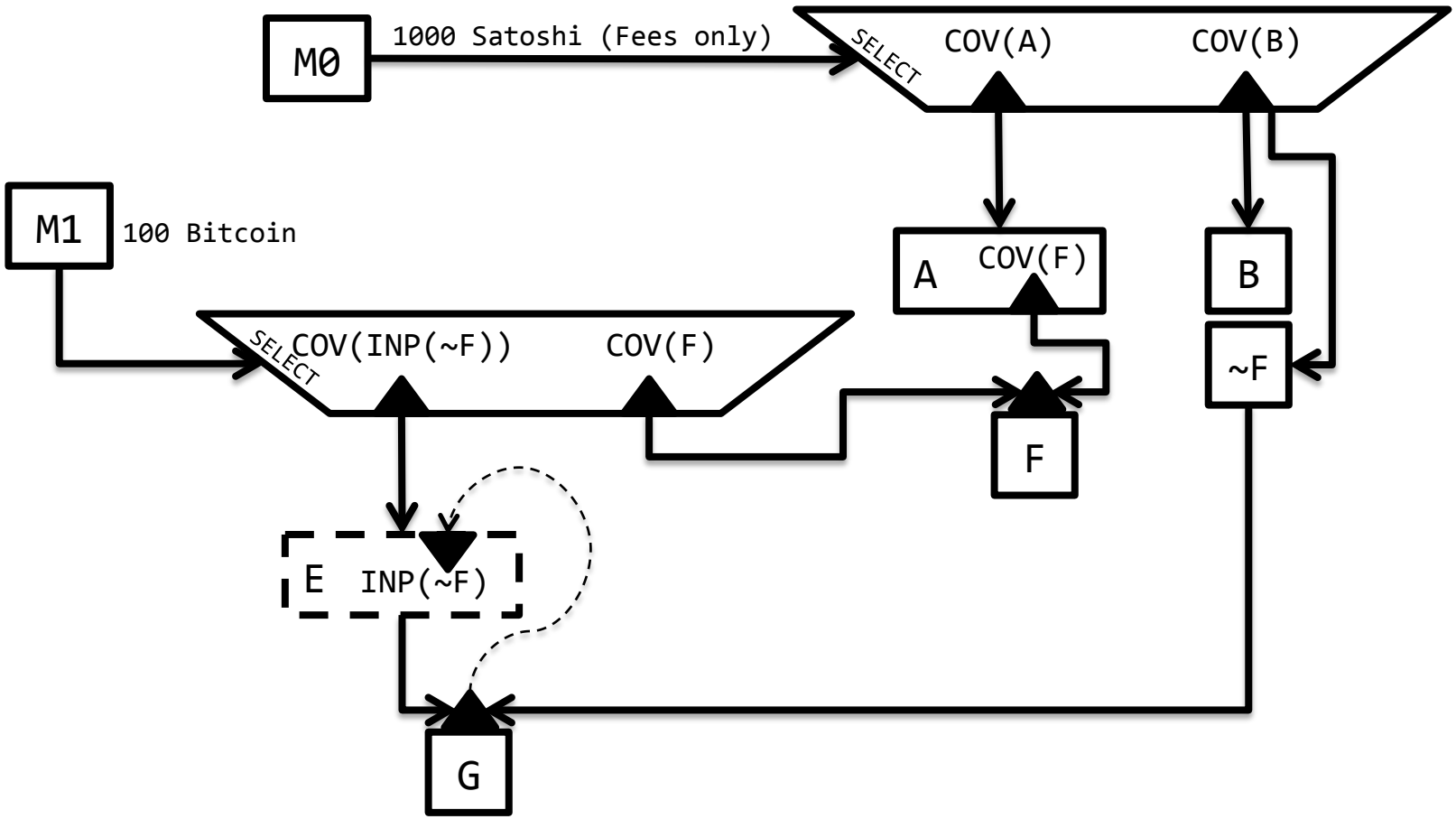
Safe High Voltage Switching

- Ask an Electrical Engineer how they keep high voltage circuits with low voltage control separate
  - Optical Isolation!

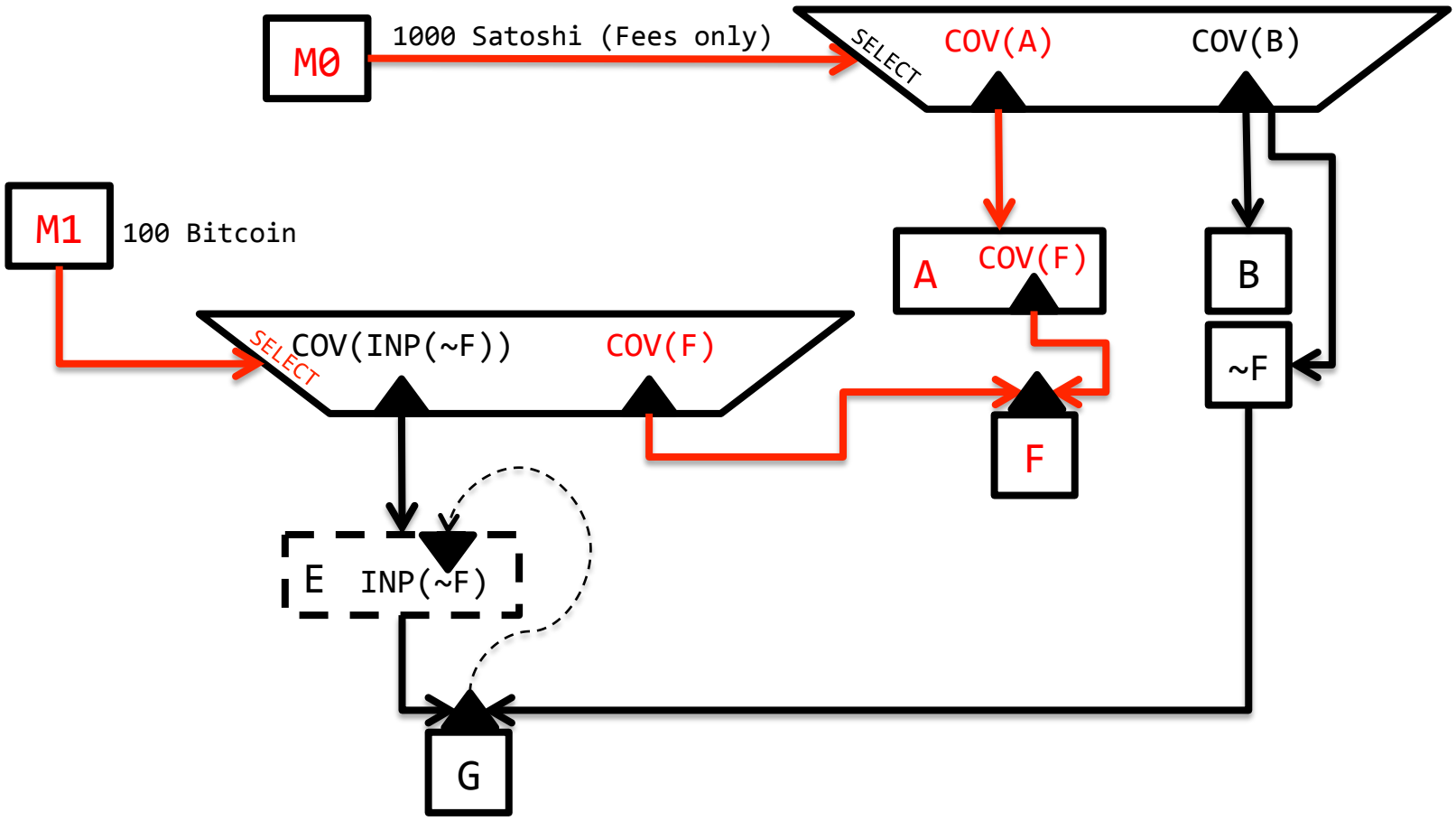
Optical Isolated Contracts

- Use separate control flow for access control and value
- Impossible input covenants ensure fund usage with protocol

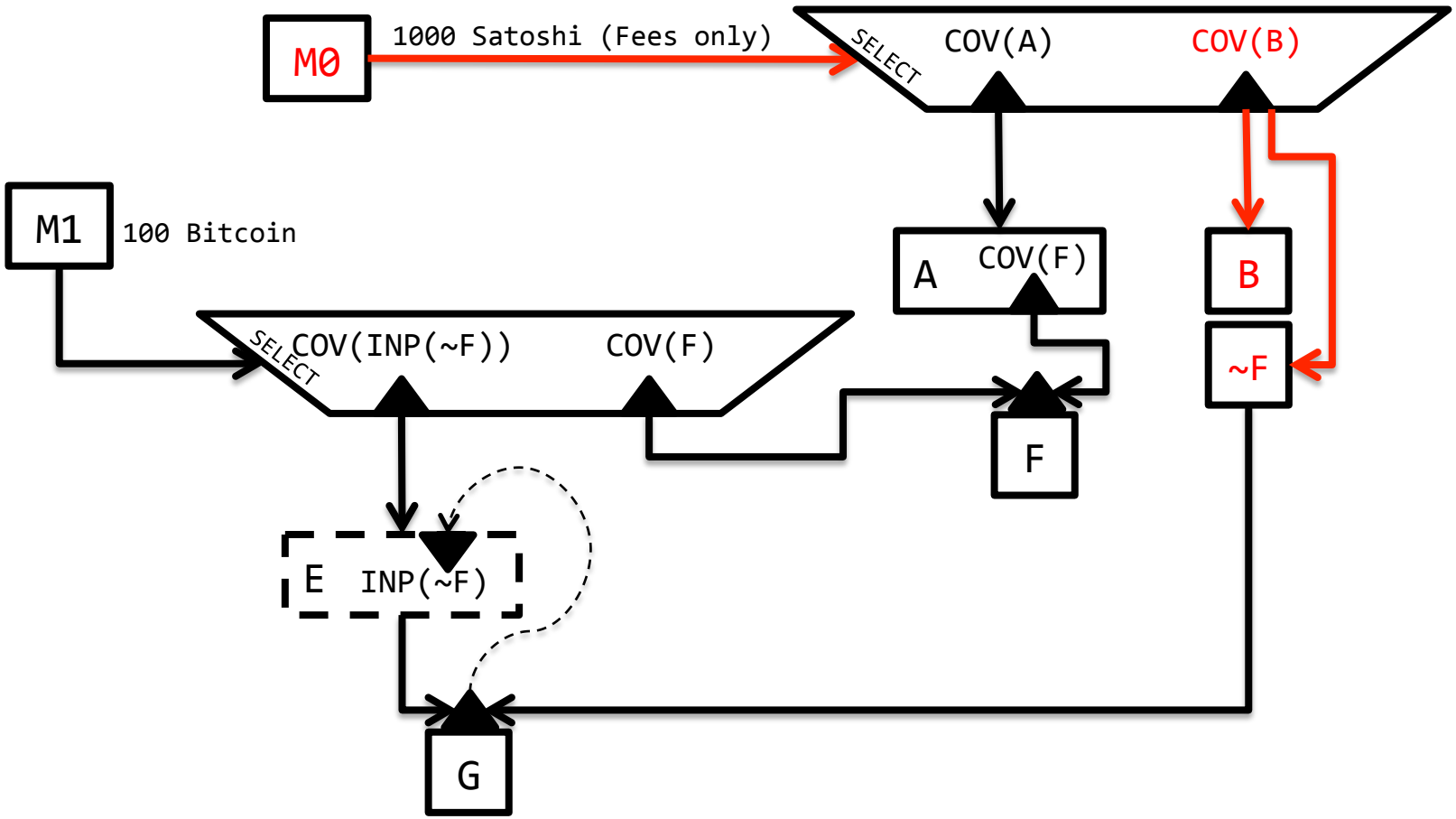
Optical Isolated Contracts



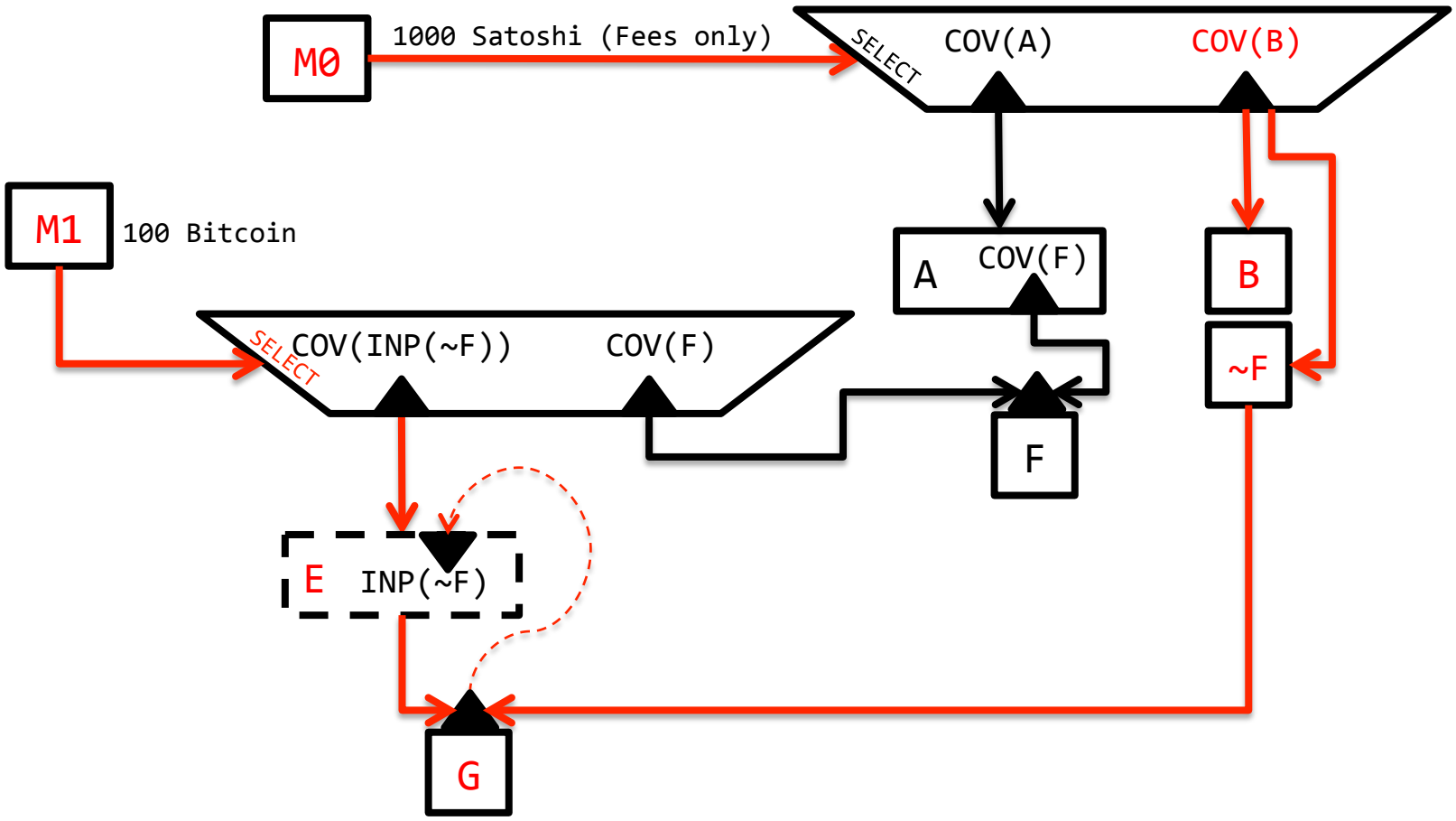
Optical Isolated Contracts



Optical Isolated Contracts



Optical Isolated Contracts



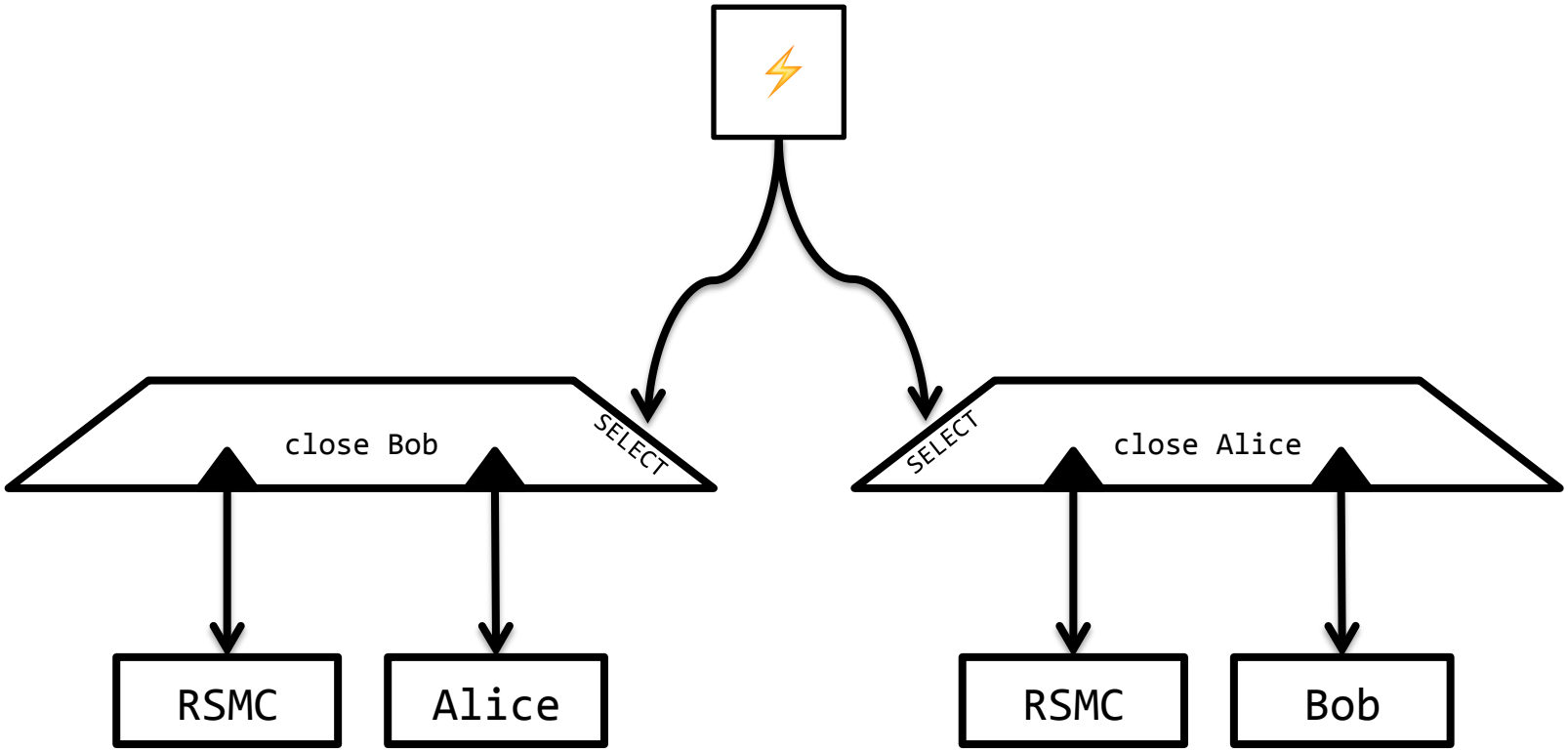
The Deli Problem

- You want to buy some deli-meats and prepared foods
  - But the line is blocking the counter
  - Deli-number congestion control?

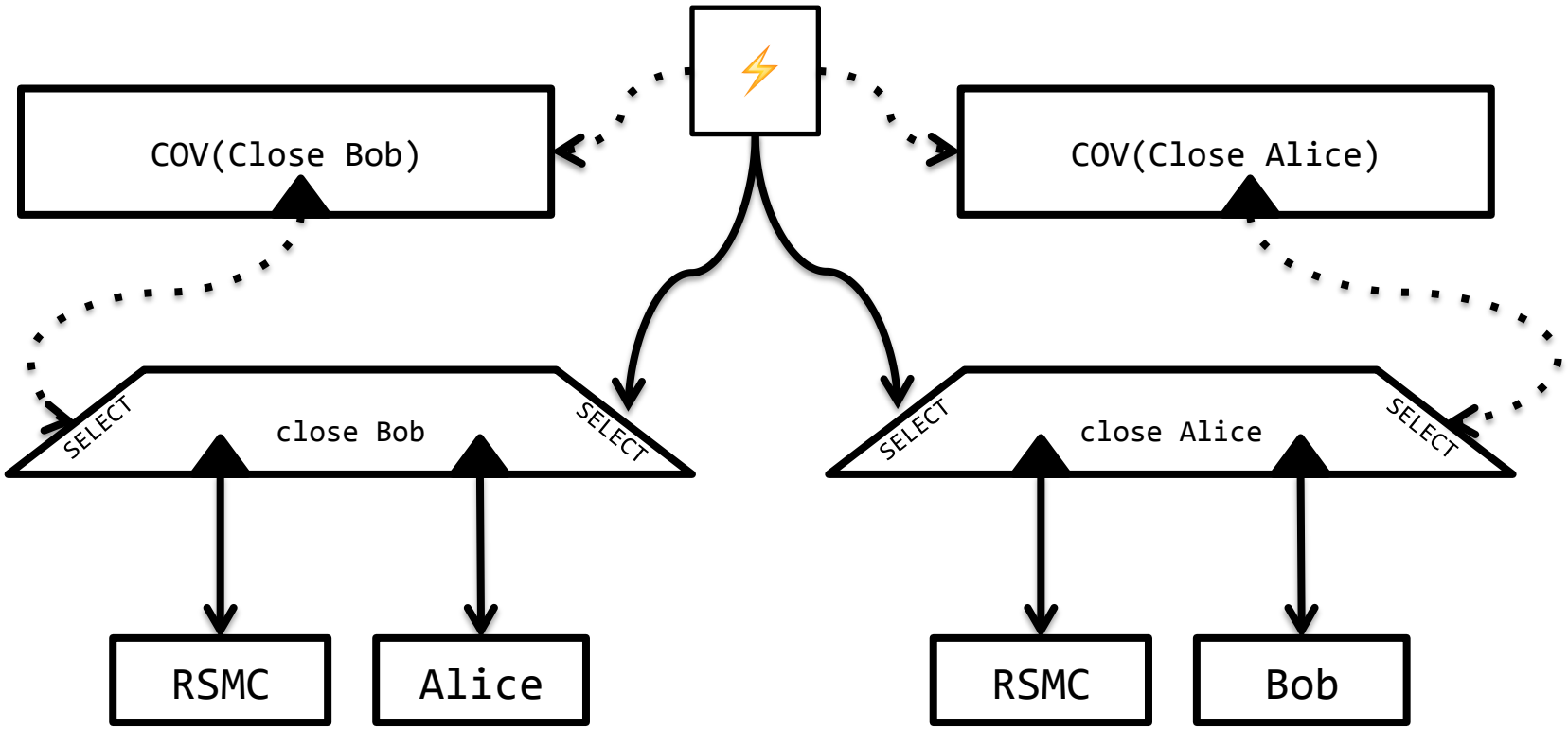
Congestion Control

- Suppose you have a time sensitive close operation
- Do a cheap “commit-close” txn
- More expensive close when excess bandwidth available
  - size(COV CLOSE) < size(CLOSE)
- Send both to miner, they can choose!
- Overall, more expensive, but faster

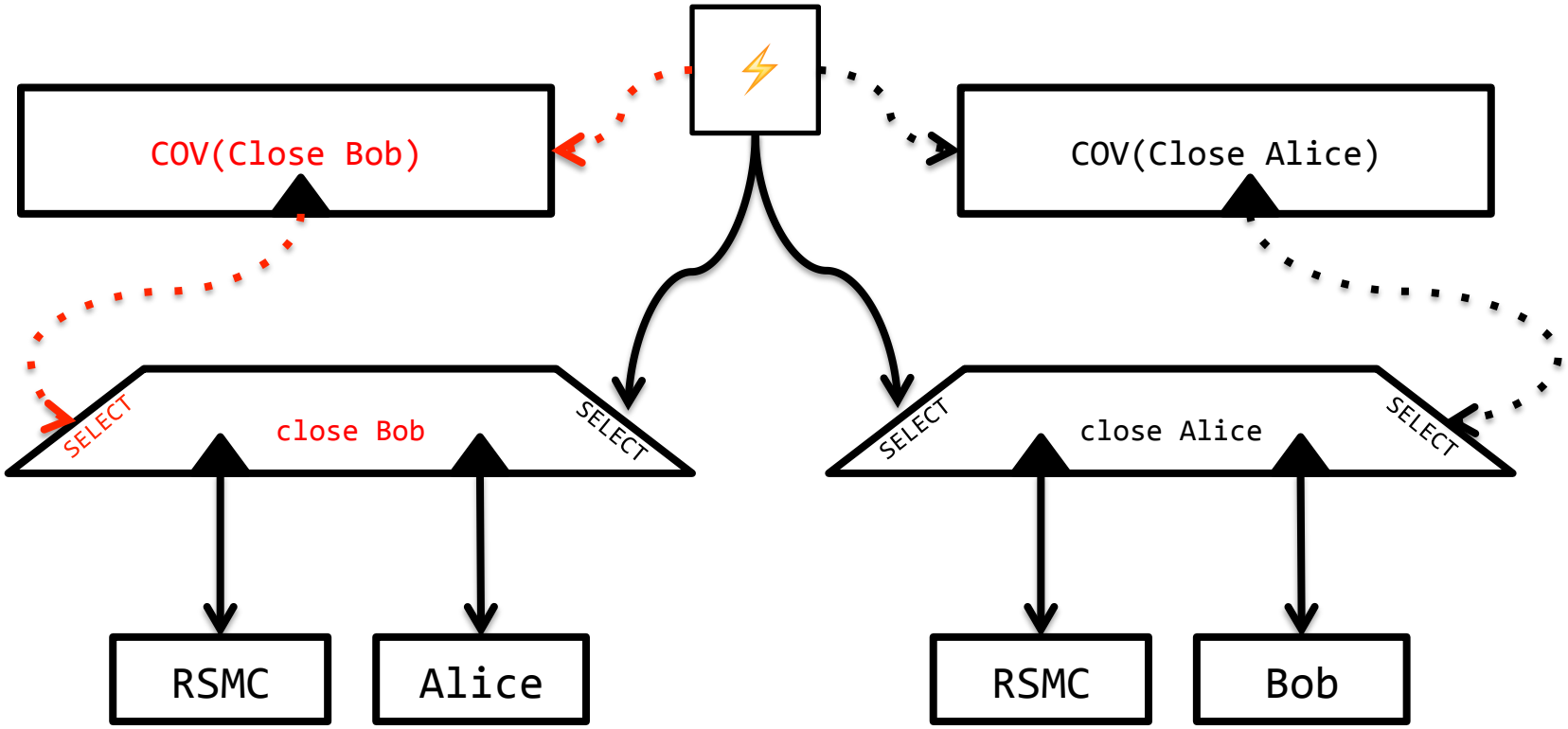
Congestion Control



Congestion Control



Congestion Control



Etc

- Inductive Execution
  - Start from the last transaction up
- Single Induction Execution
  - run forward, except for first step run as above
- Rate Limited Rollback
- Traditional M-of-N timeouts

Quality of Service Matters

- We can’t just make protocols more resource-efficient, we need to make them work better when resources are constrained

“Secure Contracts Isolate Value”

- Give your friend the keys to your car
  - but not the garage door opener
  - because you can open the garage door from your phone
- That Bitcoin transaction propagate value makes incentives harder

Covenants Are Not Evil

- There are strong reasons to fear general-purpose covenants, but they still are worth consideration
- VUTXO-only COV is low risk

Bitcoin Must Pick Battles

- Tension between security and complexity
- Keep scripts simple predicates!
- Better higher-order inter-output interaction may be safer