Randomness beacons in theory and practice

Joseph Bonneau

Real World Crypto
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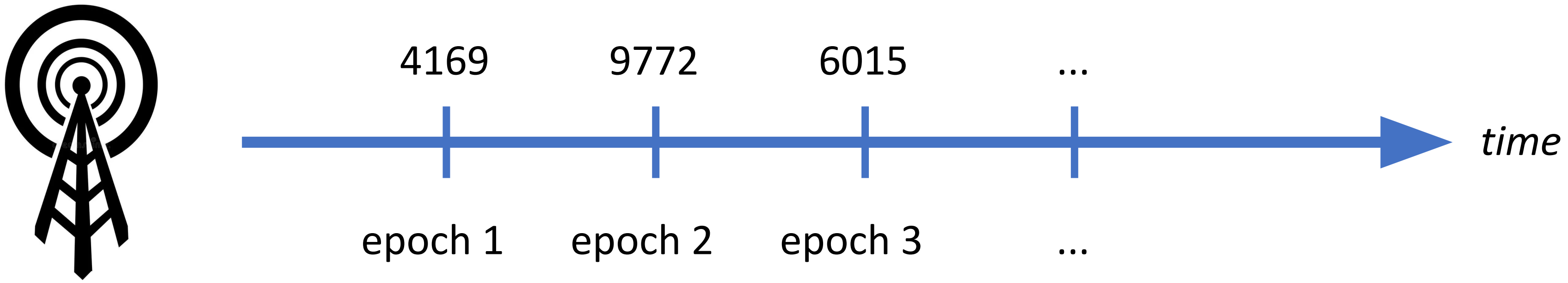
The *randomness beacon* abstraction [Rabin83]



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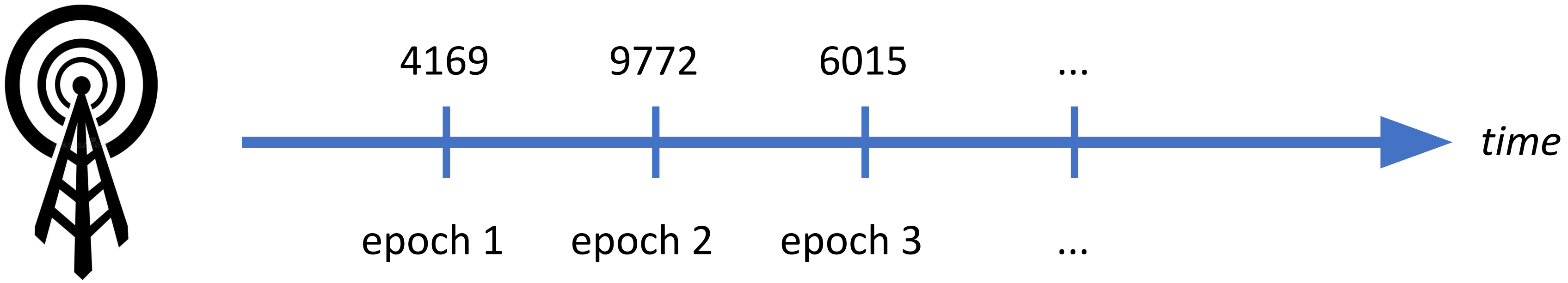
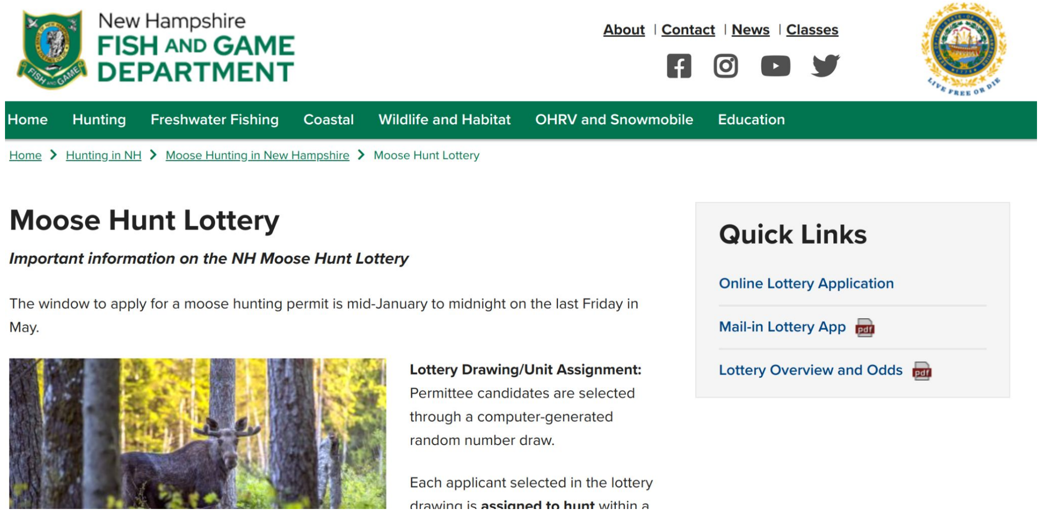


Goals (high level):

- Statistically uniform randomness
- Public consensus on values
- Regular service, high bandwidth
- Attackers can't:
  - Predict
  - Manipulate
  - Block

Beacons can power verifiable lotteries



Many use cases beyond lotteries

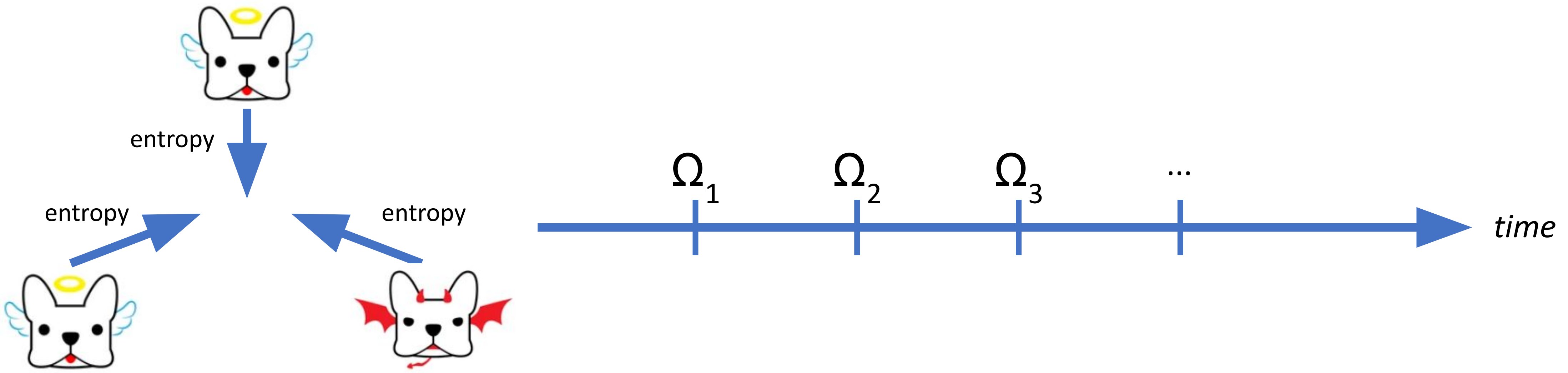
- Games
- Sampling ballots for election audits
- Selecting parameters for cryptographic protocols
- Leader election in BFT consensus & blockchains
- Randomized transaction ordering
- Challenges for non-interactive cryptographic proofs

Goal: Many applications driven by a public randomness beacon

State of the art has barely changed for millenia!

This talk: *distributed* randomness beacons

- Multiparty protocol with n participants, produce output Ω_i in epoch i
- Up to t out of n nodes are controlled by the adversary



Classic: Commit-Reveal

1. Commit
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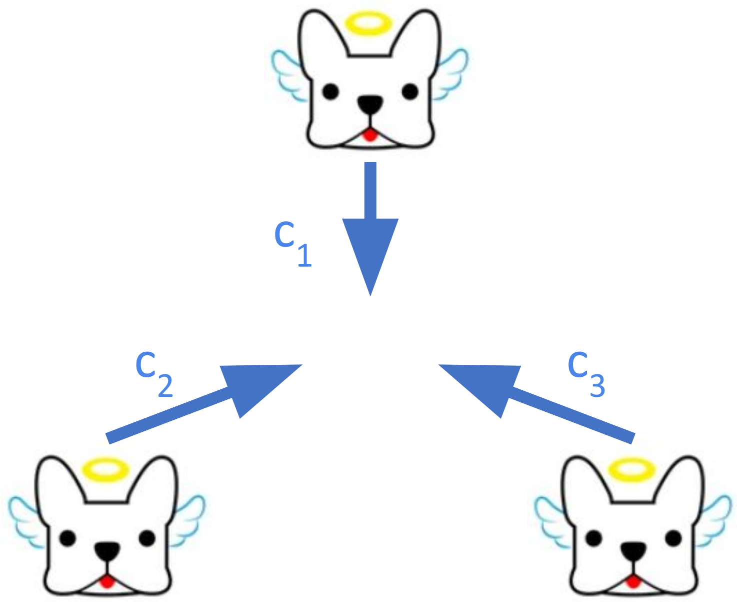
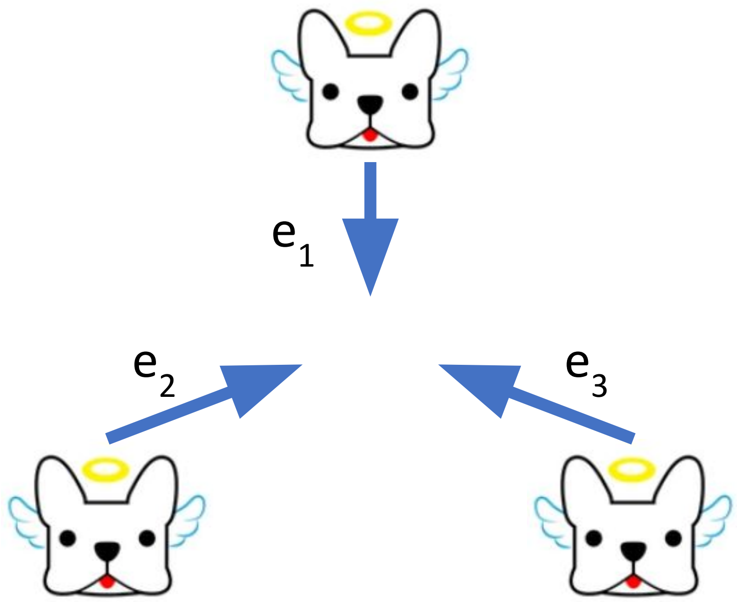


Classic: Commit-Reveal

1. Commit
   - Publish a cryptographic commitment $c_i = Commit(e_i)$ to a random value e_i
2. Reveal
   - Participants reveal their e_i values

Beacon output: $\Omega = \Sigma\, e_i$



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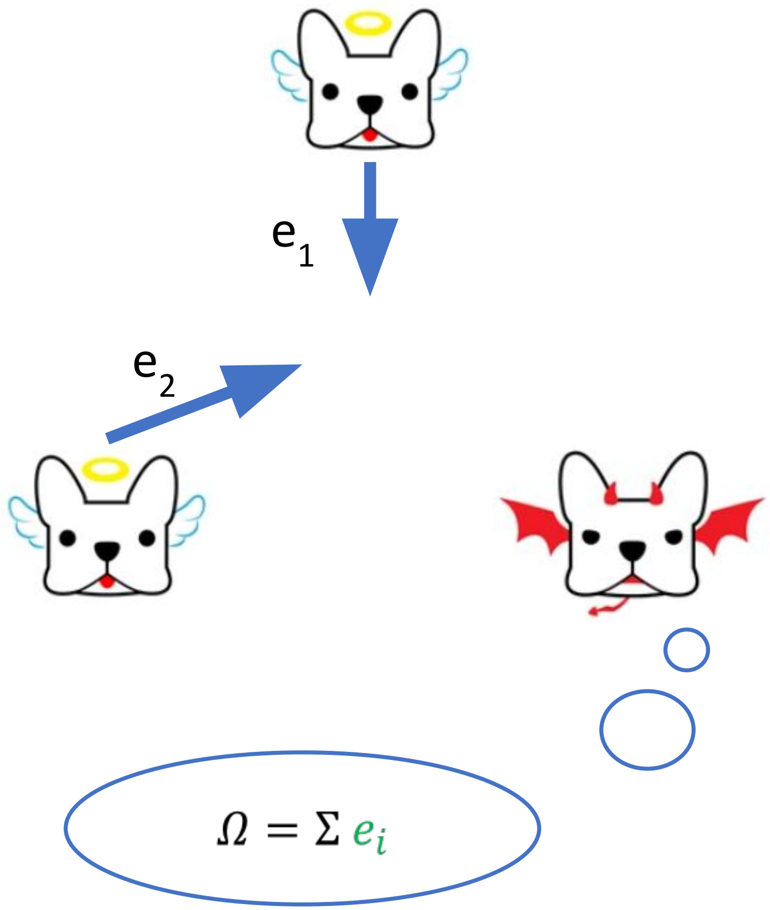

<u>Main problem: last-revealer attack</u>

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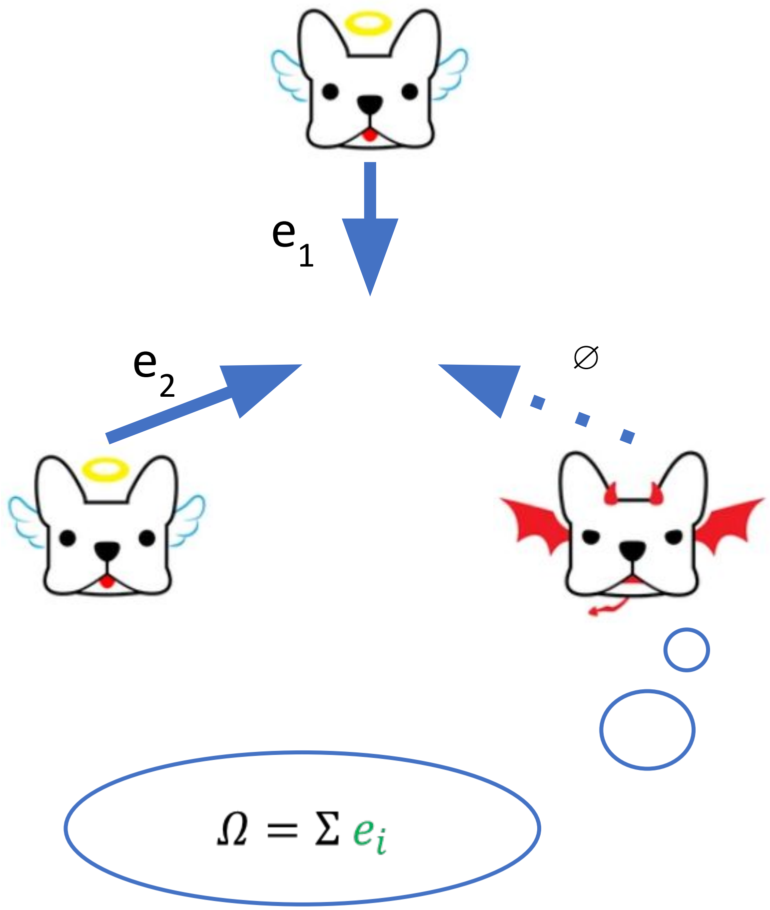

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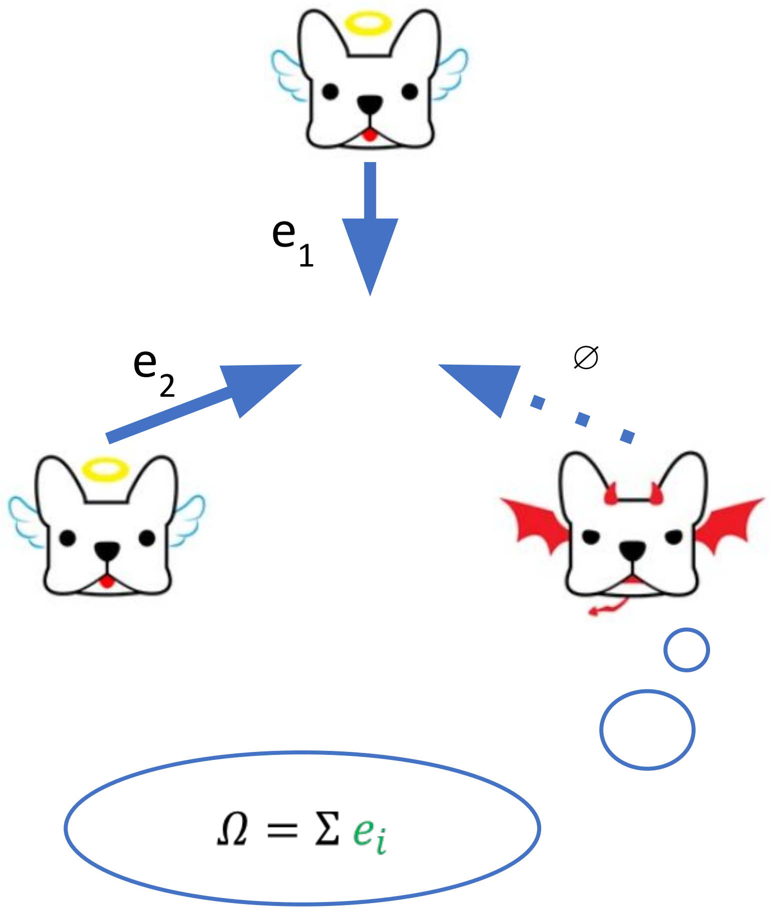

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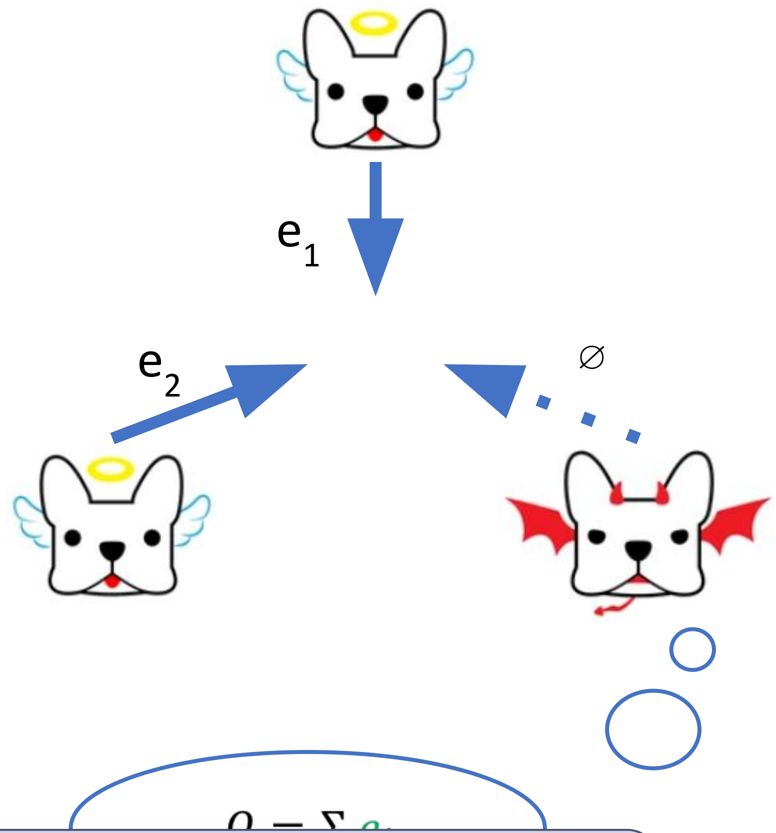
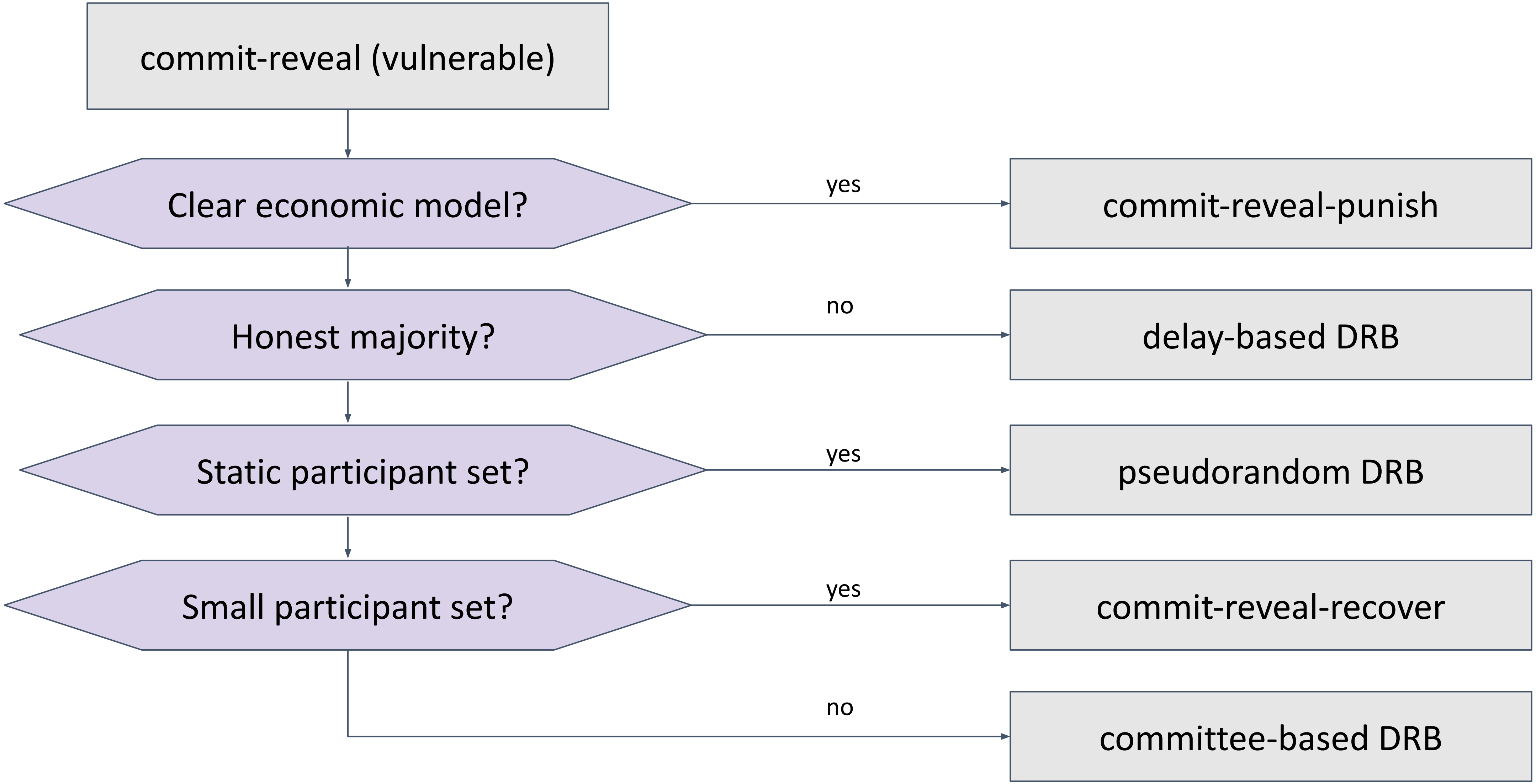


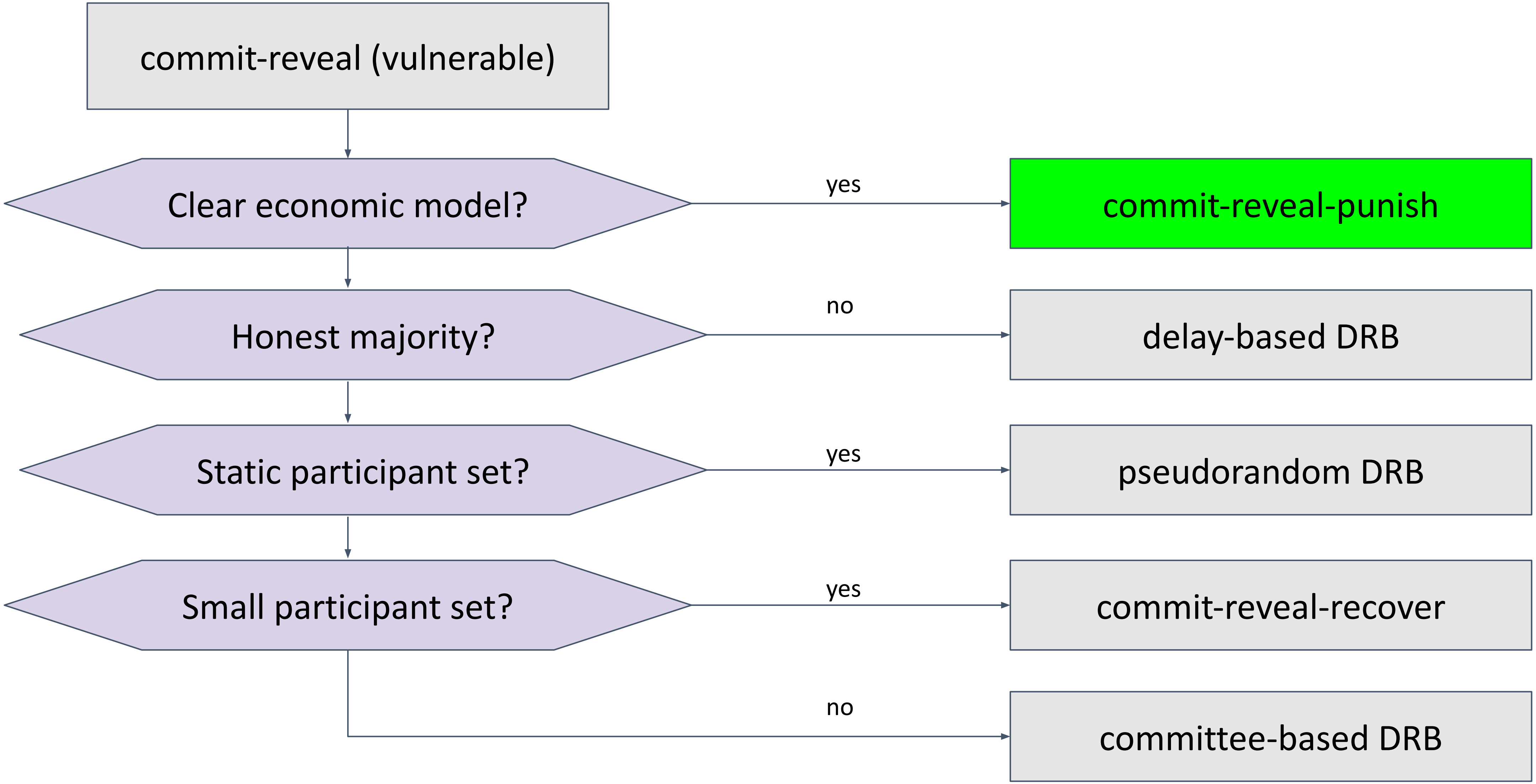
Main problem: last-revealer attack

All DRBs are essentially **patches to the last revealer attack**

DRB design flow chart

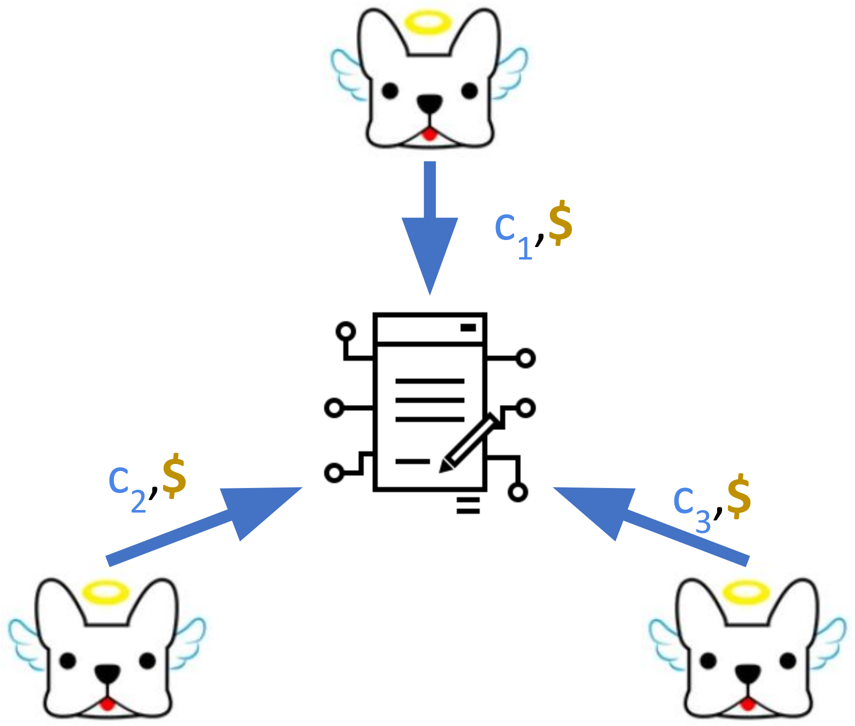


DRB design flow chart



Commit-reveal-punish

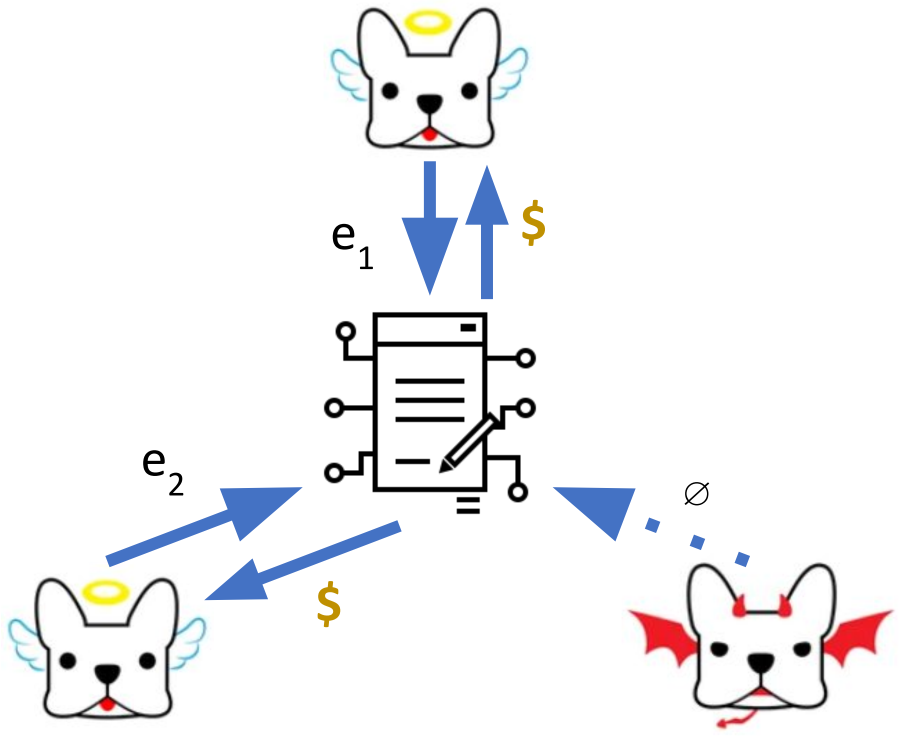
1. **Commit/deposit**



Commit-reveal-punish

1. **Commit/deposit**

2. **Reveal + refund**
   a. Participants who don't reveal lose funds
   b. Restart if any participant aborts



Commit-reveal-punish

- **Advantages**
  - efficient
    - O(n) communication, compute
  - easily implemented

- **Cons**
  - Requires capital lockup
  - Benign faults must be punished
  - Hard to bound attacker utility if beacons have multiple purposes

Commit-reveal-punish: RANDAO

ethereum

- Deployed in Ethereum since 2020
  - Used for committee selection
- Also available to smart contracts
  - `block.prevrandao`
- Proposer can reveal VRF or withhold
  - Withholding precludes block reward
- Withholding is profitable! [AW24]

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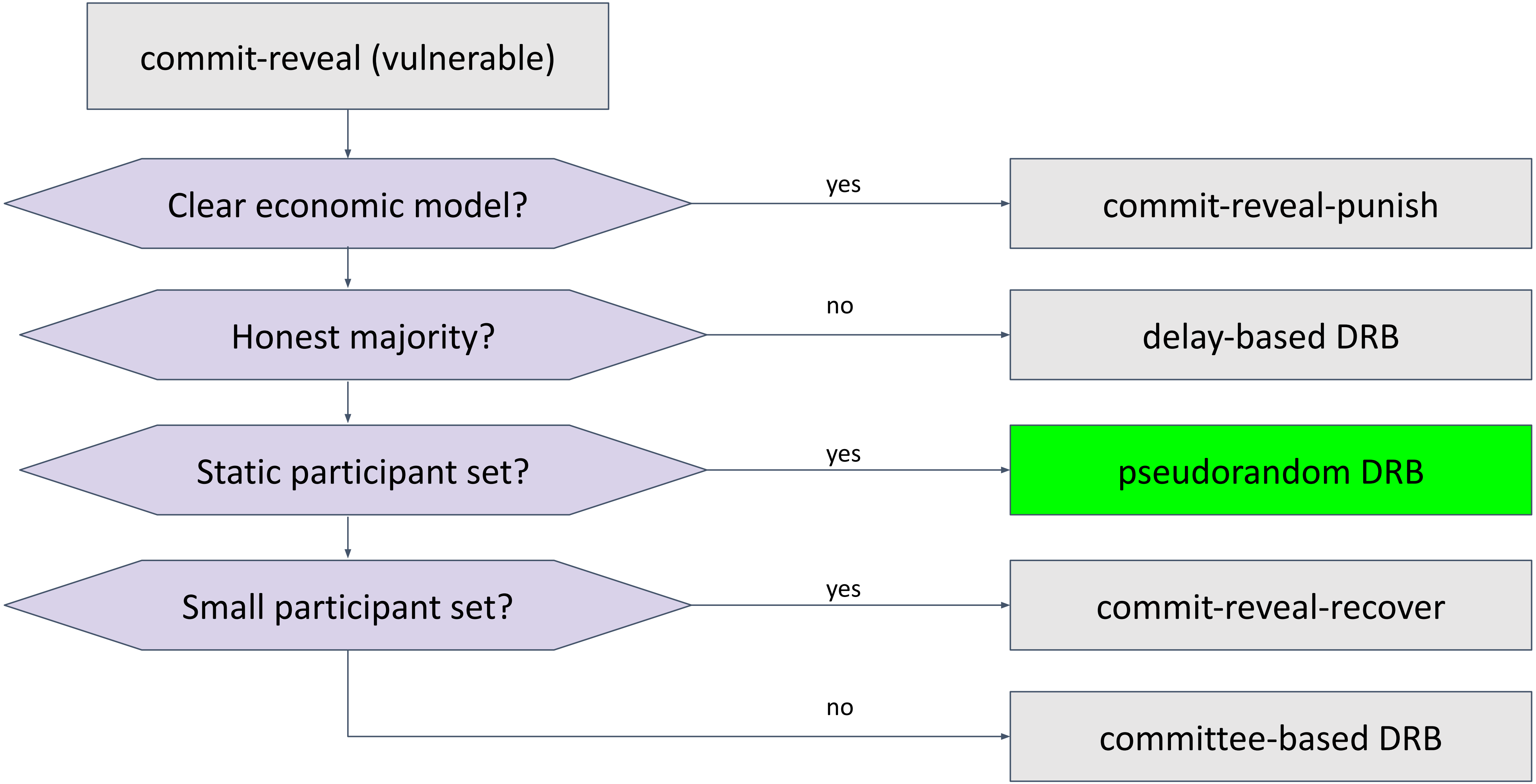
α	optimal reward
1%	1.00107%
5%	5.04834%
10%	10.18807%
15%	15.39960%
20%	20.67770%
25%	26.02472%
30%	31.45164%
35%	36.97348%
40%	42.62435%
45%	48.49184%

Optimal RANDAO Manipulation in Ethereum.
Kaya Alpturer, S. Matthew Weinberg. AFT 2024.

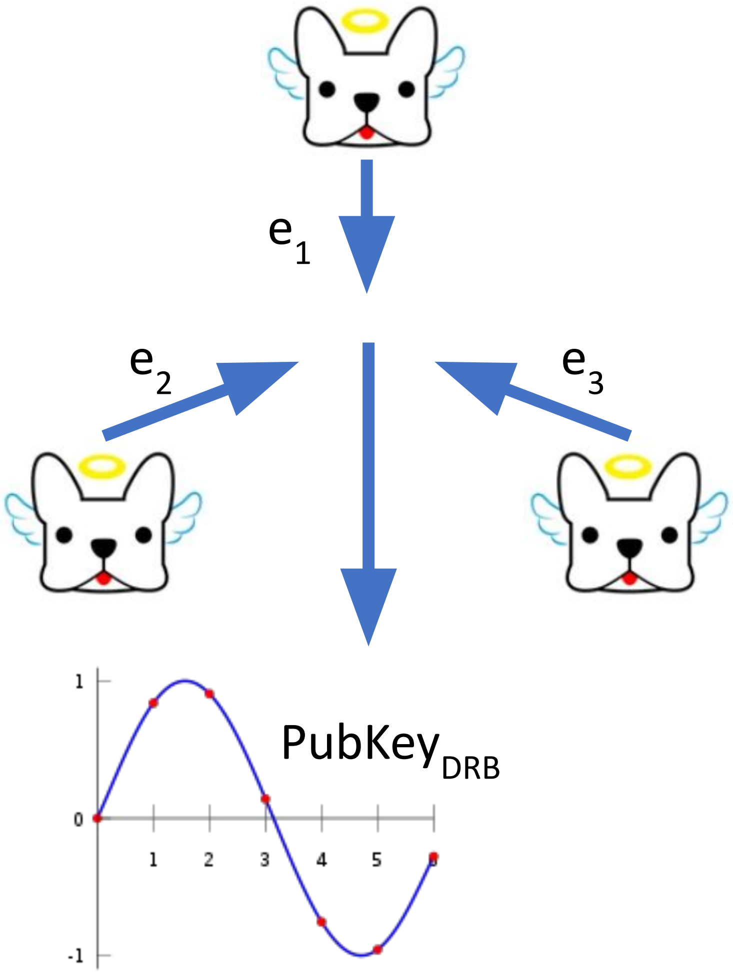
DRB design flow chart



Pseudorandom DRBs

1. **Setup**
   a. Output is *t*-out-of-*n* secret-shared VRF key
   b. Can be distributed setup (DKG) or centralized

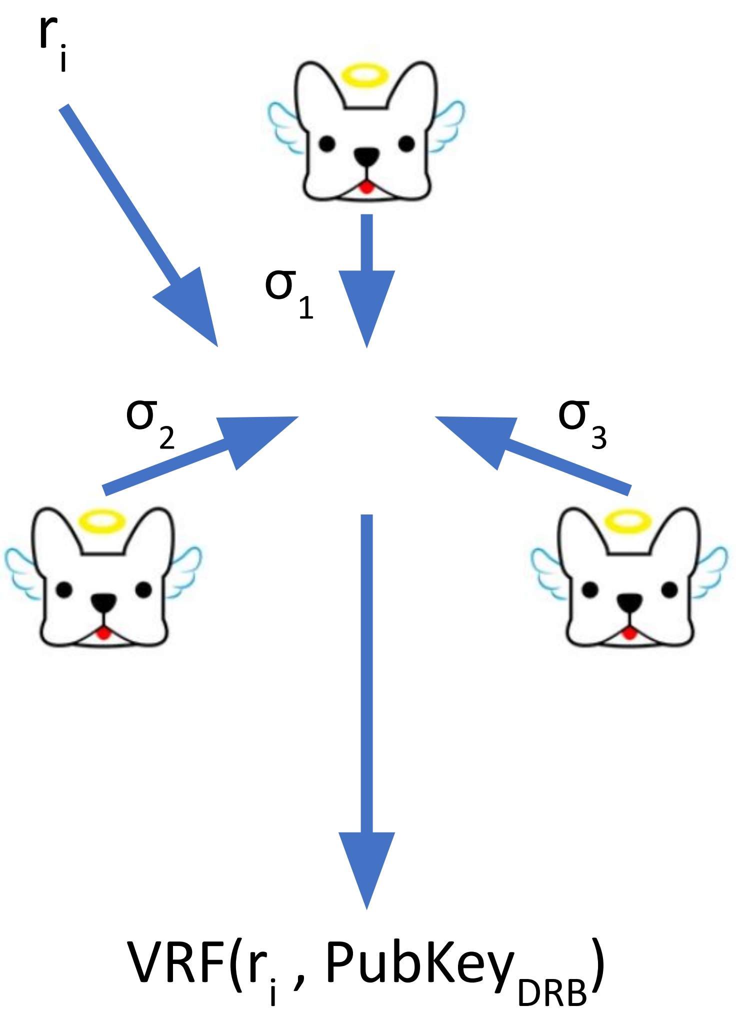
Setup itself must be a DRB!



Pseudorandom DRBs

1. **Setup**
   a. Output is *t*-out-of-*n* secret-shared VRF key
   b. Can be distributed setup (DKG) or centralized

2. **Output**
   b. Compute VRF on round input r_i
   c. Can be static (epoch number) or prior Ω
   d. Collect partial VRF evaluations
   e. Combine to output distributed VRF



Pseudorandom DRBs

- **Advantages**
  - Efficient
    - O(n) communication, compute
  - Dishonest majority cannot manipulate
    - Can only predict or stall

- **Challenges**
  - If *t* needed to compute, *n-t* can block liveness
  - Malicious coalition can predict infinitely far into the future
  - No recovery from compromise
    - Prudent to periodically re-key

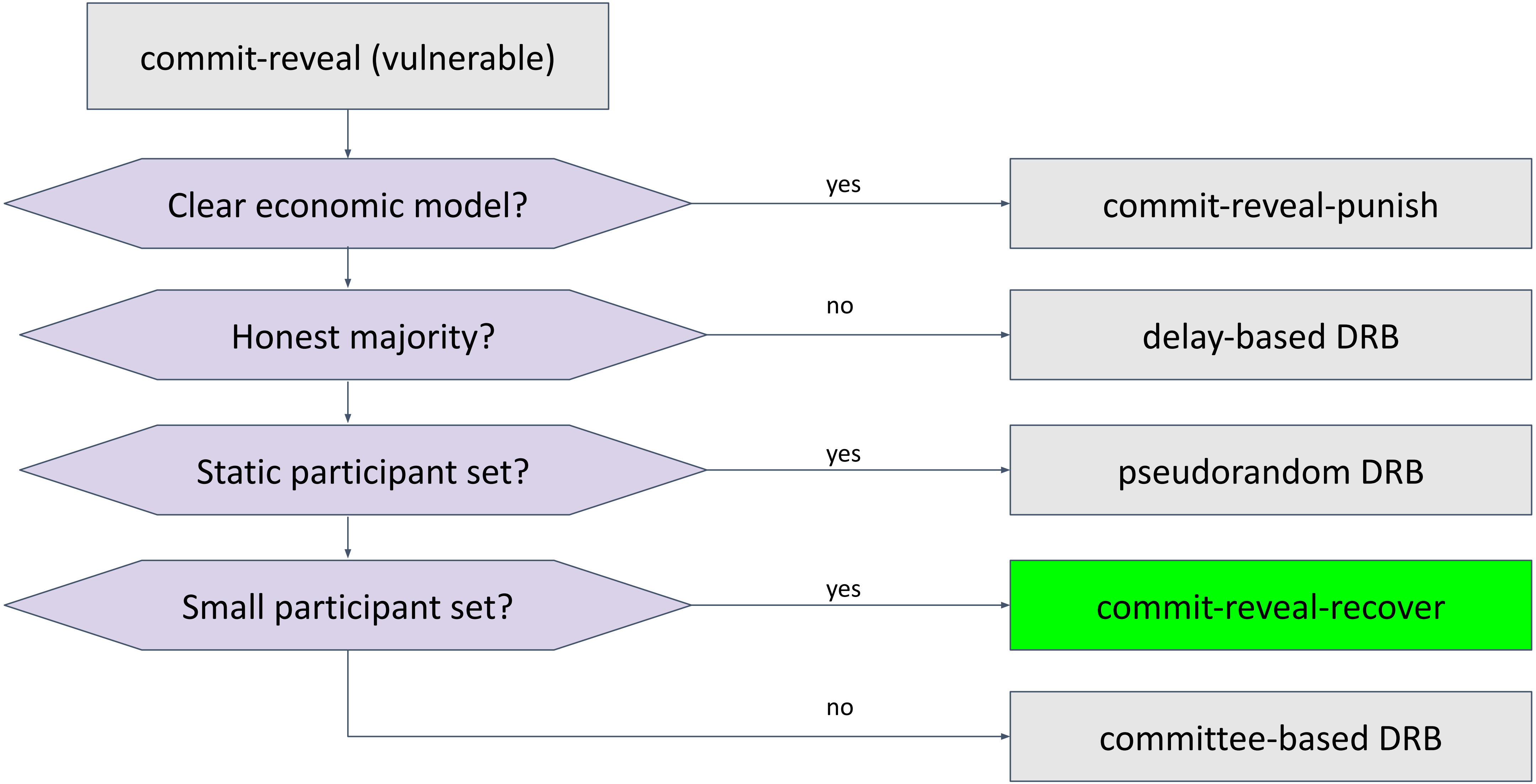
Pseudorandom DRB variants

- drand/DFINITY
  - Threshold BLS signatures
- STROBE [BCKKLNNRS 21]
  - Threshold RSA decryption, with *history generation*
- RandHerd [SJKGGKFF 17]
  - Threshold Schnorr, sharded into groups
- DDH-DRB, GLOW-DRB [GLOW 20]
  - Threshold DDH-VRF (like BLS, but NIZK instead of pairings)

drand: a production pseudorandom DRB

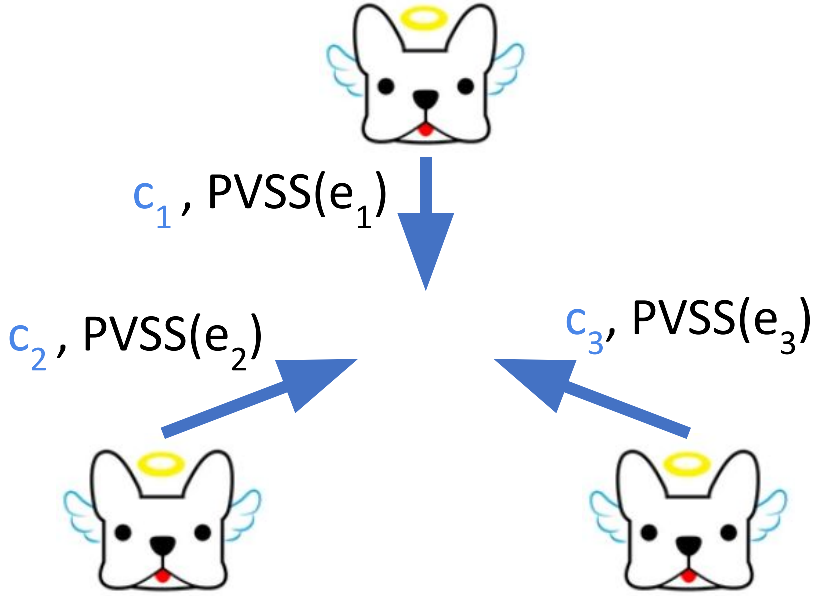
- Launched 2019
- Threshold BLS signatures
  - BLS12-381 curve
- Currently 20 nodes
  - t=11 required to sign
- 256 bits every 30 seconds
- Nodes run by academics + industry

DRB design flow chart



Commit-reveal-recover

1. **Commit**
   a. Publish c_i = Commit(e_i) as in classic CR
   b. Secret-share e_i with all other nodes
      i. PVSS: Publicly verifiable secret sharing



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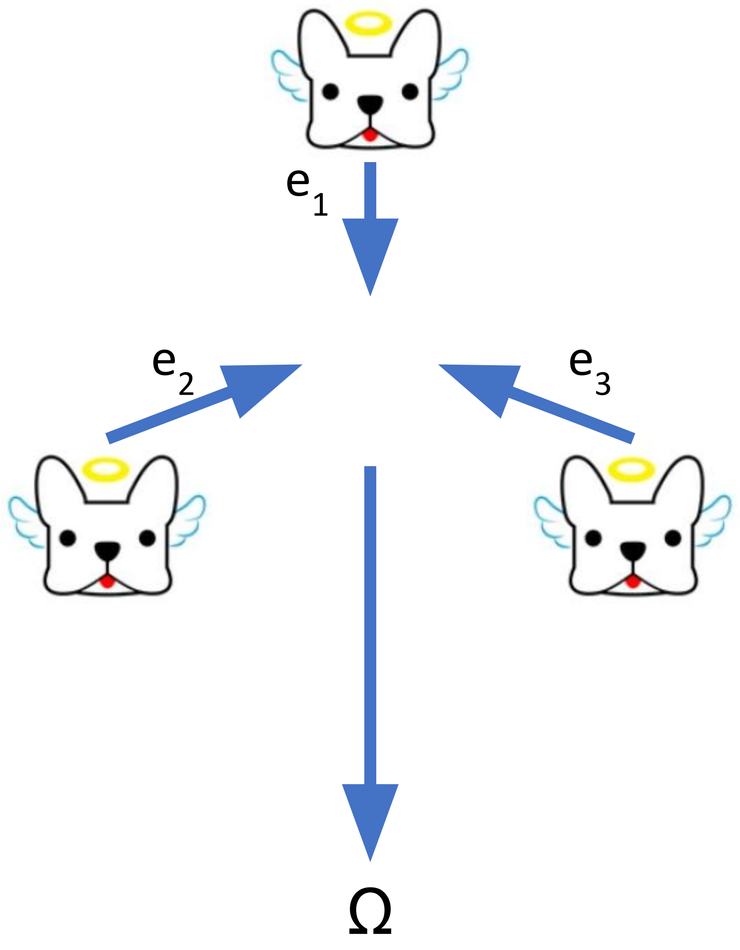

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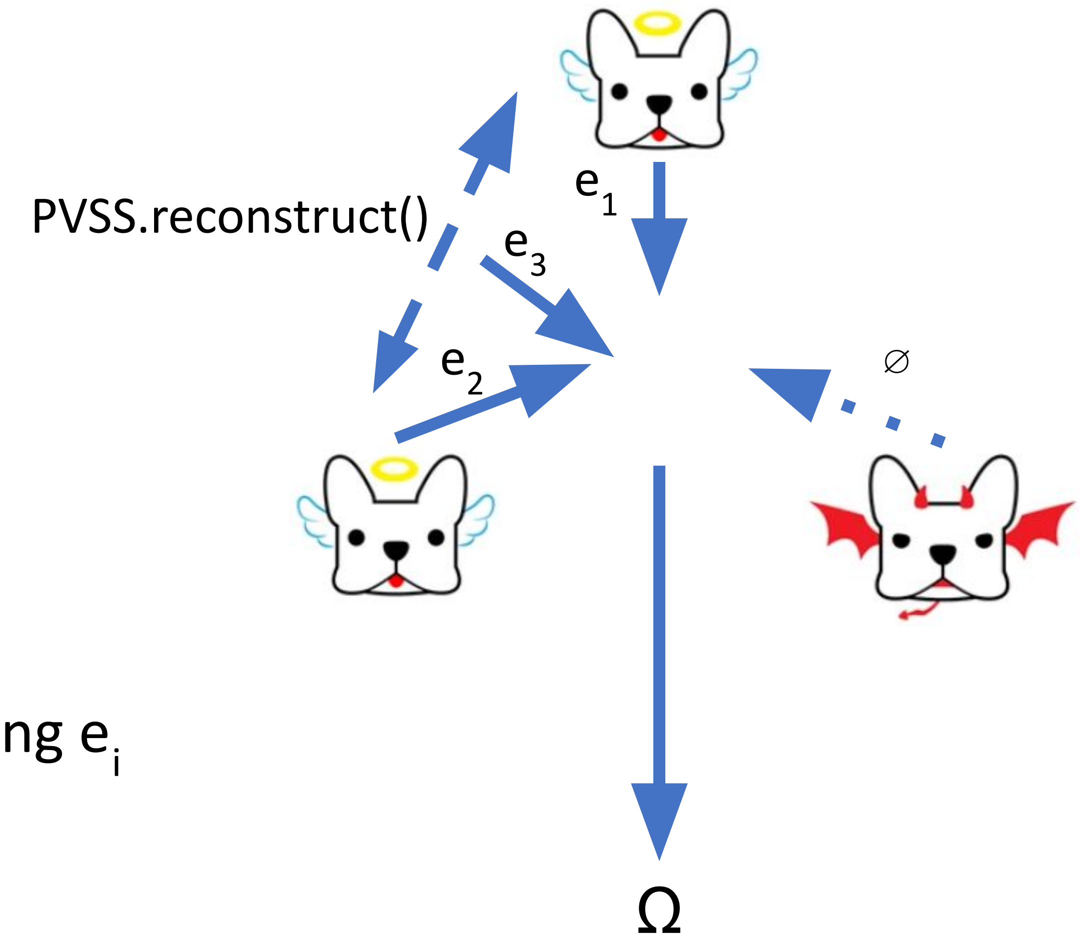
3. **Recover**
   c. Honest participants reconstruct any missing e_i



Commit-reveal-recover variants

- Better PVSS
  - SCRAPE [CD 17]

- Amortized PVSS
  - HERB [CSO 19]
  - Albatross [CD 20]

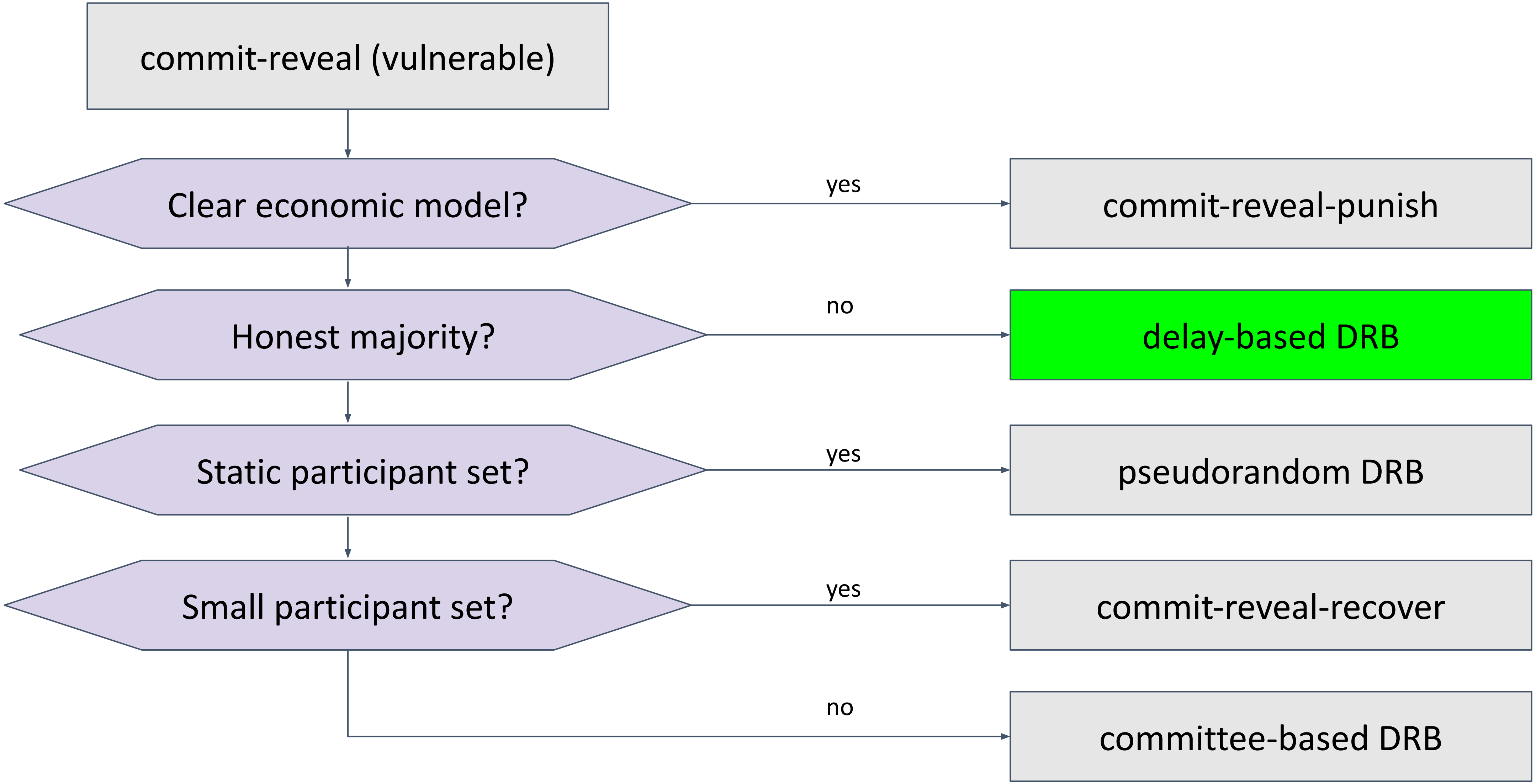
- Remove optimistic case (share-reconstruct-aggregate)
  - RandShare [SJKGGKFF 17]
  - SecRand [GSX 20]

Commit-reveal-recover

- **Advantages**
  - Flexible participation
  - Per-round entropy

- **Challenges**
  - Relatively inefficient
    - $O(n^2)$ communication
  - Complex protocols
  - If *t* needed to compute, *n-t* can block liveness
  - Reconstruction causes extra overhead

DRB design flow chart



Delay functions are *slow* (sequential) but *tractable*

Fast

Encryption
Decryption
Signing
Verification
Hashing

Delay functions:

take a *specified* number of sequential steps

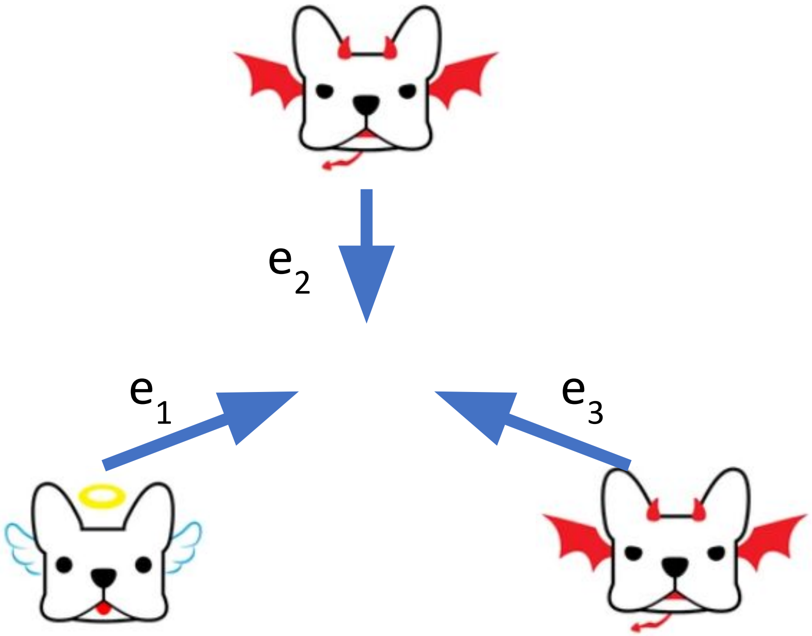
VDFs
Timed commitments
Time-lock encryption
Delay encryption
…

Intractable

Key search
Discrete log
Factoring
Collision-
findng

Reveal-delay (Unicorn) [LW15]

1. **Reveal**
   a. Raw entropy, no commitments needed!



Reveal-delay (Unicorn) [LW15]

1. **Reveal**
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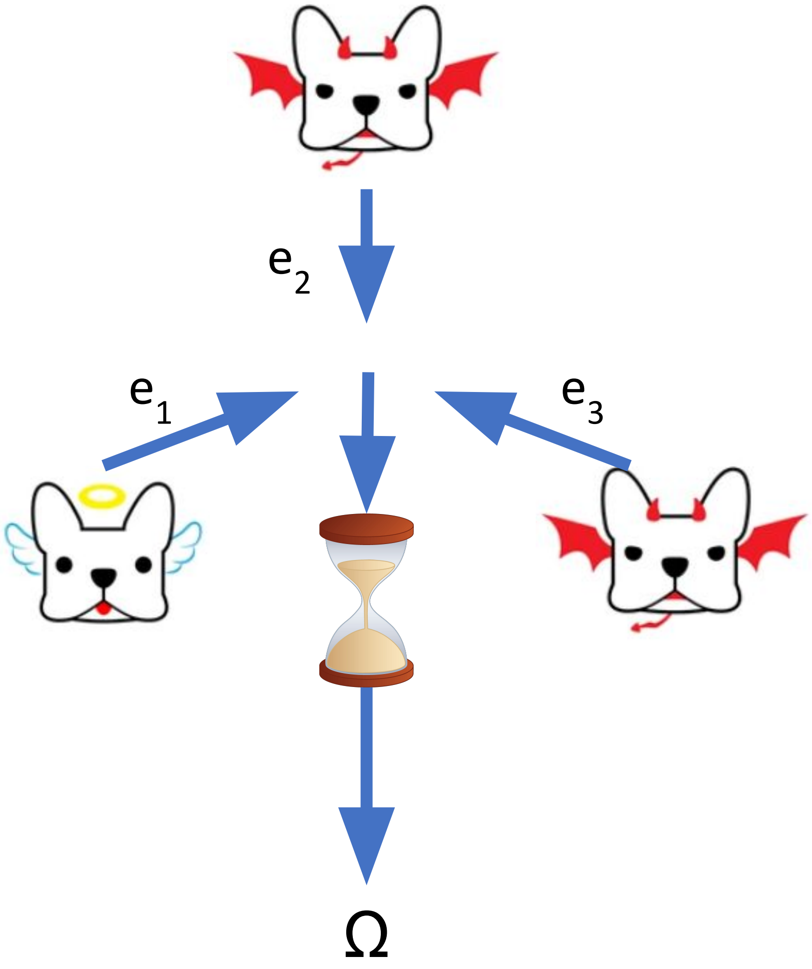
2. **Delay + combine**
   b. Modern approach: use a VDF
      i. Slow (sequential) to compute
      ii. Efficiently verifiable



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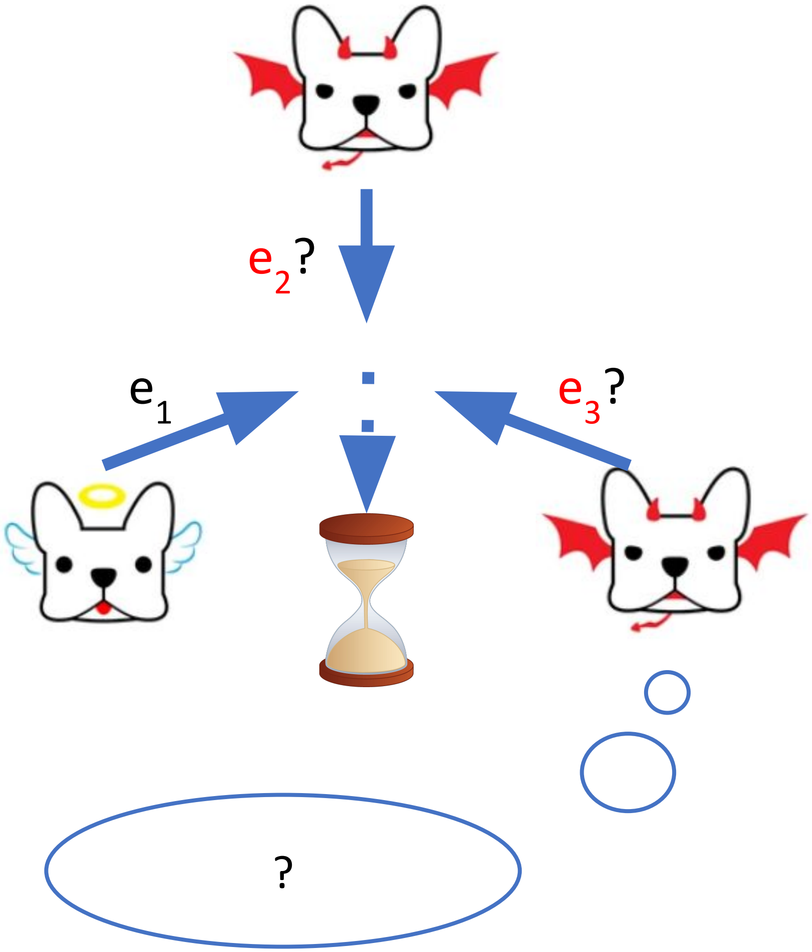

Last revealer(s) can't compute VDF fast enough to bias

Delay-based DRB variants

- **Frequent output:** RandRunner [SJSHW20]
  - Deliver output more often than delay parameter via pipelining

- **Efficient optimistic case:** Bicorn [CATB23]
  - Skip delay function if *all* participants are honest

- **Sublinear communication:** Cornucopia [CCB24]
  - Leader gathers contributions and broadcasts succinct commitment, proofs

Delay-based DRBs

- **Advantages**
  - Secure under dishonest majority
  - Efficient
    - O(n) communication, compute. Can be reduced w/leader
  - Flexible participation
  - Per-round entropy
  - Guaranteed output delivery

Delay-based DRBs in practice: Chia

- Used for consensus
  - Launched 2021
- VDF: Repeated squaring in class group
  - 1024-bit discriminant
  - Wesolowski proofs [W19]

Delay-based DRBs

- **Advantages**
  - Secure under dishonest majority
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    - O(n) communication, compute. Can be reduced w/leader
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  - Per-round entropy
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- **Challenges**
  - Delay functions induce latency
  - Some party must compute the delay function
    - a public good?
  - Relatively new cryptographic assumptions
  - Intra-predictability: attacker with faster VDF may learn outcome early

VDF designs use relatively new assumptions

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Cryptanalysis of Algebraic Verifiable Delay Functions

Alex Biryukov, University of Luxembourg, Esch-sur-Alzette, Luxembourg
Ben Fisch, Yale University, New Haven, USA
Gottfried Herold, Ethereum Foundation, Bonn, Germany
Dmitry Khovratovich, Ethereum Foundation, Luxembourg, Luxembourg
Gaëtan Leurent, INRIA, Paris, France
María Naya-Plasencia, INRIA, Paris, France
Benjamin Wesolowski, CNRS, ENS Lyon, Lyon, France

Abstract

Verifiable Delay Functions (VDF) are a class of cryptographic primitives aiming to guarantee a minimum computation time, even for an adversary with massive parallel computational power. They are useful in blockchain protocols, and several practical candidates have been proposed based on exponentiation in a large finite field: Sloth++, Veedo, MinRoot. The underlying assumption of these constructions is that computing an exponentiation x^e requires at least $\log_2 e$ sequential multiplications.

Metadata

Available format(s)

PDF

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Attacks and cryptanalysis

Publication info

A minor revision of an IACR publication in CRYPTO 2024

Keywords

Verifiable Delay Functions, MinRoot, Veedo, Sloth++, cryptanalysis, smoothness

Contact author(s)

Theorem: dishonest majority DRBs require delay!

- **Classic result:** Dishonest majority DRBs impossible in "plain model"
  - *Limits on the security of coin flips when half the processors are faulty*. Richard Cleve. TOC 1986.

- **Practical observation**: Dishonest majority DRBs possible with VDFs

- **New result**: Dishonest majority DRB *require* delay functions!
  - *Good Things Come to Those Who Wait: Dishonest-Majority Coin-Flipping Requires Delay Functions*. Joseph Bonneau, Benedikt Bünz, Miranda Christ, Yuval Efron. Eurocrypt 2025.
  - Simple delay function, not full VDF
    - Not parameterizable, not efficiently verifiable
  - Assumes network synchrony

Open questions (protocol design)

- *Secret Leader Election*
  - DRBs where only winner founds out they have won!
  - Applications in consensus and other protocols
- *Silent setup*
  - Use existing public keys for threshold DRB with no (or limited) setup phase
- *Optimistic protocols*
  - Faster execution if a chosen leader is honest
  - Faster execution if *all* nodes are honest

Open questions (engineering)

- Simpler API for developers
  - Smart contract integration: Aptos Roll, Mysten sui::random
- VDF deployment
  - Security model requires public access to VDF hardware
- Local randomness generation
  - DRB is no better than nodes' RNGs!
- Public trust

Thank you!

For more, please see 3 derailed surveys:

SoK: Decentralized randomness beacon protocols. Raikwar, Mayank, and Danilo Gligoroski. ACISP 2022. https://arxiv.org/pdf/2205.13333

SoK: Distributed Randomness Beacons. Kevin Choi, Athira Manoj and Joseph Bonneau. IEEE S&P 2023. https://eprint.iacr.org/2023/728

SoK: Public Randomness. Kavousi, Alireza, Zhipeng Wang, and Philipp Jovanovic. EuroS&P 2024. https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=10629002

Backup slides

Is a dishonest majority model worthwhile?

- Consensus requires an honest majority...
  - **Counterpoint:** Attacks on DRBs are *invisible*

- Dishonest majority enables *open participation*
  - No security downside to adding more participants!