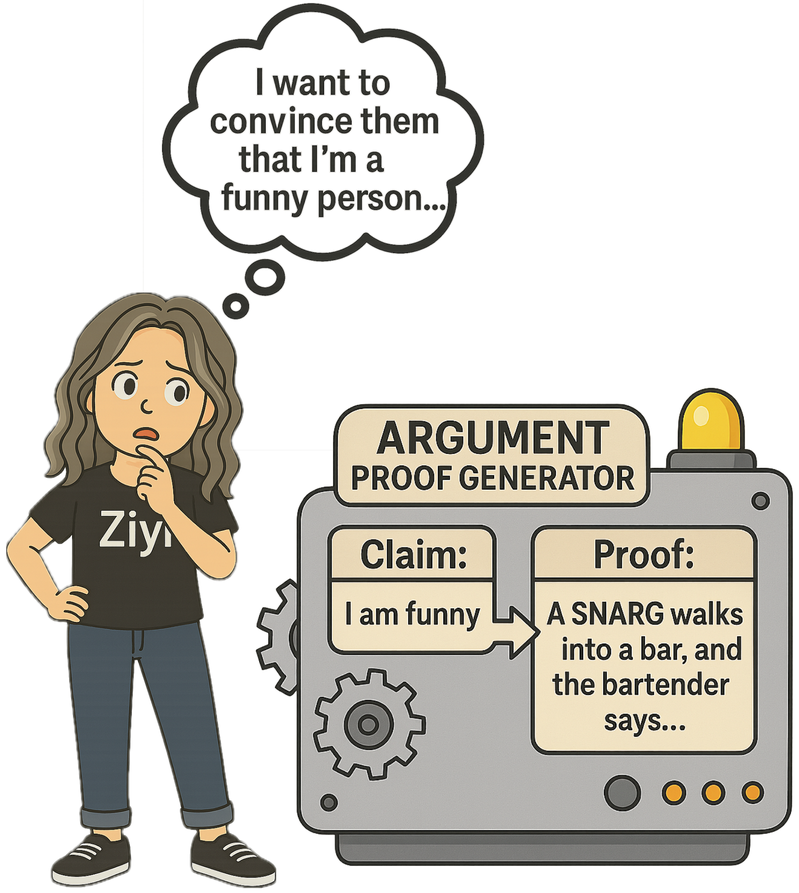
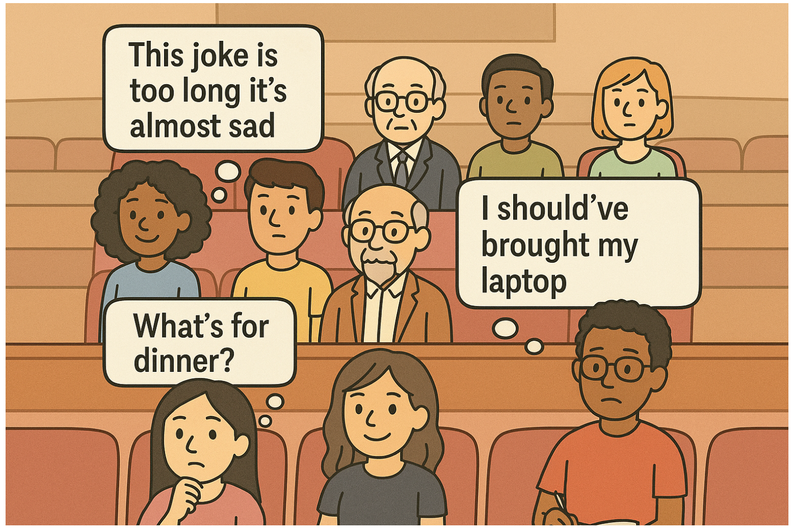
On the Security of Succinct Arguments from Probabilistic Proofs

Ziyi Guan

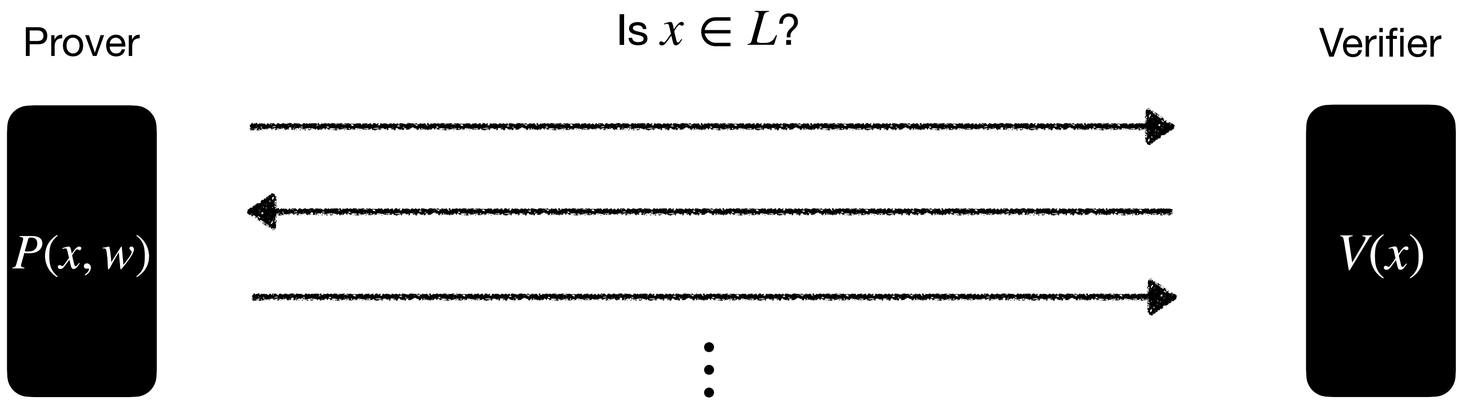




EPFL

What are succinct arguments?

Interactive proofs



Completeness: $\forall\, x \in L, \Pr\left[\langle P(x,w), V(x)\rangle = 1\right] = 1$

Soundness: $\forall\, x \notin L$ and adversary $\tilde{P}$, $\Pr\left[\langle \tilde{P}, V(x)\rangle = 1\right] \leq \epsilon$

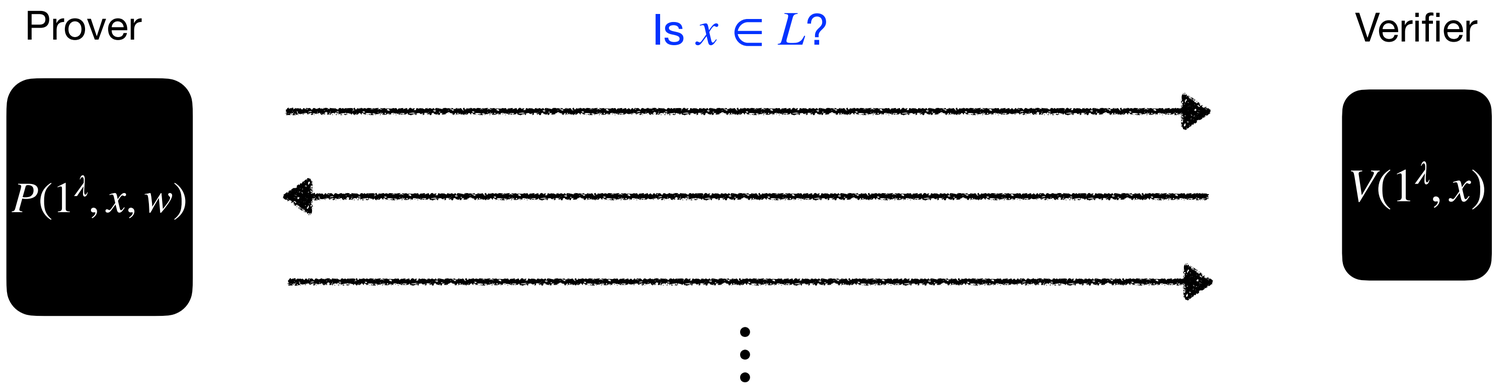
Target metric: COMMUNICATION COMPLEXITY

Limitation: NP-complete languages do not have IPs with **CC** $\ll |w|$

[GH97]: IP[CC] $\subseteq$ BPTIME[2^{CC}]

Interactive arguments

Interactive proofs with computational soundness



Computational soundness: $\forall\, x \notin L$ and t_{ARG}-time adversary $\tilde{P}$, $\Pr\left[\langle \tilde{P}, V(x)\rangle = 1\right] \leq \epsilon_{\mathsf{ARG}}(t_{\mathsf{ARG}})$

AMAZING: $\exists$ interactive arguments for NP with **CC** $\ll |w|$ (given basic cryptography)

Today's protagonist:
Succinct Interactive Arguments

$CC \ll |w|$

Why study succinct interactive arguments?

$\text{time}(V) \ll |w|$

They exist based on simple crypto assumptions...

... so they play a role in numerous cryptotheory results.

zero-knowledge with non-black-box simulation

malicious MPC

...

They are a stepping stone for SNARGs, which have numerous real-world applications.

Succinct

RISC ZERO

Aztec

VALIDA

Irreducible

STARKWARE

polygon

NEXUS

Ligero

MatterLabs

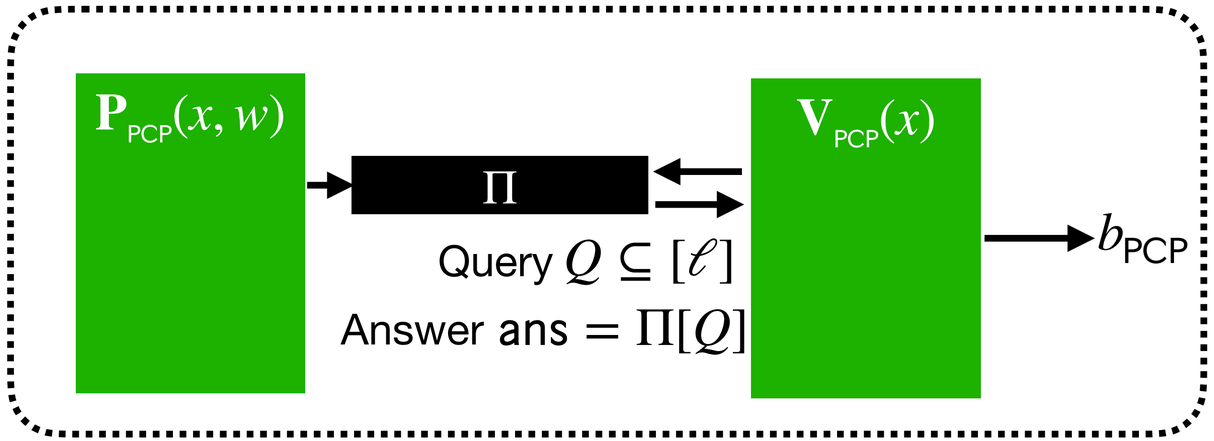
...

Kilian's protocol:
The first and simplest succinct argument

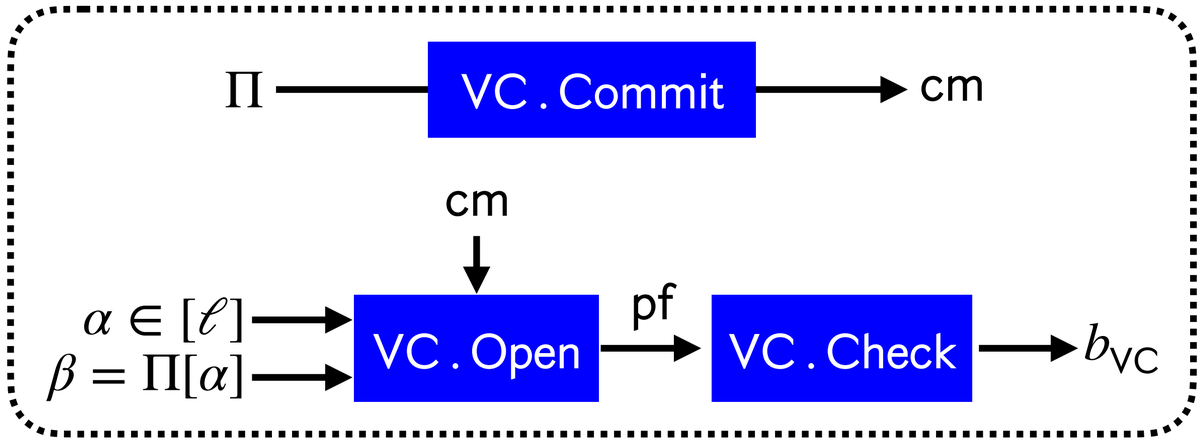
[Kilian92]

How to construct succinct arguments?

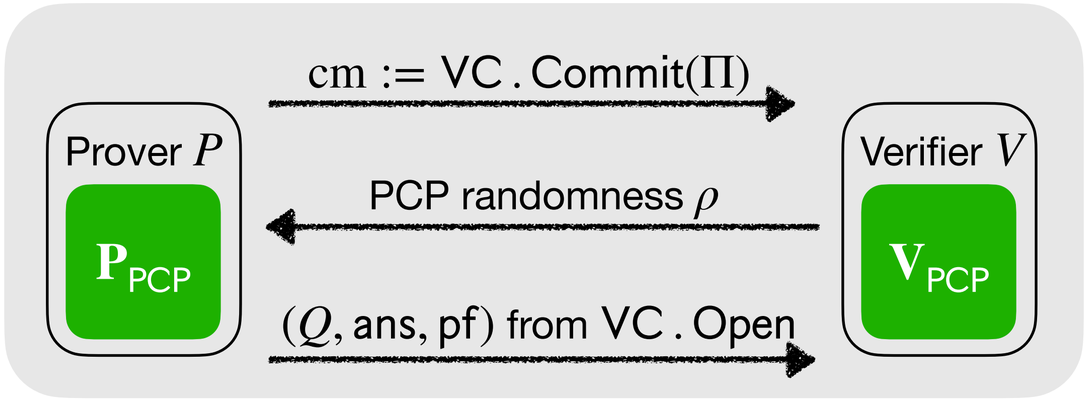
Building block #1: probabilistically checkable proof (PCP)



Building block #2: vector commitment scheme (VC)

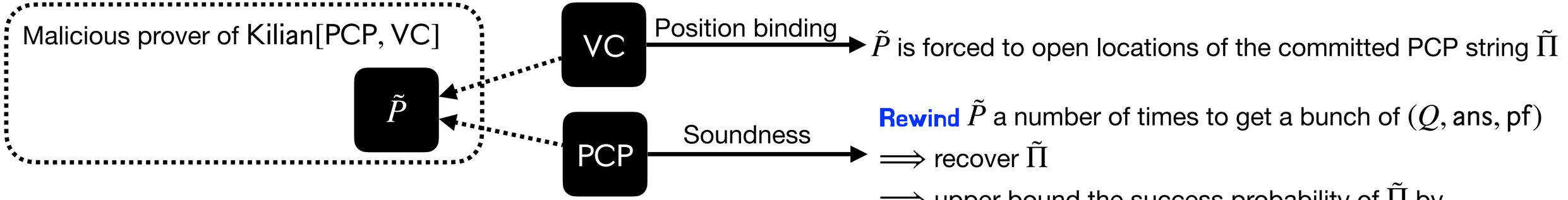


Kilian's protocol

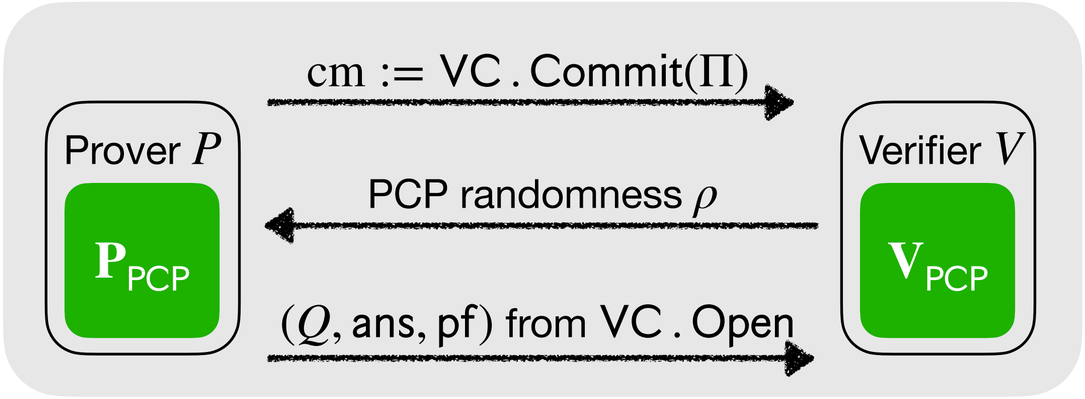


Simple (and only known) security analysis

Goal: relate the soundness error of Kilian[PCP, VC]
to the soundness error of PCP and the position binding error of VC.



Kilian's protocol



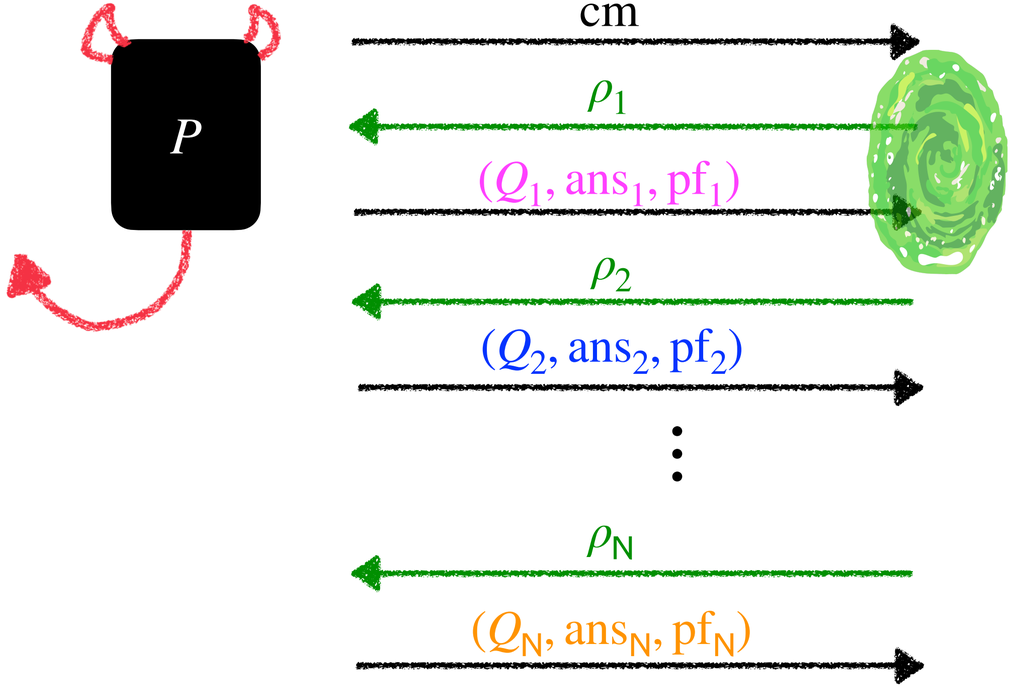
Position binding

$$\Pr\left[\begin{array}{l}(\text{cm}, Q, Q', \text{ans}, \text{ans}', \text{pf}, \text{pf}') \leftarrow \text{Adv} \\ \text{Check}(\text{cm}, Q, \text{ans}, \text{pf}) = 1 \\ \text{Check}(\text{cm}, Q', \text{ans}', \text{pf}') = 1\end{array}\right] \leq \epsilon_{\text{VC}}$$

Security from rewinding

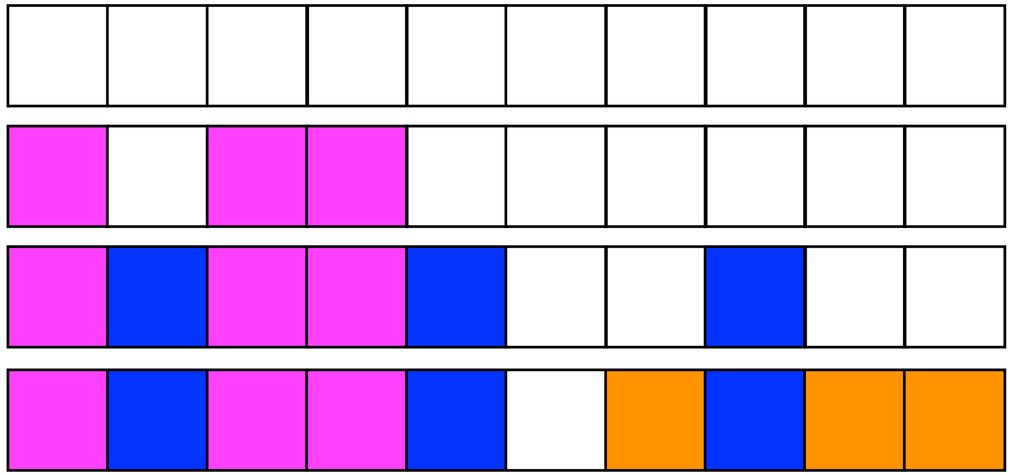
How to rewind?

Malicious Prover $\tilde{P}$

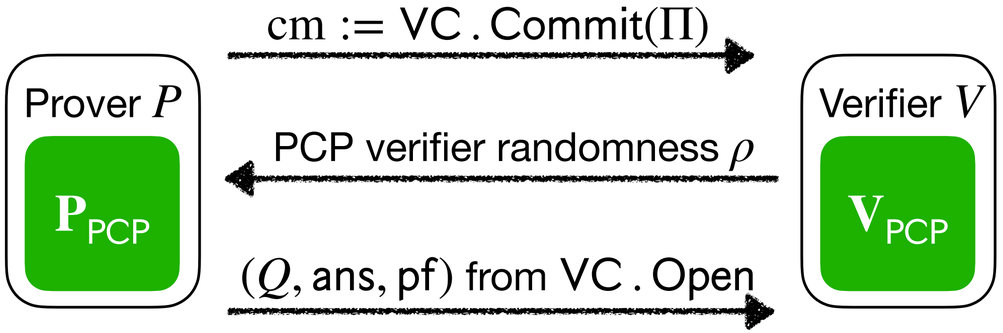


Reductor $\mathscr{R}^{\tilde{P}}(\text{cm}, \epsilon)$

Recover $\tilde{\Pi}$



What is the security of Kilian's protocol?



Previously:

- [Kilian92] gives an informal analysis
- [BG08] $\epsilon_{\mathsf{ARG}} \leq 8 \cdot \epsilon_{\mathsf{PCP}} + \sqrt[3]{\epsilon_{\mathsf{VC}}}$ and **assuming** PCP is non-adaptive & reverse-samplable
- [CMSZ21] Kilian is secure when ϵ_{PCP} negligible (in a paper about post-quantum security)

non-trivial restrictions

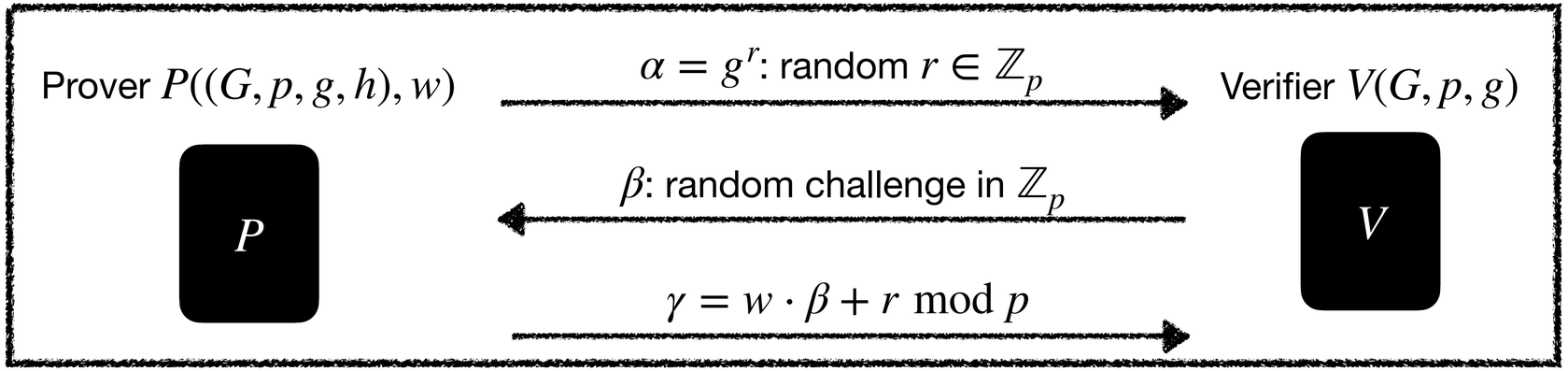
We expect that $\epsilon_{\mathsf{ARG}} \leq \epsilon_{\mathsf{PCP}} + \epsilon_{\mathsf{VC}}$ ... right?

Surprise! A limitation:

$\epsilon_{\mathsf{ARG}} \leq \epsilon_{\mathsf{PCP}} + \epsilon_{\mathsf{VC}}$
$\Longrightarrow$ breakthrough on Schnorr

More on this later…

Schnorr's identification scheme



Lots of work on Schnorr security [Sho97,PS00,BP02,FPS20,BD20,RS21,SSY23] ...
... and yet there are still open questions on its optimal security!

Theorem. ∃ PCP and VC s.t.

$$\epsilon_{\mathsf{Schnorr}}(t) \leq \epsilon_{\mathsf{ARG}}(t).$$

Similar bound holds for expected-time adversary

Improved security for Kilian

Theorem. $\forall\, \epsilon > 0$,

$$\epsilon_{\text{ARG}}(t_{\text{ARG}}) \leq \epsilon_{\text{PCP}} + \epsilon_{\text{VC}}(t_{\text{VC}}) + \epsilon, \text{ where } t_{\text{VC}} = O\left(t_{\text{ARG}} \cdot l \cdot 1/\epsilon\right).$$

This seems large…
Can we improve it?

Why $l \cdot 1/\epsilon$ overhead?

- l locations in Π

$\Longrightarrow$ Rewind at least l times (e.g. maybe all PCP queries but 1 are fixed)

- Some rewinds yield garbage:
  - The locations were already found
  - VC check fails

$\Longrightarrow$ Need $1/\epsilon$ times for each location as buffer

Folklore may remain legend for now...

$\epsilon_{\mathsf{ARG}} \le \epsilon_{\mathsf{PCP}} + \epsilon_{\mathsf{VC}}$
$\Longrightarrow$ breakthrough on Schnorr!

Suppose $\epsilon_{\mathsf{VC}}(t) \le O(t^2/2^\lambda)$ (e.g. an ideal Merkle tree)

λ: security parameter

By **Theorem**: $\epsilon_{\mathsf{ARG}}(t_{\mathsf{ARG}}) \le \epsilon_{\mathsf{PCP}} + \epsilon_{\mathsf{VC}}(t_{\mathsf{ARG}} \cdot l/\epsilon) + \epsilon \le \epsilon_{\mathsf{PCP}} + l^{2/3} \cdot O\left(\sqrt[3]{t_{\mathsf{ARG}}^2/2^\lambda}\right)$

That is, $\epsilon_{\mathsf{ARG}} \le \epsilon_{\mathsf{PCP}} + \sqrt[3]{\epsilon_{\mathsf{VC}}}$

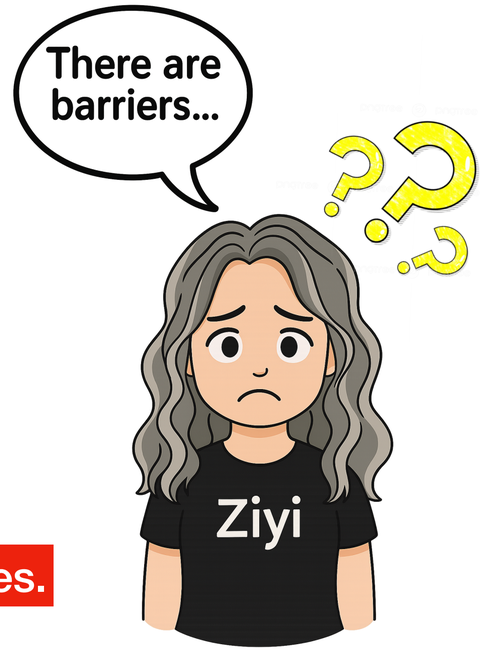
Our lower bound
$\epsilon_{\mathsf{Schnorr}}(t) \le \epsilon_{\mathsf{ARG}}(t)$

+

Suppose
$\epsilon_{\mathsf{ARG}} \le \epsilon_{\mathsf{PCP}} + \epsilon_{\mathsf{VC}}$

$\Longrightarrow$ $\epsilon_{\mathsf{Schnorr}}(t_{\mathsf{Schnorr}}) \le \epsilon_{\mathsf{DLOG}}(O(t_{\mathsf{Schnorr}}))$

Best analysis of Schnorr [PS00]: $\epsilon_{\mathsf{Schnorr}}(t_{\mathsf{Schnorr}}) \le \sqrt{\epsilon_{\mathsf{DLOG}}(O(t_{\mathsf{Schnorr}}))}$



... so the folklore is beyond current rewinding techniques.

Hope: expected-time regime

PCP for language L with
- proof length l
- query complexity q
- soundness error ϵ_{PCP}

→ ARG := Kilian[PCP, VC] ←

Vector commitment scheme with expected-time position binding error $\epsilon^{\star}_{\text{VC}}$

Theorem. $\forall\ \epsilon > 0$,

$$\epsilon^{\star}_{\text{ARG}}(t^{\star}_{\text{ARG}}) \leq \epsilon_{\text{PCP}} + \epsilon^{\star}_{\text{VC}}(t^{\star}_{\text{VC}}) + \epsilon, \text{ where } t^{\star}_{\text{VC}} = O\left(t^{\star}_{\text{ARG}} \cdot \log(\text{q}/\epsilon)\right).$$

Set $\epsilon^{\star}_{\text{VC}}(t^{\star}) \leq O\left(\sqrt{(t^{\star})^2/2^{\lambda}}\right)$ (e.g. an ideal Merkle tree)

λ: security parameter

Theorem $\Longrightarrow$

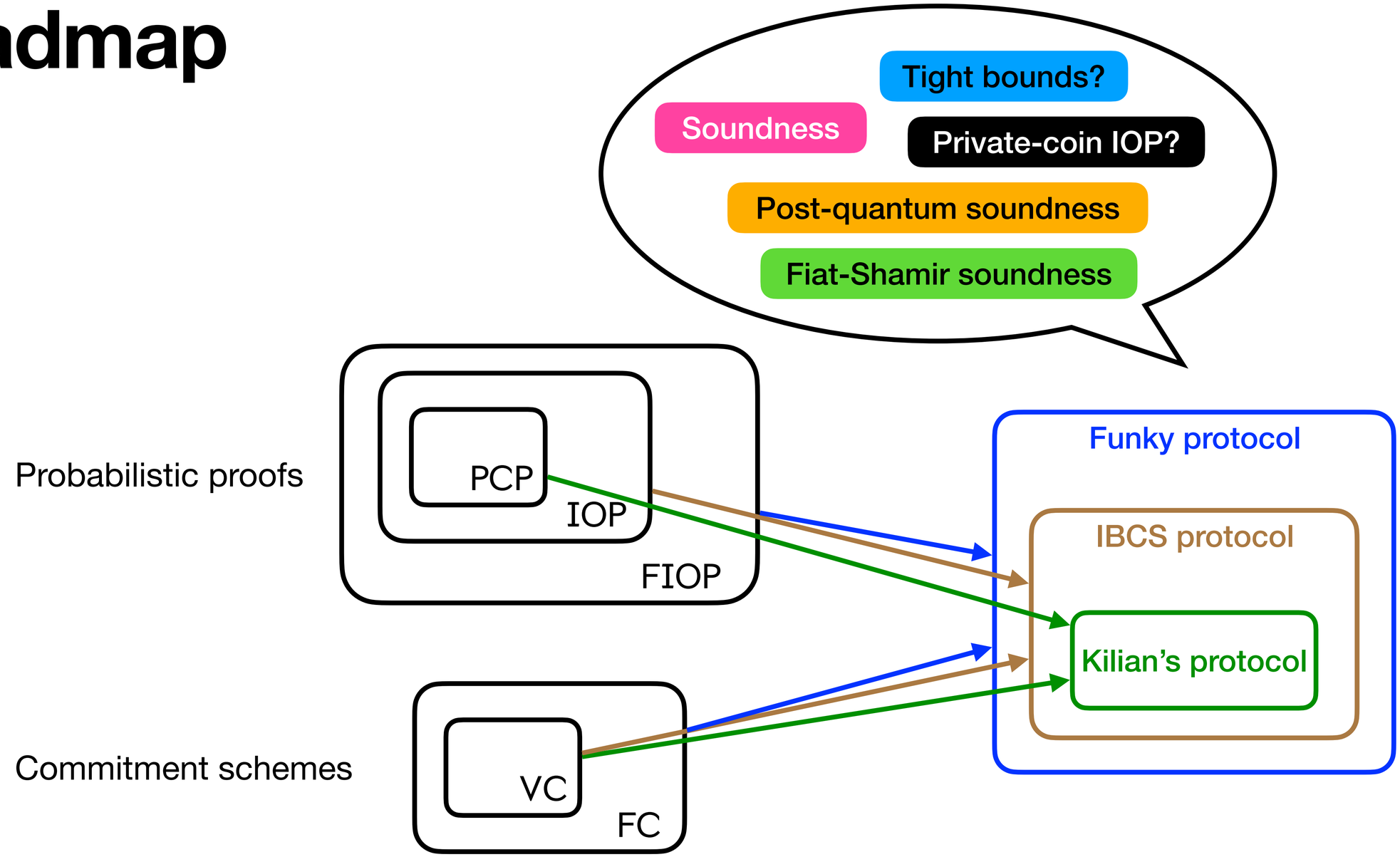
$$\epsilon^{\star}_{\text{ARG}}(t^{\star}_{\text{ARG}}) \leq \epsilon_{\text{PCP}} + \epsilon^{\star}_{\text{VC}}(t^{\star}_{\text{ARG}} \cdot \log(\text{q}/\epsilon)) + \epsilon$$

$$\leq \epsilon_{\text{PCP}} + \text{polylog}\left(\text{q} \cdot \sqrt{(t^{\star}_{\text{ARG}})^2/2^{\lambda}}\right) \cdot O\left(\sqrt[2]{(t^{\star}_{\text{ARG}})^2/2^{\lambda}}\right)$$

small factor

We achieved $\epsilon^{\star}_{\text{ARG}} \leq \epsilon_{\text{PCP}} + \epsilon^{\star}_{\text{VC}}$!

Roadmap


Tight bounds?
Soundness
Private-coin IOP?
Post-quantum soundness
Fiat-Shamir soundness
Probabilistic proofs
PCP
IOP
FIOP
Funky protocol
IBCS protocol
Kilian's protocol
Commitment schemes
VC
FC

On security notions of arguments

Today: focus on soundness only

Classical | Post-quantum

Soundness

Fiat-Shamir soundness

Post-quantum soundness

Actually: many properties/nuances to care about

Knowledge soundness

Fiat-Shamir knowledge soundness

Post-quantum knowledge soundness

...

Simulation extractability

...

Zero knowledge

...

Ethereum Unlocks Millions To Prepare For The Post-quantum Era

Sun 11 May 2025 ▪ 4 min read ▪ by Mikaia A.

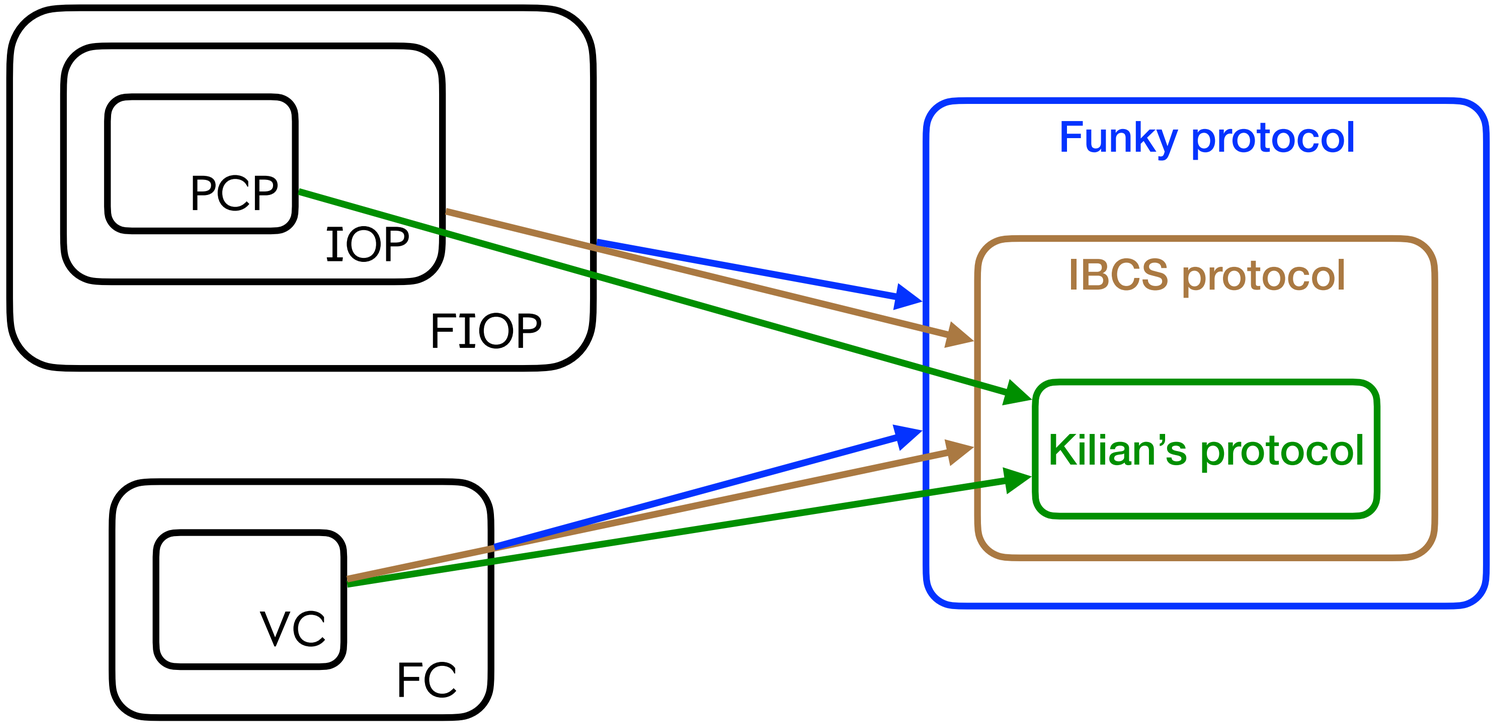
Strict-time adversary
vs.
Expected-time adversary

e.g., [BL02] zero-knowledge protocols do not have strict poly-time (black-box) extractor

zkEVM Formal Verification Project

A project by the Ethereum Foundation to accelerate the application of formal verification methods to zkEVMs

IBCS protocol:
Using IOPs instead of PCPs



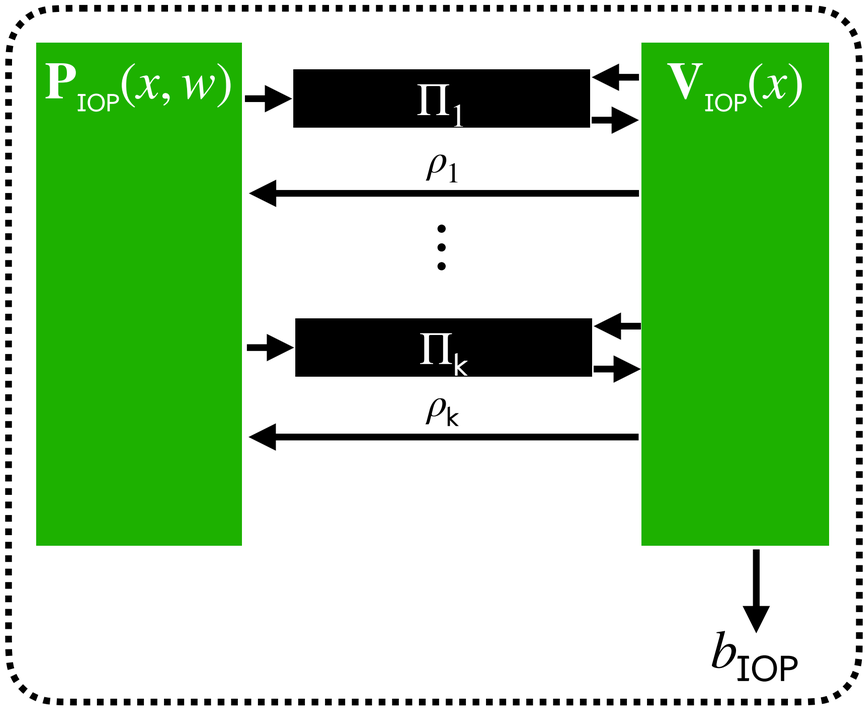
[BCS16; CDGS23]

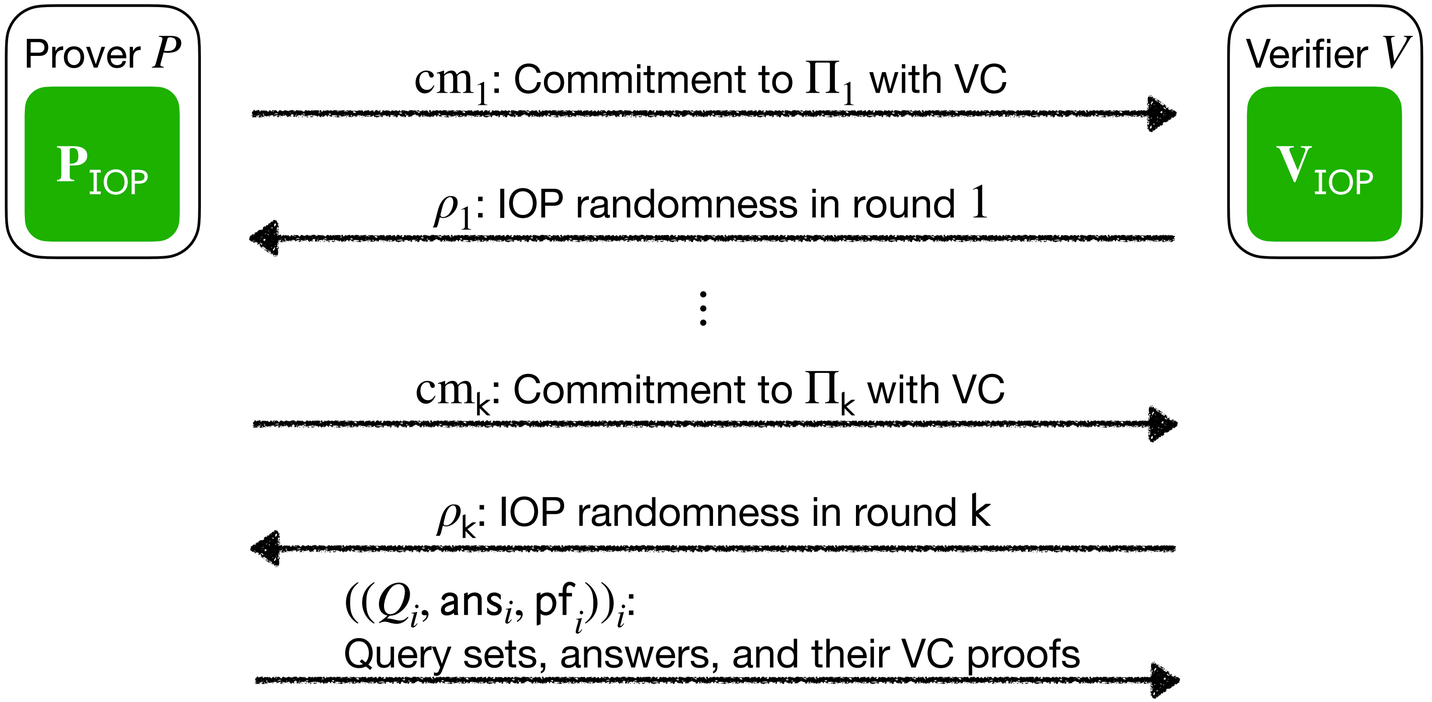
IBCS protocol

Existing PCPs are not concretely efficient: prover time too big

People use IOPs

Public-coin interactive oracle proof (IOP)





Security of IBCS protocol

The ideal bound $\epsilon_{\text{ARG}} \leq \epsilon_{\text{IOP}} + \epsilon_{\text{VC}}$ is not possible… What can we get?

Theorem. $\forall\, \epsilon > 0$,

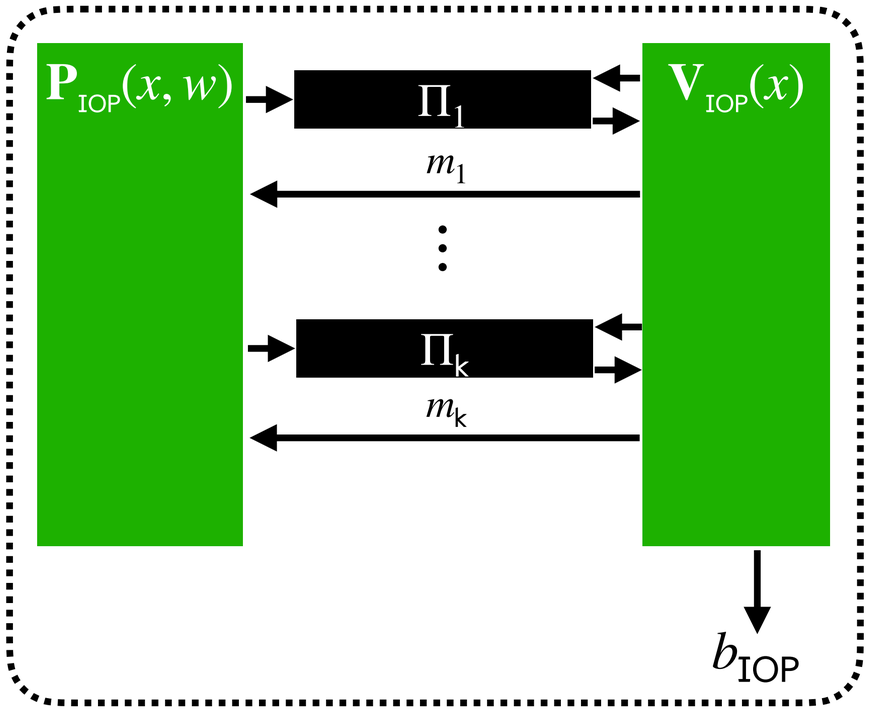
$$\epsilon_{\text{ARG}}(t_{\text{ARG}}) \leq \epsilon_{\text{IOP}} + \text{k} \cdot \epsilon_{\text{VC}}(t_{\text{VC}}) + \epsilon, \text{ where } t_{\text{VC}} = O\left(t_{\text{ARG}} \cdot l/\epsilon\right).$$

Recall, for Kilian's protocol: $\forall\, \epsilon > 0$,

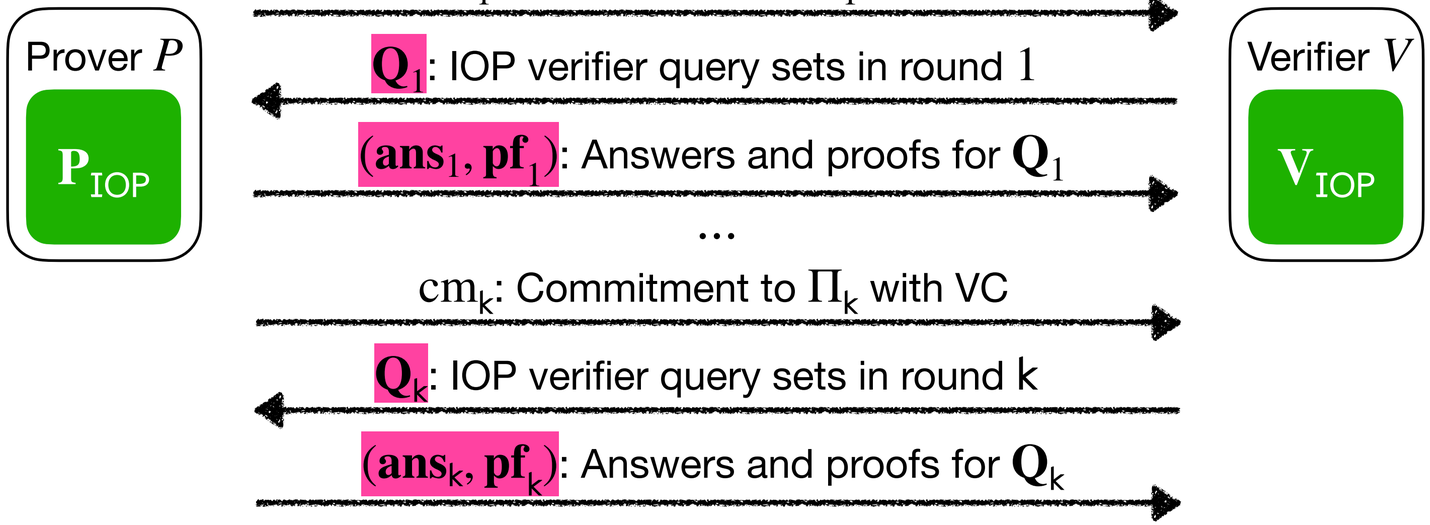
$$\epsilon_{\text{ARG}}(t_{\text{ARG}}) \leq \epsilon_{\text{PCP}} + 1 \cdot \epsilon_{\text{VC}}(t_{\text{VC}}) + \epsilon, \text{ where } t_{\text{VC}} = O\left(t_{\text{ARG}} \cdot l/\epsilon\right).$$

Why do we need public-coin IOPs?

Private-coin interactive oracle proof (IOP)



$\mathbf{Q}_i$ contains verifier's queries to $\Pi_1, \ldots, \Pi_i$



Not secure!
e.g. IOP verifier accepts if IOP prover guesses all its queries

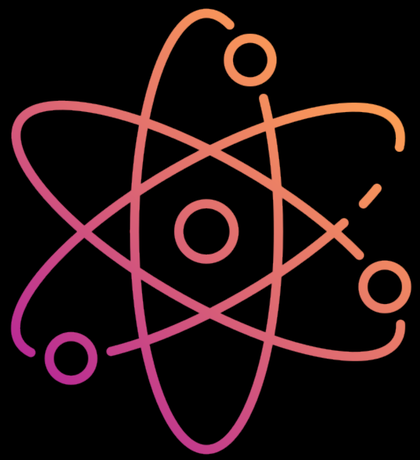
How about public-query IOPs?

Queries can be learned by the prover (in "real-time")

Clearly, the IBCS protocol is secure whenever the underlying IOP is public-query... right?

Lemma: secure if IOP has an "efficient random continuation sampler"

Open question: can we prove security for ALL public-query IOPs?
(Or maybe there is a black-box barrier?)

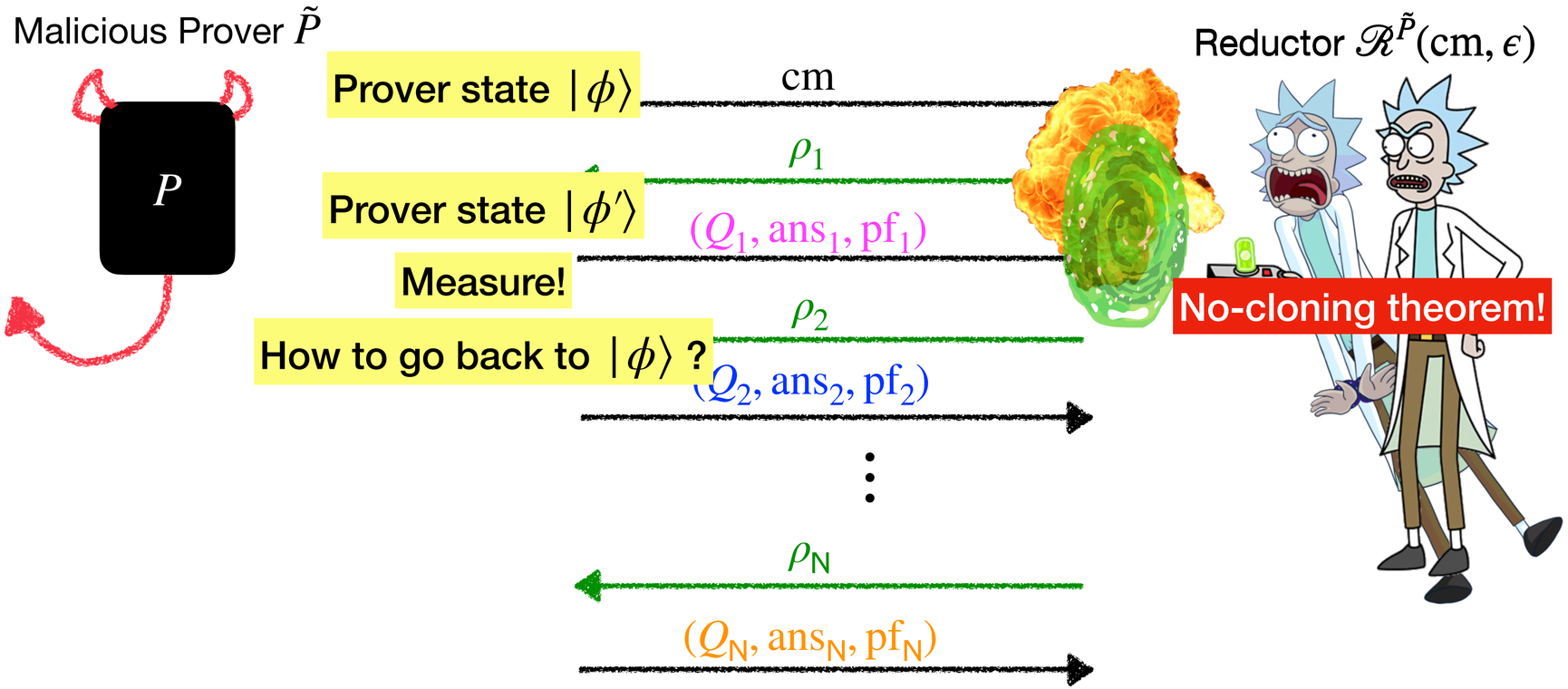


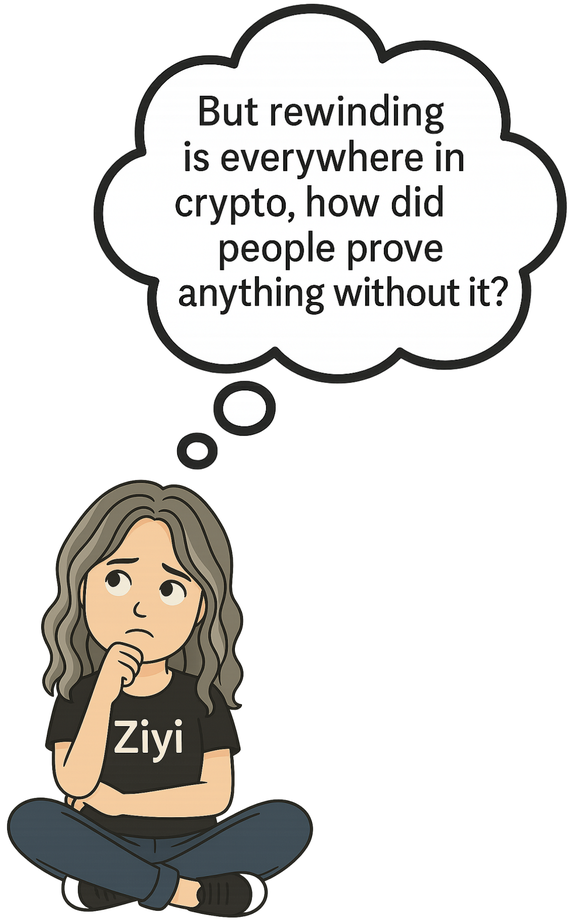
Interlude: post-quantum security

Post-quantum soundness: same as classical soundness but adversary is quantum.

$$\forall\ t_{\mathsf{ARG}}\text{-time } \textbf{QUANTUM} \text{ adversary } \tilde{P},\ \Pr\left[\langle \tilde{P}, V\rangle = 1\right] \leq \epsilon_{\mathsf{ARG}}(t_{\mathsf{ARG}})$$

On quantum rewinding





For many years: can rewind O(1) times [Wat06,Unr12,Unr16b]

Problem: Kilian's protocol needs many rewindings

Recent new tools for quantum rewinding [CMSZ21]: "repair" the state instead of "rewind"
$\Longrightarrow$ post-quantum security of Kilian's protocol

- Quantum rewinding toolset is cumbersome.
- Only other paper studying many-round interactive arguments [LMS22] had to white-box adapt the tools in [CMSZ21]… (work for log rounds)

Adapting for IBCS protocol runs into challenges

Post-quantum security of IBCS protocol

Technical contribution: We build on [CMSZ21] and more…

Theorem. $\forall\ \epsilon > 0$,

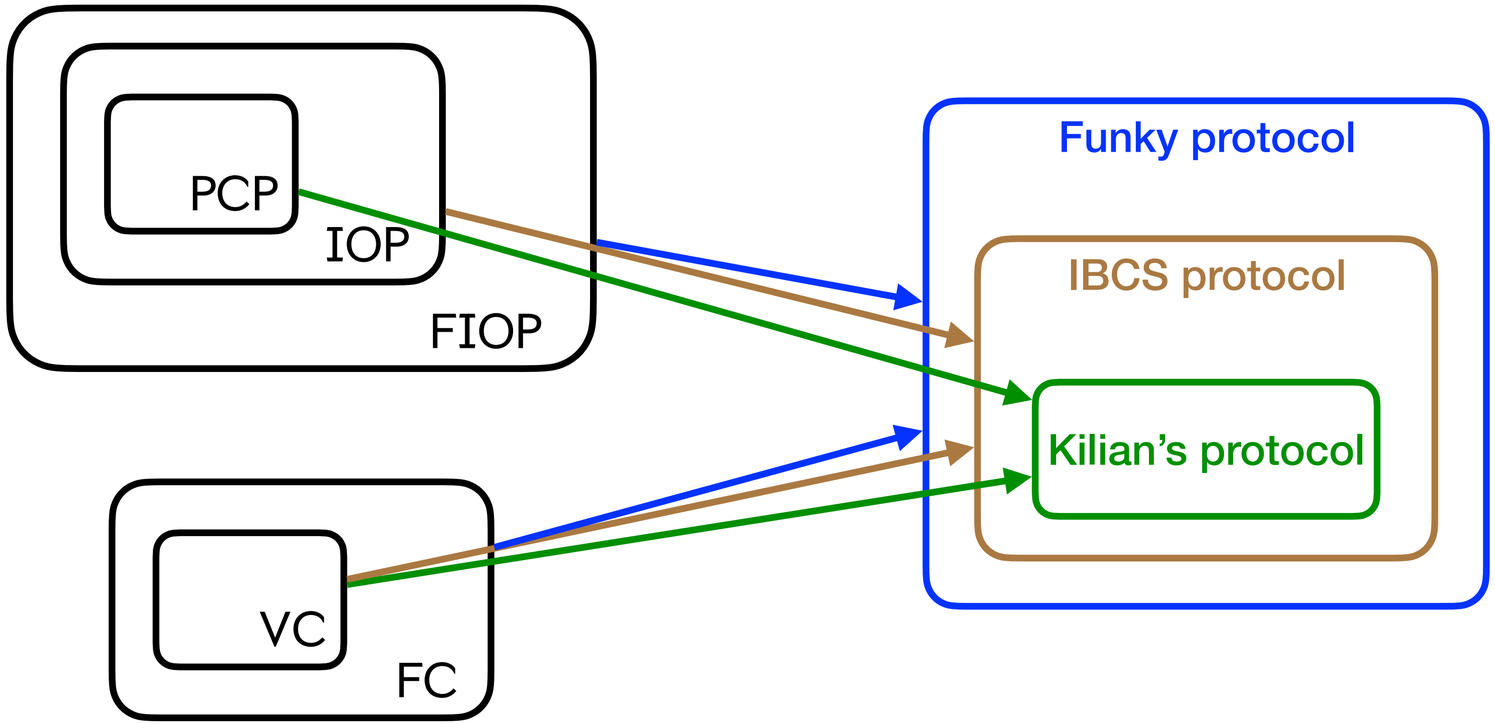
$$\epsilon_{\text{ARG}}^{\text{PQ}}(t_{\text{ARG}}) \leq \epsilon_{\text{IOP}}^{\text{PQ}} + \mathsf{k} \cdot l \cdot \epsilon_{\text{VCCollapse}}(t_{\text{VC}}) + \epsilon, \text{ where } t_{\text{VC}} = \text{poly}\left(t_{\text{ARG}} \cdot l/\epsilon\right).$$

Extra l factor: cost of quantum rewinding

IBCS soundness: $\epsilon_{\text{ARG}}(t_{\text{ARG}}) \leq \epsilon_{\text{IOP}} + \mathsf{k} \cdot \epsilon_{\text{VC}}(t_{\text{VC}}) + \epsilon$, where $t_{\text{VC}} = O\left(t_{\text{ARG}} \cdot l/\epsilon\right)$.

Corollary: post-quantum secure succinct arguments in the standard model (no oracles), with the best asymptotic complexity known.

Funky protocol:
Construction from all probabilistic proofs

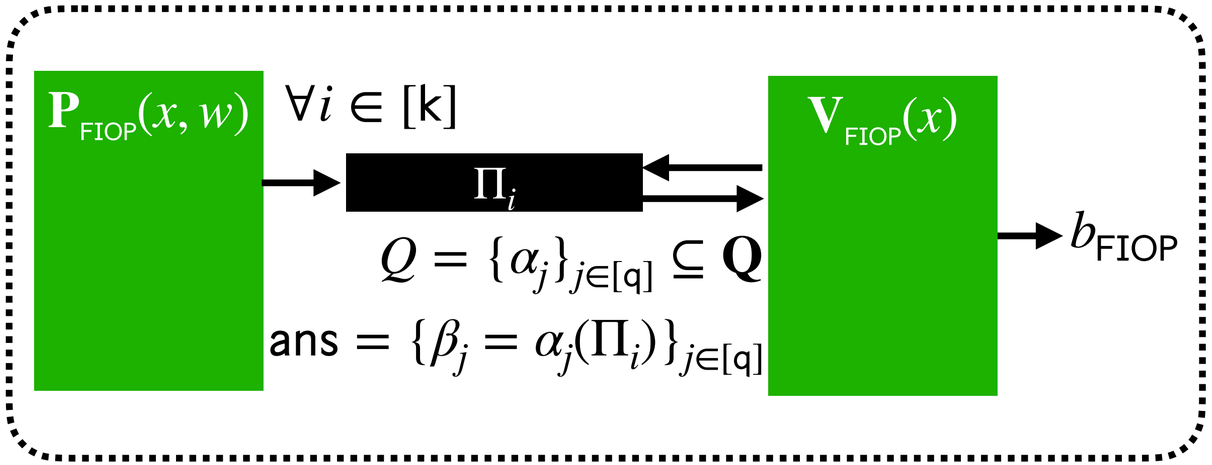


[CGKY25]

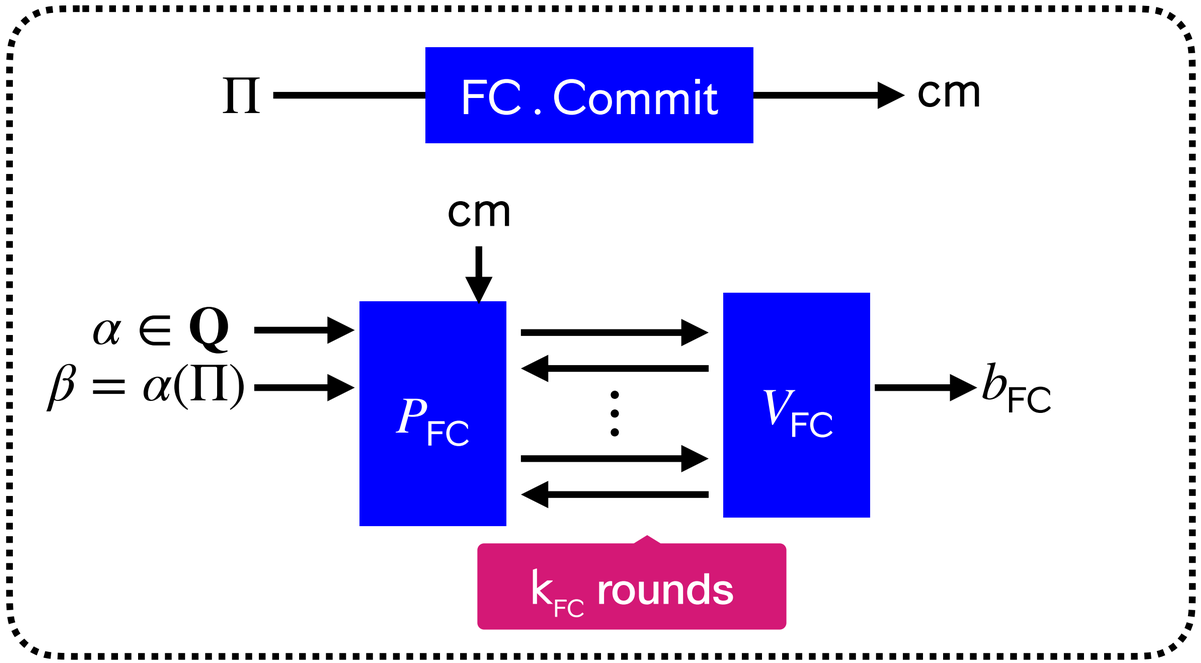
Building blocks

Building block #1: query class $\mathbf{Q}$
- $\mathbf{Q} \subseteq \{\alpha : \Sigma^{\ell} \to \mathbb{D}\}$

Building block #2: functional interactive oracle proof (FIOP)

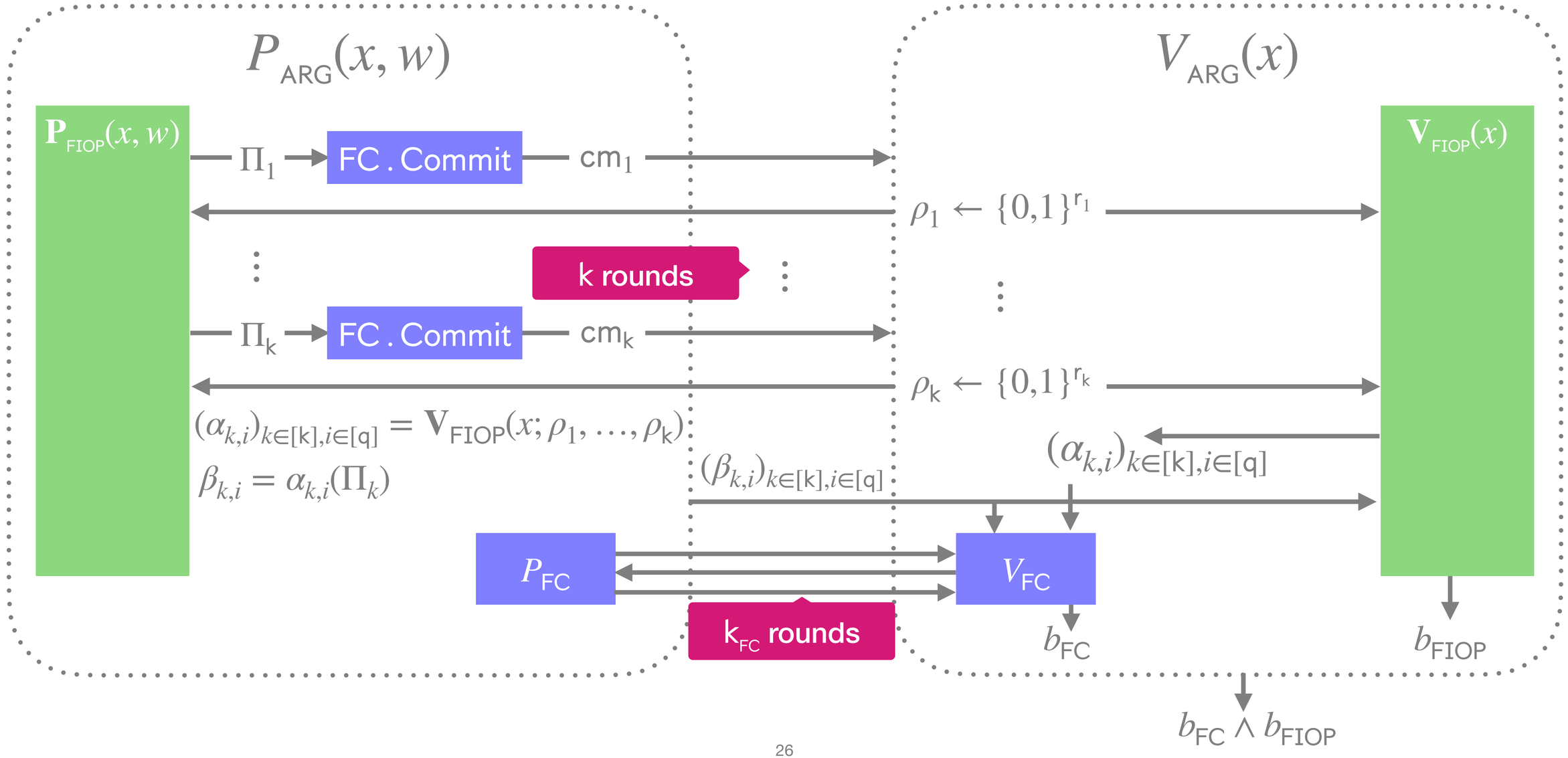


Building block #3: functional commitment scheme (FC)



[CGKY25]

Funky protocol



Some instantiations of the Funky protocol

	Proof string	Query class	Answer
PCP+VC [Kilian92] **IOP+VC** [BCS16,CDGS23]	$\Pi \in \Sigma^{\ell}$	point queries $\mathbf{Q}_{\text{point}}$	$\beta = \Pi[\alpha]$ for $\alpha \in [\ell]$
LPCP+LC [LM19]	$\Pi \in \mathbb{F}^{\ell}$	linear queries $\mathbf{Q}_{\text{lin}}$	$\beta = \sum_{i \in [\ell]} \Pi[i] \cdot \alpha[i]$ for $\alpha \in \mathbb{F}^{\ell}$
PIOP+PC [CHM+20,BFS20]	$\Pi \in \mathbb{F}[X]^{\leq \mathsf{D}}$	evaluation queries on polynomials $\mathbf{Q}_{\text{poly}}$	$\beta = \sum_{i \in [\ell]} \Pi[i] \cdot \alpha^{i-1}$ for $\alpha \in \mathbb{F}$
PIOP*+PC* [GWC19]	$\Pi \in (\mathbb{F}[X]^{\leq \mathsf{D}})^{m+n}$ $= (f_1, \ldots, f_m, g_1, \ldots, g_n)$	evaluation queries on structured polys $\mathbf{Q}_{\text{poly}*}$	$\beta = \sum_{k \in [n]} h_k(f_1(\alpha), \cdots, f_m(\alpha)) \cdot g_k(\alpha)$

Beyond Funky: Bulletproofs (and other sumcheck-based arguments), linear-only encodings [BCIOP13, GGPR13, Groth16], …

Some instantiations of the Funky protocol

Beyond Funky: Bulletproofs (and other sumcheck-based arguments), linear-only encodings [BCIOP13, GGPR13, Groth16], …

Which security property for FC?

Earlier IOP+VC

$\epsilon_{\text{ARG}} \approx \epsilon_{\text{IOP}} + \epsilon_{\text{VC}}^{\text{PB}}$

Vector Commitments position binding:

$$\Pr\left[\begin{array}{l} \beta_1 \neq \beta_2 \\ \wedge\ \forall i : \text{FC}.\text{Check}(\text{pp}, \text{cm}, \alpha_i, \beta_i, \text{pf}_i) = 1 \end{array} \middle| \ (\text{cm}, \alpha, \beta_1, \text{pf}_1, \beta_2, \text{pf}_2) \leftarrow A(\text{pp}) \right] \leq \epsilon$$

[LM19] LPCP+LC

$\epsilon_{\text{ARG}} \approx \epsilon_{\text{LPCP}} + \epsilon_{\text{LC}}^{\text{FB}}$

Linear Commitments function binding:

$$\Pr\left[\begin{array}{l} \nexists \Pi : \forall i : \langle \alpha_i, \Pi \rangle = \beta_i \\ \wedge\ \forall i : \text{FC}.\text{Check}(\text{pp}, \text{cm}, \alpha_i, \beta_i, \text{pf}_i) = 1 \end{array} \middle| \ (\text{cm}, (\alpha_i, \beta_i, \text{pf}_i)_{i\in[n]}) \leftarrow A(\text{pp}) \right] \leq \epsilon$$

[CHMMVW20, BFS20] PIOP+PC

$\epsilon_{\text{ARG}} \approx \epsilon_{\text{PIOP}} + \kappa_{\text{PC}}$

Polynomial Commitments binding? strong correctness? interpolation binding? extractability?

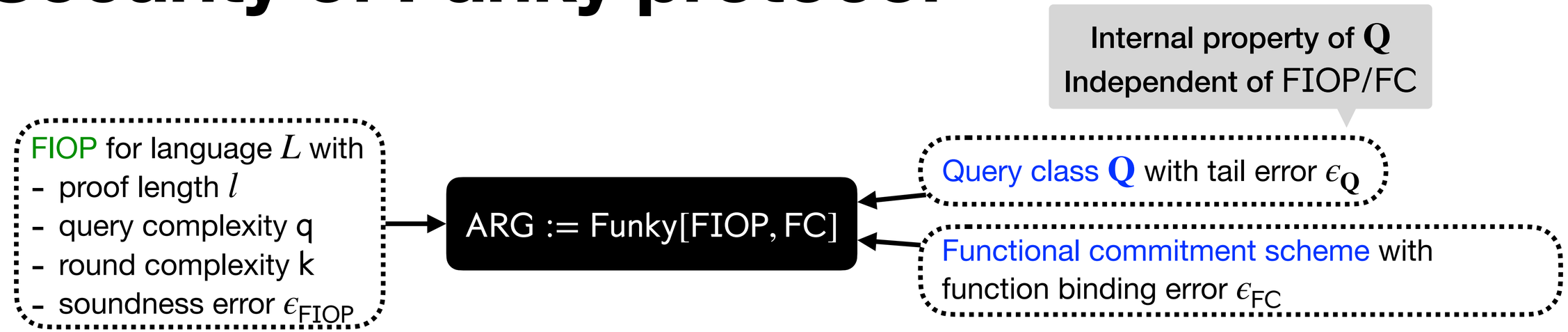
Too strong

[KZG10] [AJMMS23] [CHM+20, BFS20]

Functional Commitments function binding:

$$\Pr\left[\begin{array}{l} \nexists \Pi : \forall i : \alpha_i(\Pi) = \beta_i \\ \wedge\ \forall i : \text{FC}.\text{Check}(\text{pp}, \text{cm}, \alpha_i, \beta_i, \text{pf}_i) = 1 \end{array} \middle| \ (\text{cm}, (\alpha_i, \beta_i, \text{pf}_i)_{i\in[n]}) \leftarrow A(\text{pp}) \right] \leq \epsilon$$

Security of Funky protocol



Theorem. $\forall\, \mathsf{N} \in \mathbb{N}$,

$$\epsilon_{\text{ARG}}(t_{\text{ARG}}) \leq \epsilon_{\text{FIOP}} + \mathsf{k} \cdot \epsilon_{\text{FC}}(t_{\text{FC}}) + \mathsf{k} \cdot \epsilon_{\mathbf{Q}}(l, \mathsf{N}), \text{ where } t_{\text{FC}} = O\left(t_{\text{ARG}} \cdot \mathsf{N}\right).$$

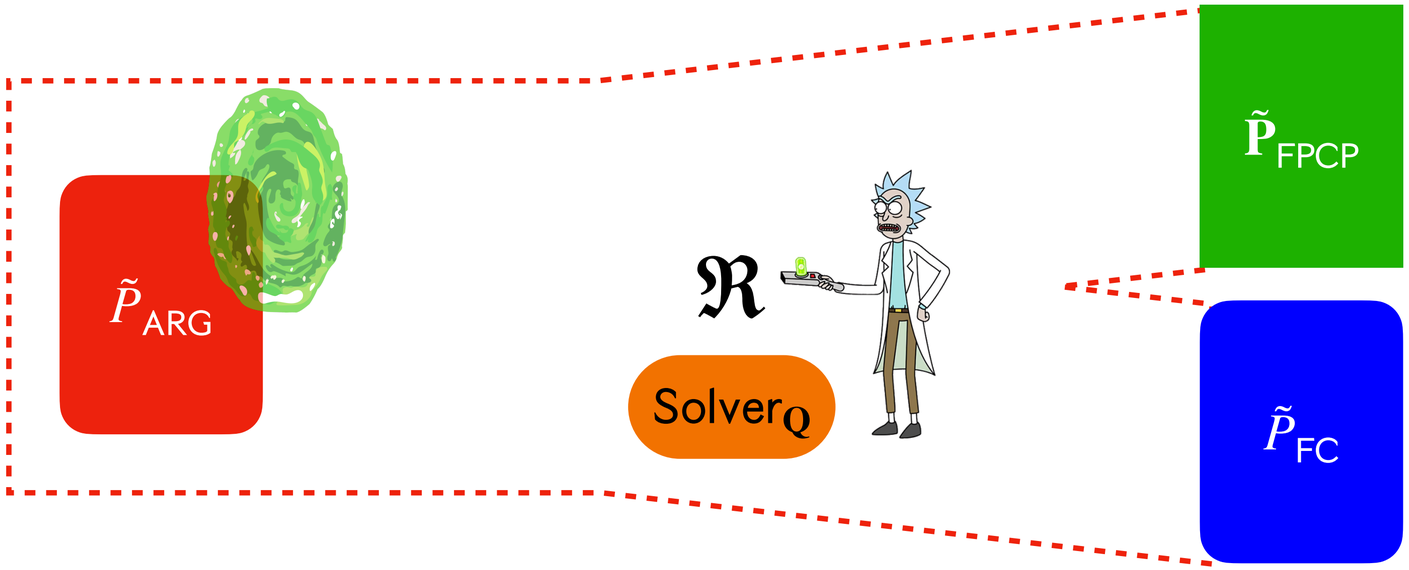
$\epsilon_{\mathbf{Q}_{\text{point}}}(l, \mathsf{N}) = l/\mathsf{N} \Longrightarrow$ recovers the bounds for Kilian's protocol and IBCS protocol

Security of Funky from FPCP and non-interactive FC

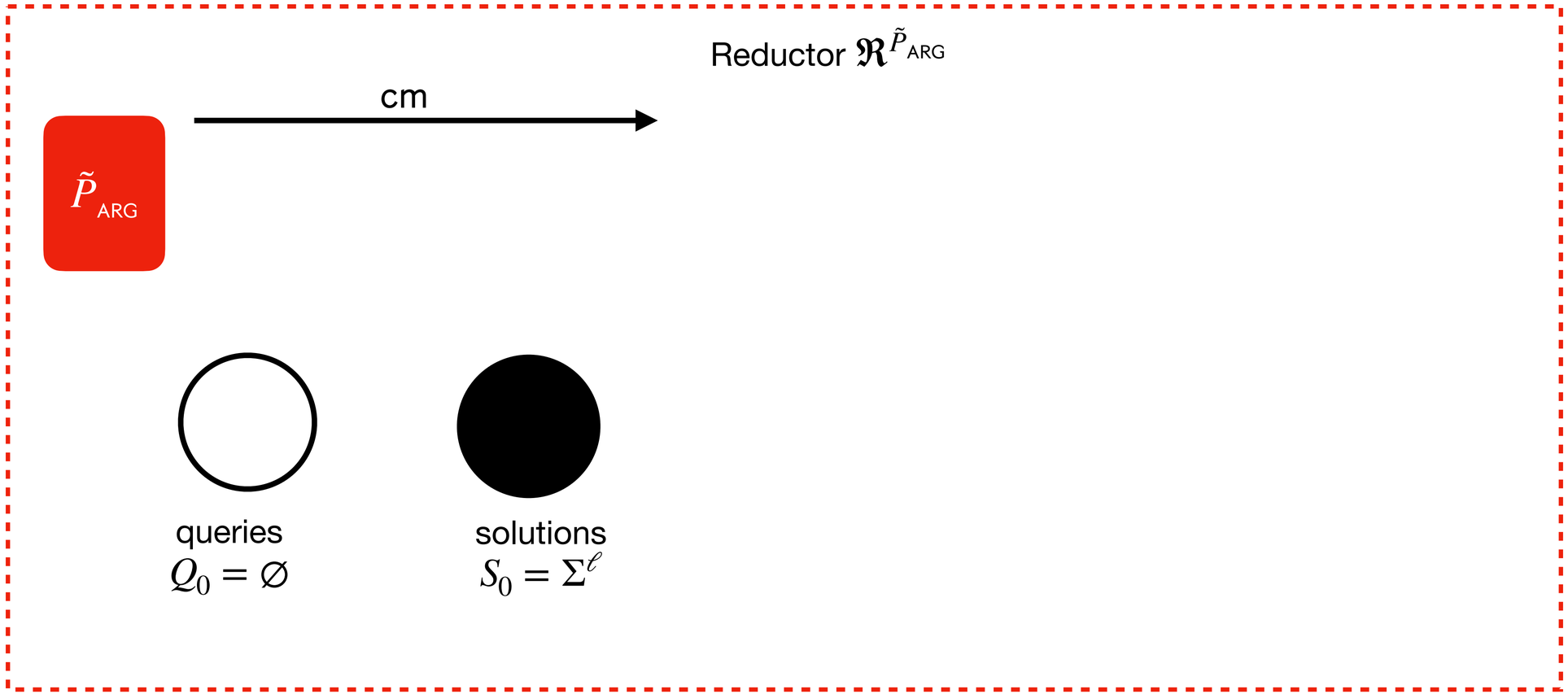
Security reduction for Funky[FPCP, FC]

Goal:
(for FPCPs and non-interactive FCs)

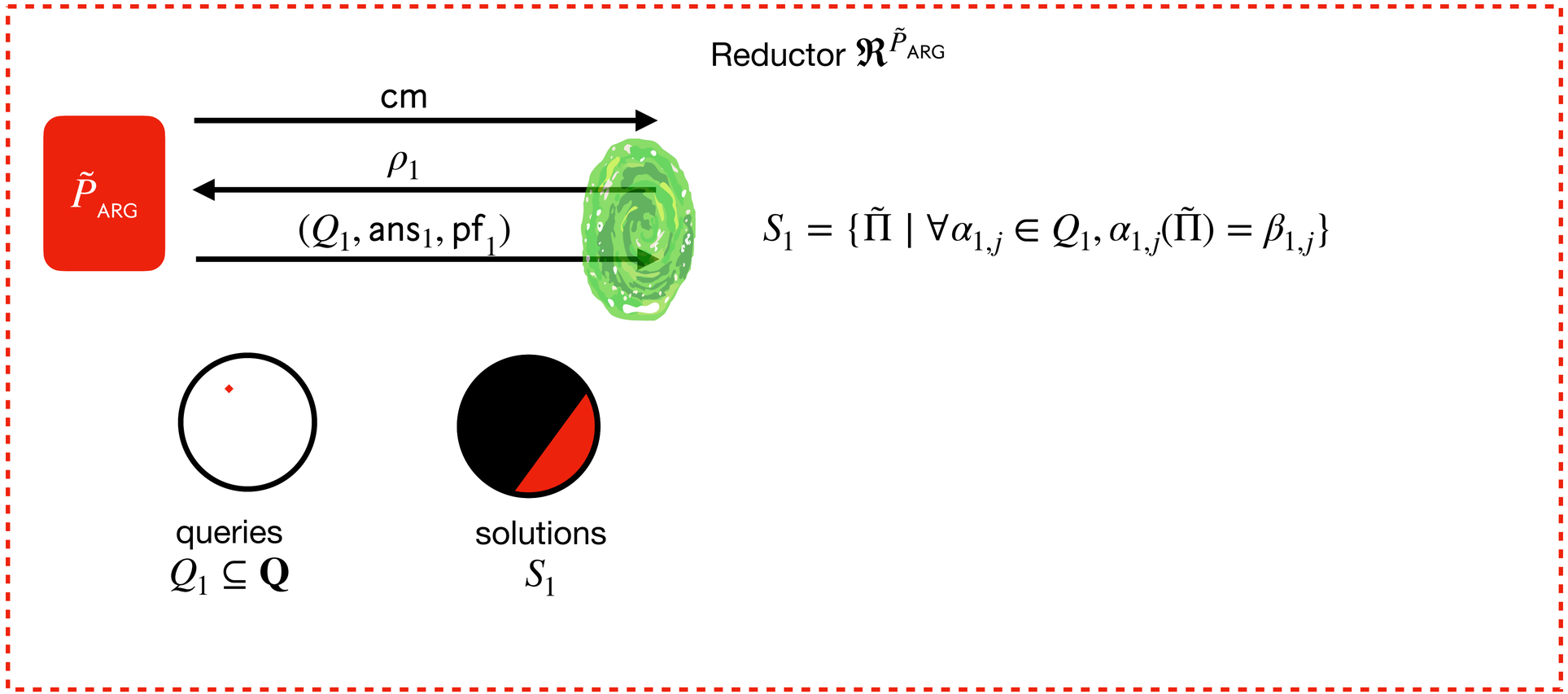
$$\epsilon_{\mathsf{ARG}}(t_{\mathsf{ARG}}) \leq \epsilon_{\mathsf{FIOP}} + \mathsf{k} \cdot \epsilon_{\mathsf{FC}}(t_{\mathsf{FC}}) + \mathsf{k} \cdot \epsilon_{\mathbf{Q}}(l, \mathsf{N}), \text{ where } t_{\mathsf{FC}} = O\left(t_{\mathsf{ARG}} \cdot \mathsf{N}\right)$$



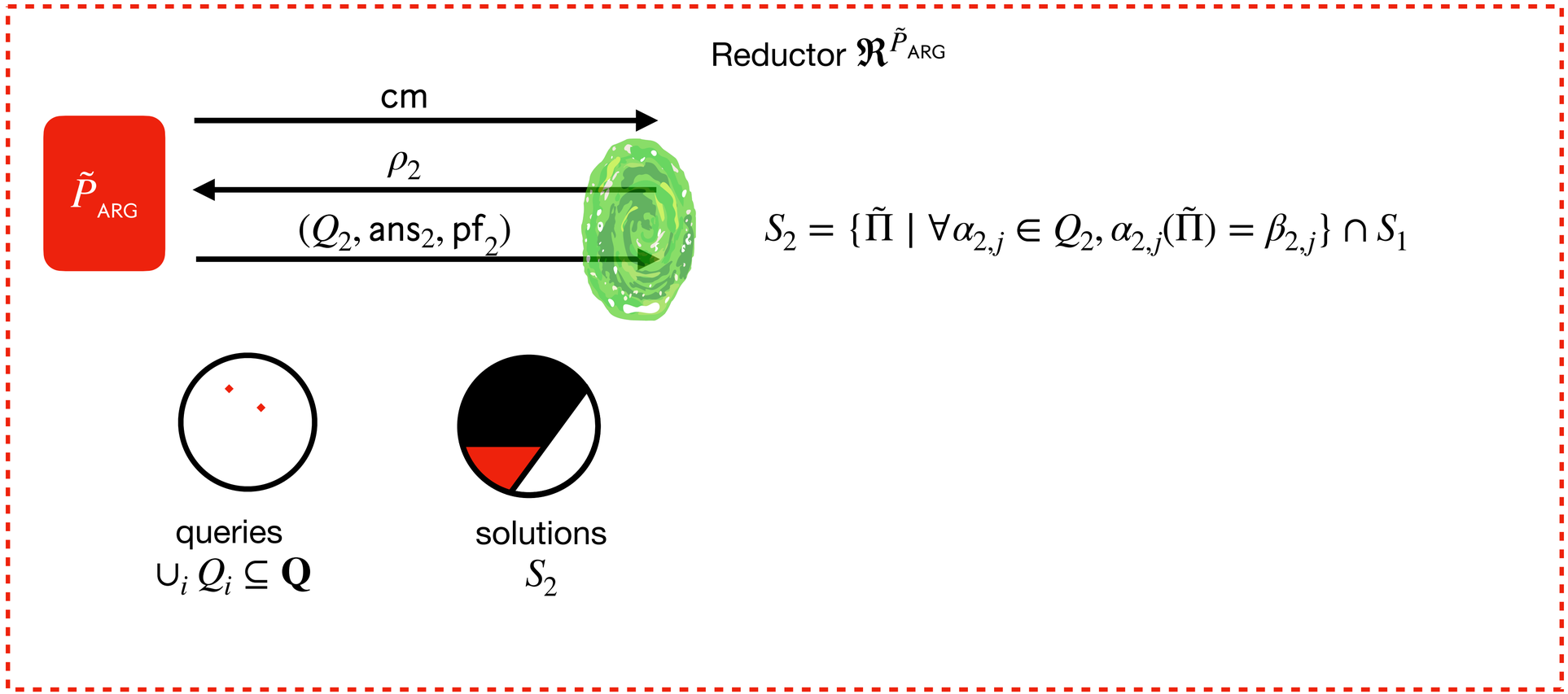
Security reduction for Funky[FPCP, FC]



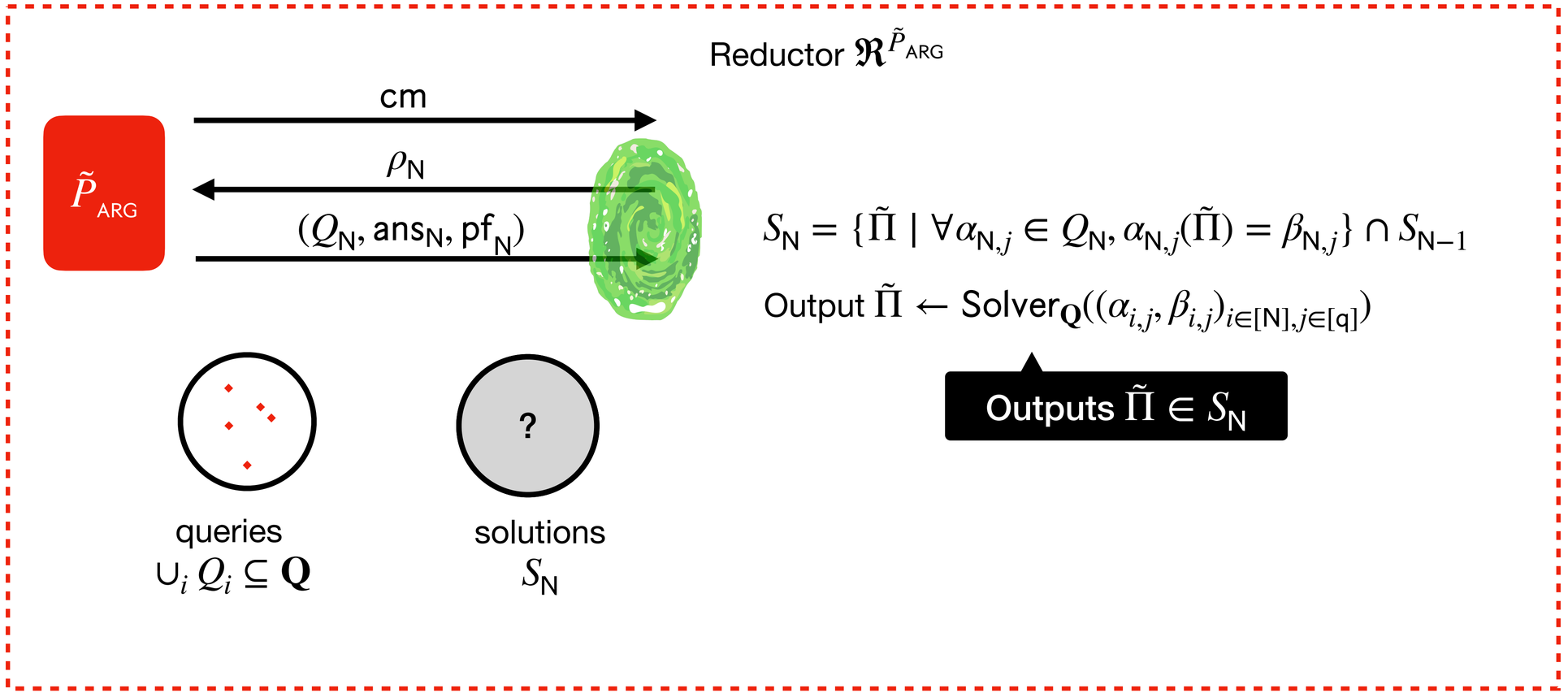
Security reduction for Funky[FPCP, FC]



Security reduction for Funky[FPCP, FC]



Security reduction for Funky[FPCP, FC]



Security reduction for Funky[FPCP, FC]

$$\Pr\left[\langle \tilde{P}, V(x)\rangle = 1\right] \leq \Pr\left[\begin{array}{l}\text{Sample } \rho \\ \text{FPCP verifier accepts: } \mathbf{V}^{\tilde{\Pi}}(x;\rho) = 1 \\ \text{ARG verifier accepts: } V(x;\rho;Q, \text{ans}, \text{pf})\rangle = 1\end{array}\right]$$

Produced by the reductor $\mathfrak{R}^{\tilde{P}_{\text{ARG}}}$

FPCP soundness
$\leq \epsilon_{\text{FPCP}}(x)$

Produced by a t_{ARG}-time adversary $\tilde{P}_{\text{ARG}}$ given ρ

$$+ \Pr\left[\begin{array}{l}\text{Sample } \rho \\ \text{FPCP verifier rejects: } \mathbf{V}^{\tilde{\Pi}}(x;\rho) \neq 1 \\ \text{ARG verifier accepts: } V(x;\rho;Q, \text{ans}, \text{pf})\rangle = 1\end{array}\right]$$

Security reduction lemma
$\leq \epsilon_{\text{FC}}(t_{\text{FC}}) + \epsilon_{\mathbf{Q}}(\ell, \text{N})$

- Either (Q, ans) is inconsistent with $\tilde{\Pi}$; or
- (Q, ans) contains "new queries"

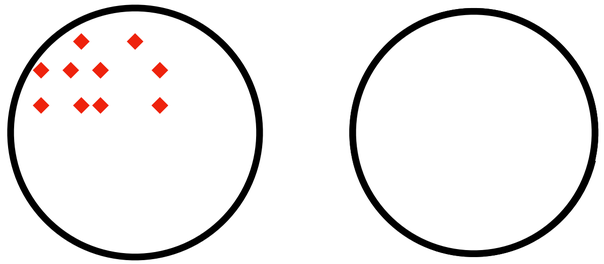
$S_{\text{N+1}} = \emptyset$ (no solution)
→ FC verifier accepts all FC proofs

$S_{\text{N+1}} \neq \emptyset \wedge S_{\text{N+1}} \neq S_{\text{N}}$
→ *tail error* of the query class $\mathbf{Q}$

Security reduction lemma

queries $\cup_i Q_i$ solutions S_i

Case 1:

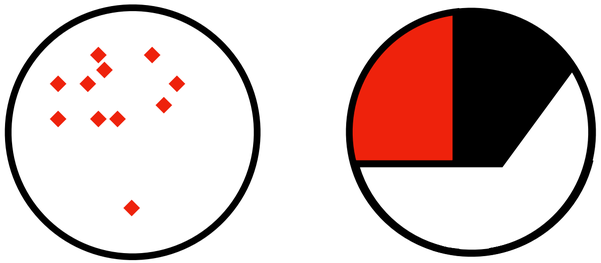


$$\Pr\left[\begin{array}{l}\nexists\tilde{\Pi} : \forall\alpha \in \cup_i Q_i : \alpha(\tilde{\Pi}) = \mathsf{ans}[\alpha] \\ \text{Yet all FC checks pass}\end{array}\right] \leq \epsilon_{\mathsf{FC}}(t_{\mathsf{FC}})$$

Function binding

$S_{\mathsf{N}+1} = \varnothing$ (no solution)
→ FC verifier accepts all FC proofs

Case 2:



$i = \mathsf{N} + 1$

Internal property of $\mathbf{Q}$
Independent of FIOP/FC

$$\Pr\left[S_{\mathsf{N}+1} \neq \varnothing \wedge S_{\mathsf{N}+1} \neq S_{\mathsf{N}}\right] \leq \epsilon_{\mathbf{Q}}(\ell, \mathsf{N})$$

Tail error

$S_{\mathsf{N}+1} \neq \varnothing \wedge S_{\mathsf{N}+1} \neq S_{\mathsf{N}}$
→ *tail error* of the query class $\mathbf{Q}$

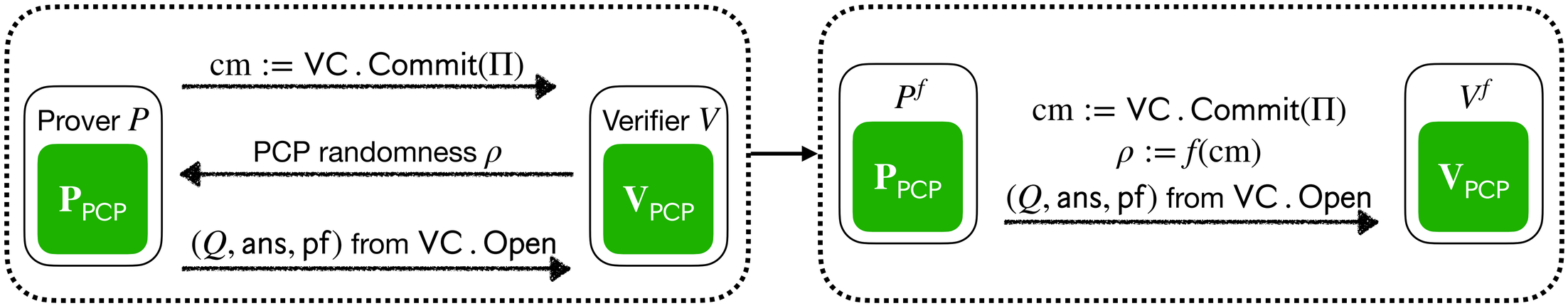
Tail error well-behaved for reasonable query classes:
For large N, unlikely that the $(\mathsf{N}+1)$-th rewind gives new info

Fiat-Shamir security: From succinct arguments to SNARGs

Fiat-Shamir transformation

Random oracle: $\mathcal{O} = \{\mathcal{O}_\lambda\}_{\lambda \in \mathbb{N}}$
$\mathcal{O}_\lambda$: uniform distribution over $\{f\colon \{0,1\}^* \to \{0,1\}^\lambda\}$

Succinct interactive arguments → Succint non-interactive arguments



Central question: Is security preserved after the Fiat-Shamir transformation?

In generical no [CY24]: $\epsilon_{\mathsf{NARG}}(x, t, m) \leq (m+1)^{\mathsf{k}} \cdot \epsilon_{\mathsf{ARG}}(x, t)$

RO queries

k might be superconstant!

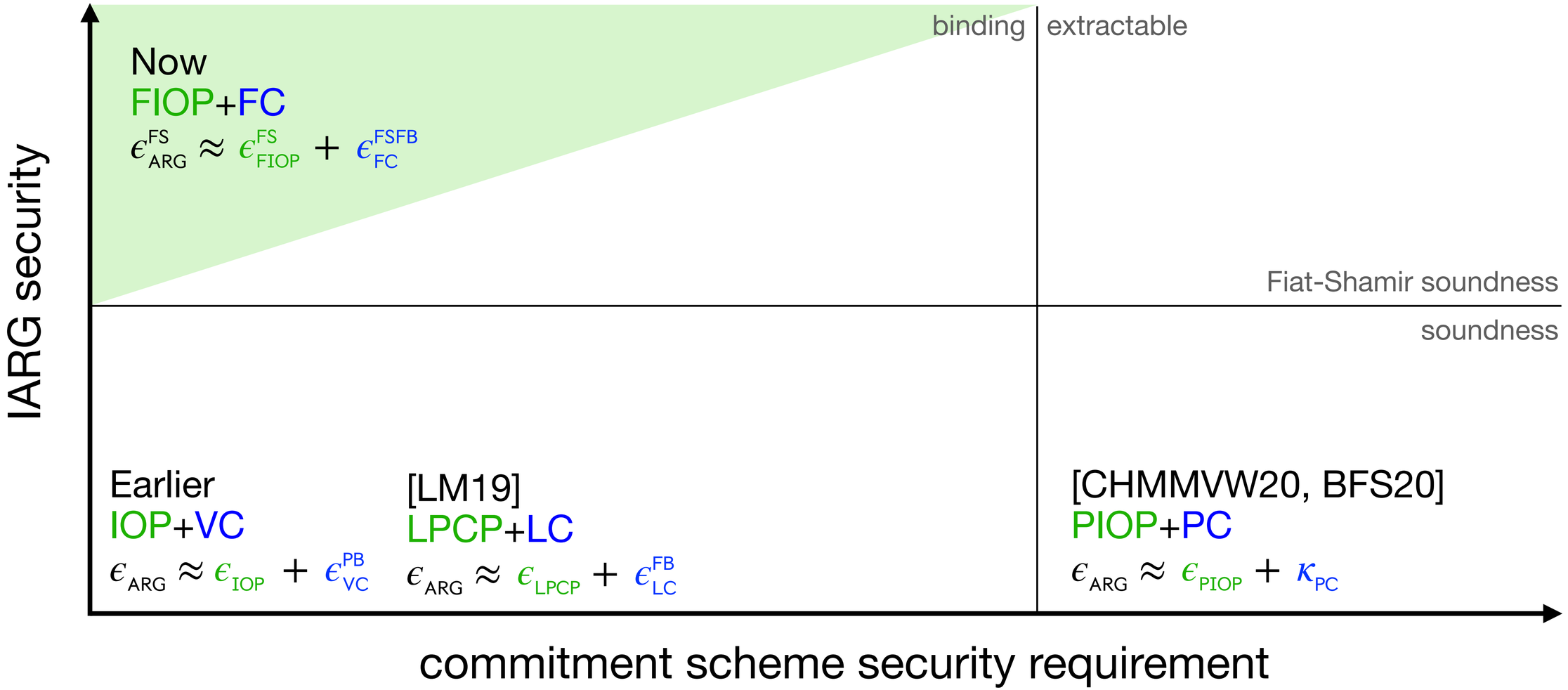
Fiat-Shamir security

Theorem. $\forall\, \mathsf{N} \in \mathbb{N}$,

$$\epsilon_{\text{NARG}}(t_{\text{ARG}}, m_{\text{ARG}}) \leq \epsilon_{\text{FIOP}}^{\text{FS}}(O(m_{\text{ARG}})) + \mathsf{k} \cdot \epsilon_{\text{FC}}^{\text{FSFB}}(t_{\text{FC}}, m_{\text{FC}}) + \mathsf{k} \cdot \epsilon_{\mathbf{Q}}(l, \mathsf{N}), \text{ where } \begin{cases} t_{\text{FC}} = O\left(t_{\text{ARG}} \cdot \mathsf{N}\right) \\ m_{\text{FC}} = O\left(m_{\text{ARG}} \cdot \mathsf{k} \cdot \mathsf{N}\right) \end{cases}.$$

A theorem that generalizes everything we saw (except post-quantum)

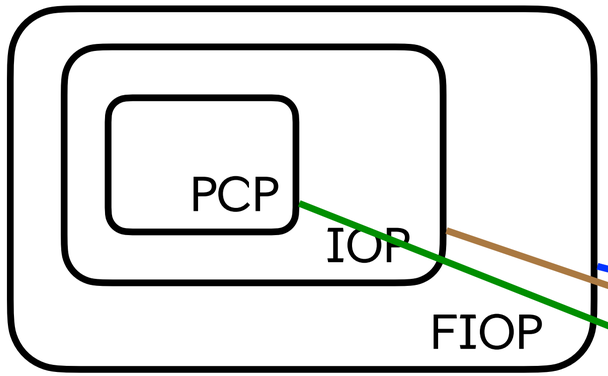
Previous standard-model analyses

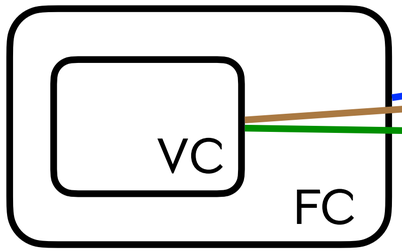


Open problems

Probabilistic proofs

Commitment schemes





Standard model Fiat-Shamir?

Quantum analogue?

Funky protocol
- Soundness
- Fiat-Shamir soundness

Post-quantum security?

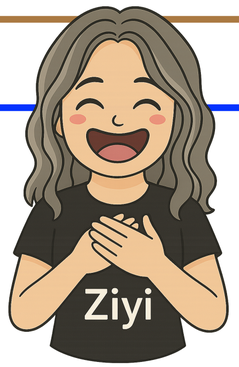
Expected-time regime?

Practical security in idealized models?

IBCS protocol
- Soundness
- Private-coin IOPs
- Post-quantum soundness

Kilian's protocol
- Soundness
- Lower bounds on soundness

Kilian vs. Sigma protocols?



Thank you!

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