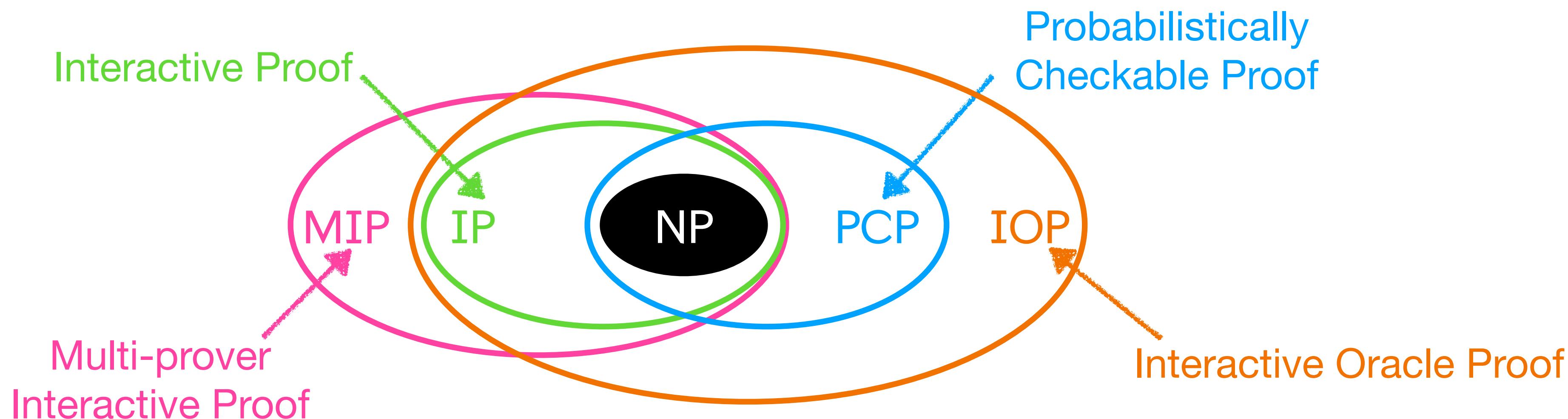


On Parallel Repetition of PCPs

Alessandro Chiesa, Ziyi Guan, Burcu Yıldız

What is parallel repetition?

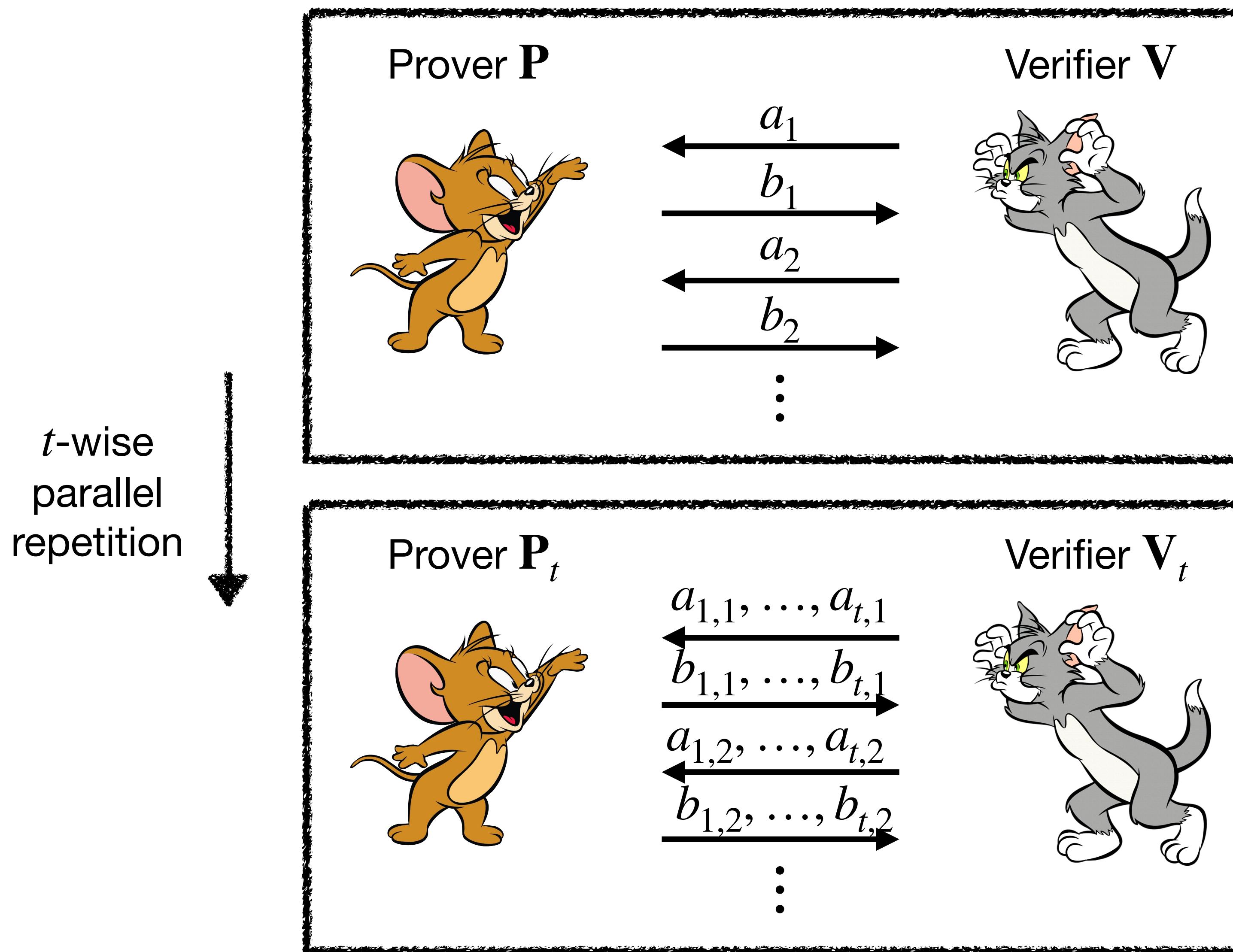
Probabilistic proof systems



Fundamental question: How to **reduce soundness error** for probabilistic proofs?

- **Rerun** the proof system for t times: soundness error $\beta \mapsto \beta^t$, but other efficiency measures increase as t increases.
 - Sometimes we call this rerunning strategy the **sequential repetition**.
- **Parallel repetition**: reduce soundness error while preserve key efficiency measures.
 - Defined differently for different probabilistic proofs.

Parallel repetition for IPs (interactive proofs)



Sequential repetition:
Round complexity $k \mapsto t \cdot k$

Round complexity $k \mapsto k \checkmark$

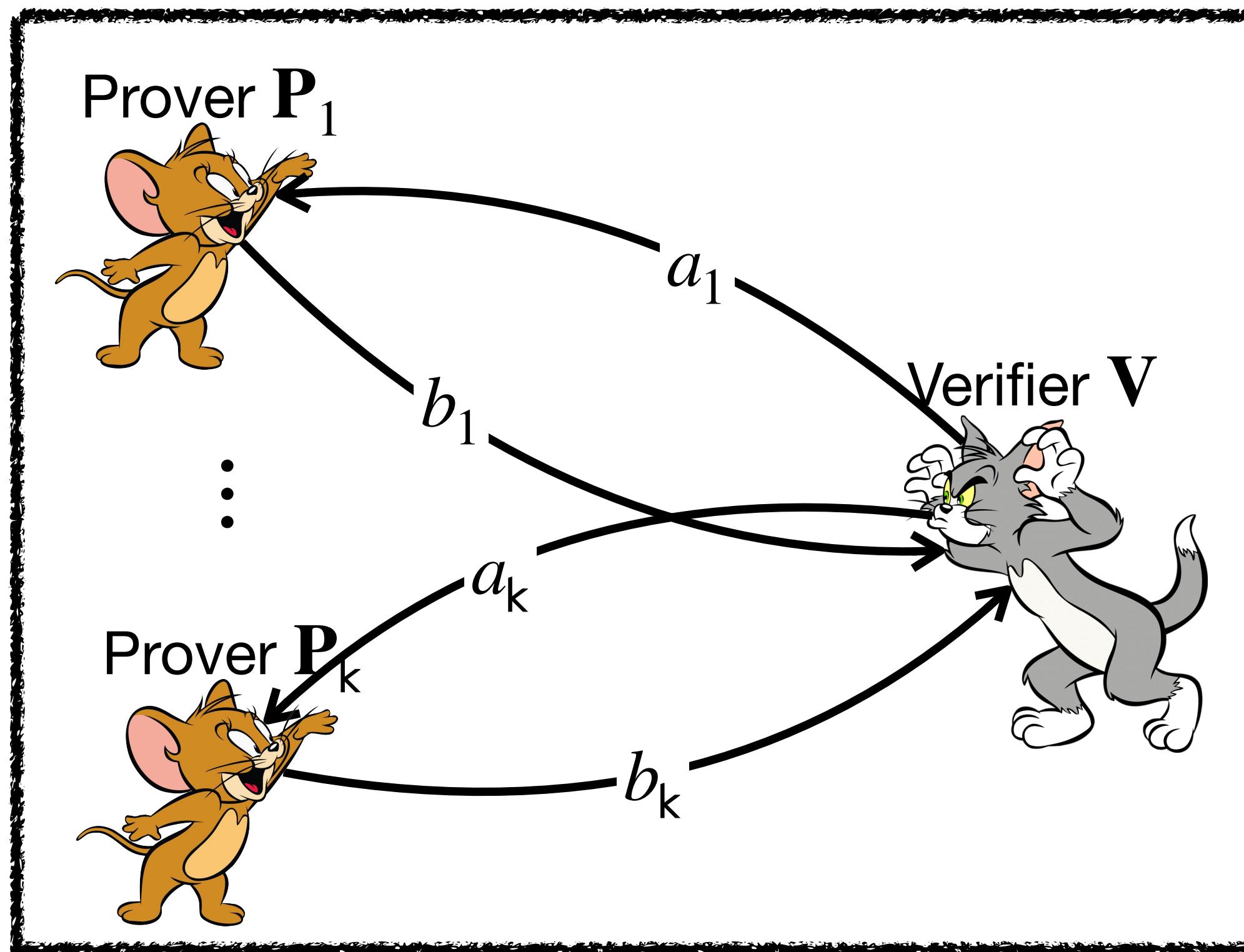
Verifier communication complexity $vc \mapsto t \cdot vc$

Verifier randomness complexity $r \mapsto t \cdot r$

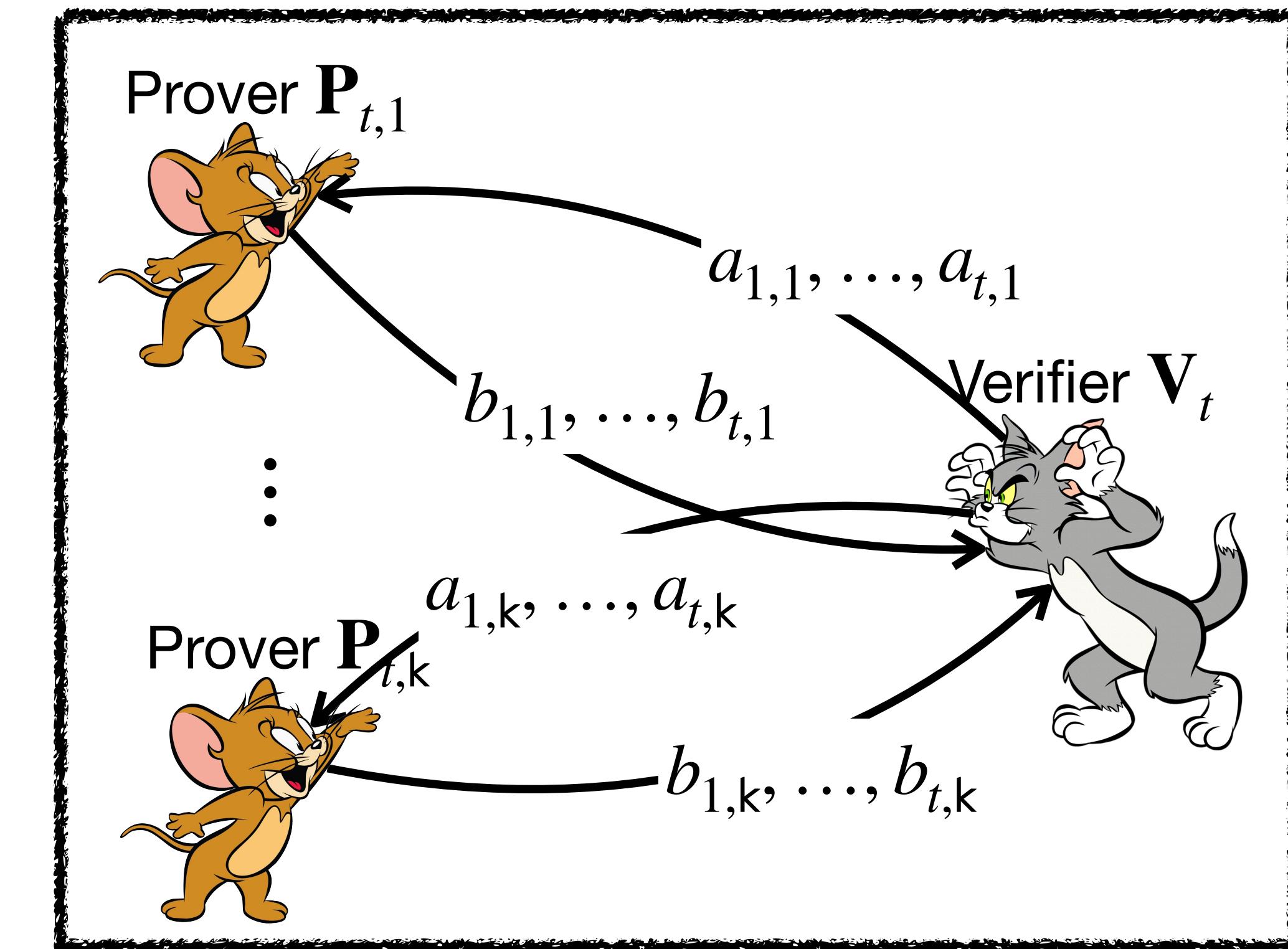
How about the soundness error?

- Soundness error $\beta \mapsto \beta^t \checkmark$

Parallel repetition for MIPs (multi-prover interactive proofs)



t -wise
parallel
repetition



Number of provers $k \mapsto k$ ✓

Round complexity preserved ✓

Prover communication complexity $pc \mapsto t \cdot pc$

Verifier communication complexity $vc \mapsto t \cdot vc$

Verifier randomness complexity $r \mapsto t \cdot r$

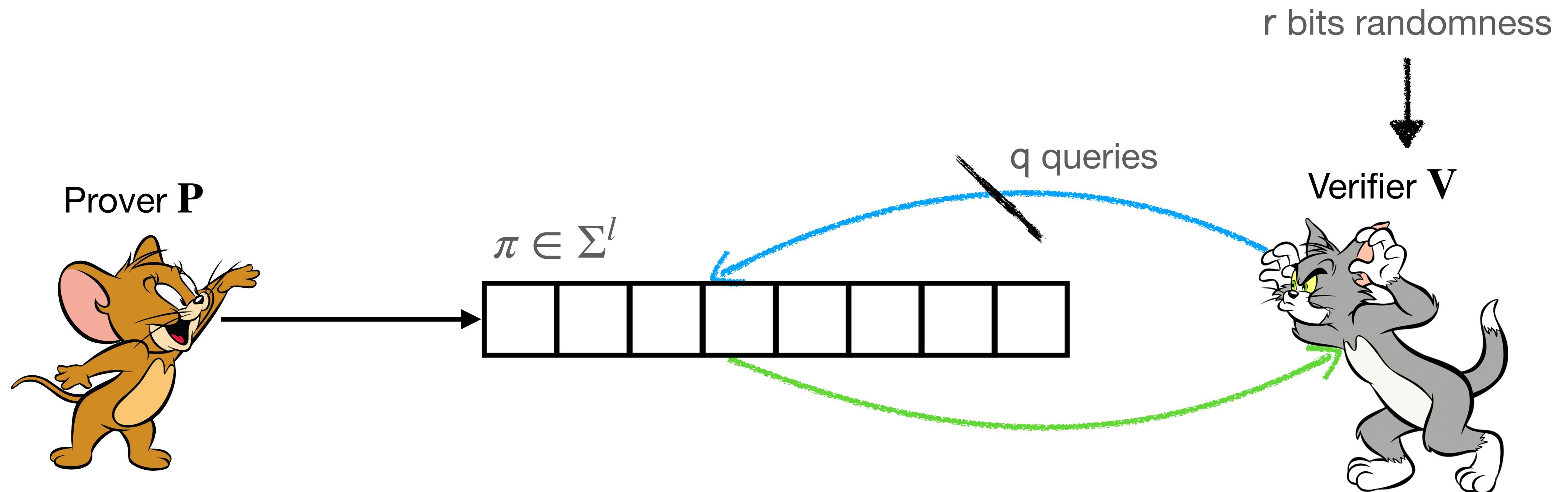
How about the soundness error?

- $\beta^t \leq \beta_t \leq \beta$
- Soundness error $\beta < 1 \implies \lim_{t \rightarrow \infty} \beta_t = 0$

[Verbitsky96]

- 2-prover MIP: $\beta_t \leq \beta^{c_V t}$ [Raz98]
- k -prover MIP: open
- Not as good as parallel repetition for IP

Probabilistically checkable proof (PCP)

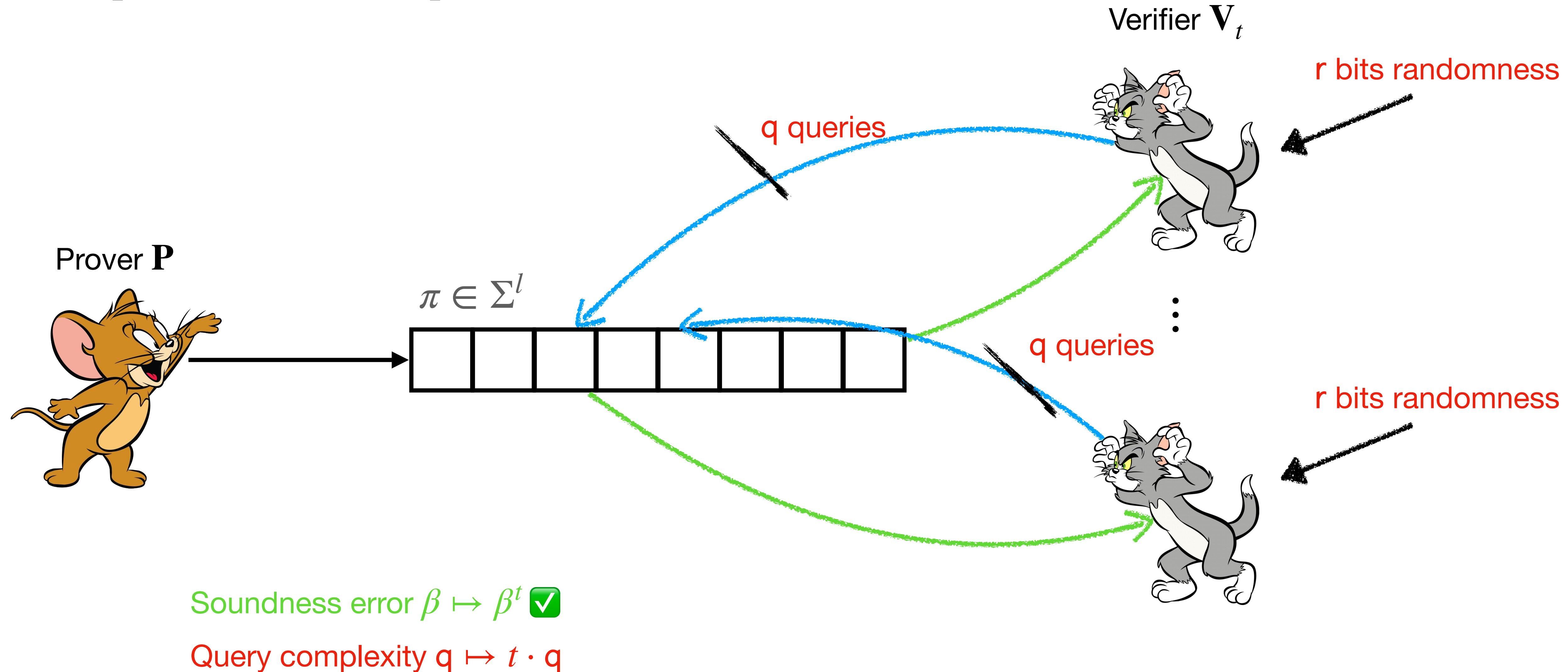


Perfect completeness: for every $x \in L$, let $\pi := P(x)$, $\Pr_{\rho \leftarrow \{0,1\}^r} [V^\pi(x; \rho) = 1] = 1$.

Soundness: for every $x \notin L$ and $\tilde{\pi} \in \Sigma^l$, $\Pr_{\rho \leftarrow \{0,1\}^r} [V^{\tilde{\pi}}(x; \rho) = 1] \leq \beta$.

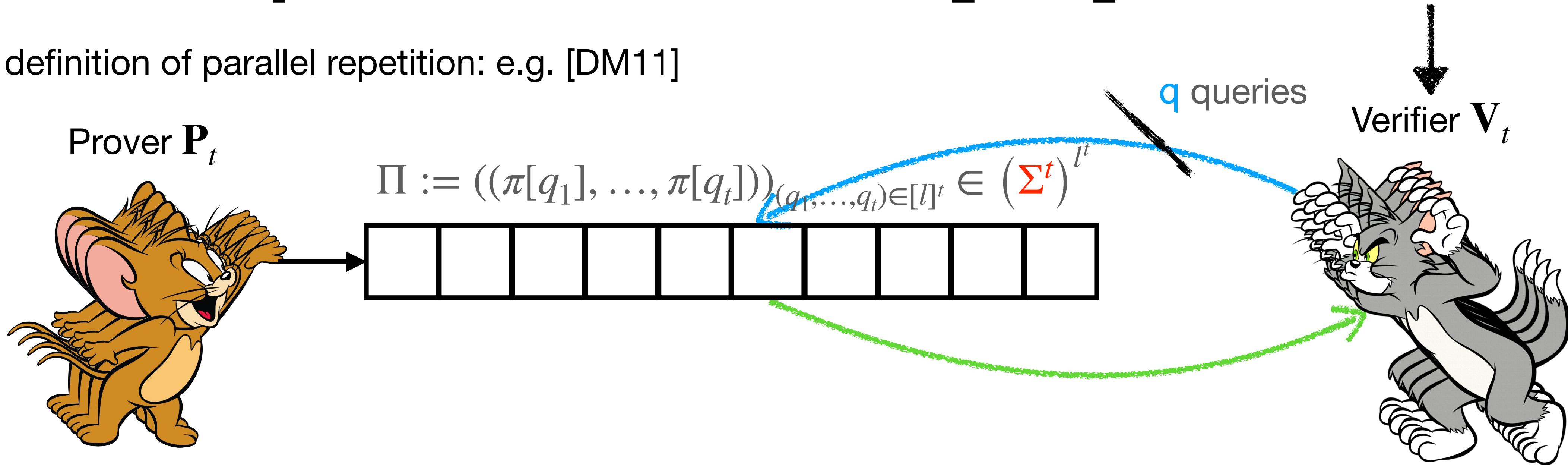
How to **reduce soundness error** for PCPs?

Sequential repetition for PCPs



Parallel repetition for PCPs [1/3]

Natural definition of parallel repetition: e.g. [DM11]



	ρ_1	ρ_2	\dots	ρ_t
Q_1	$Q_1[1]$	$Q_2[1]$	\dots	$Q_t[1]$
Q_2	$Q_1[2]$	$Q_2[2]$	\dots	$Q_t[2]$
\vdots	\vdots	\vdots	\vdots	\vdots
Q_q	$Q_1[q]$	$Q_2[q]$	\dots	$Q_t[q]$

1. Sample t randomness for V : $(\rho_i)_{i \in [t]} \leftarrow (\{0,1\}^r)^t$.
2. Compute query lists of V : $Q_i := V_q(x; \rho_i)$.
3. Compute queries of V_t : $Q_i := (Q_j[i])_{j \in [t]}$.
4. Query the PCP string Π : $\text{ans}_i := \Pi[Q_i]$.
5. Check that for every repetition $i \in [t]$: $V_d(x, \rho_i, (\text{ans}_j[i])_{j \in [q]})$.

Parallel repetition for PCPs [2/3]

E.g.: 2-wise parallel repetition of a 3-query PCP

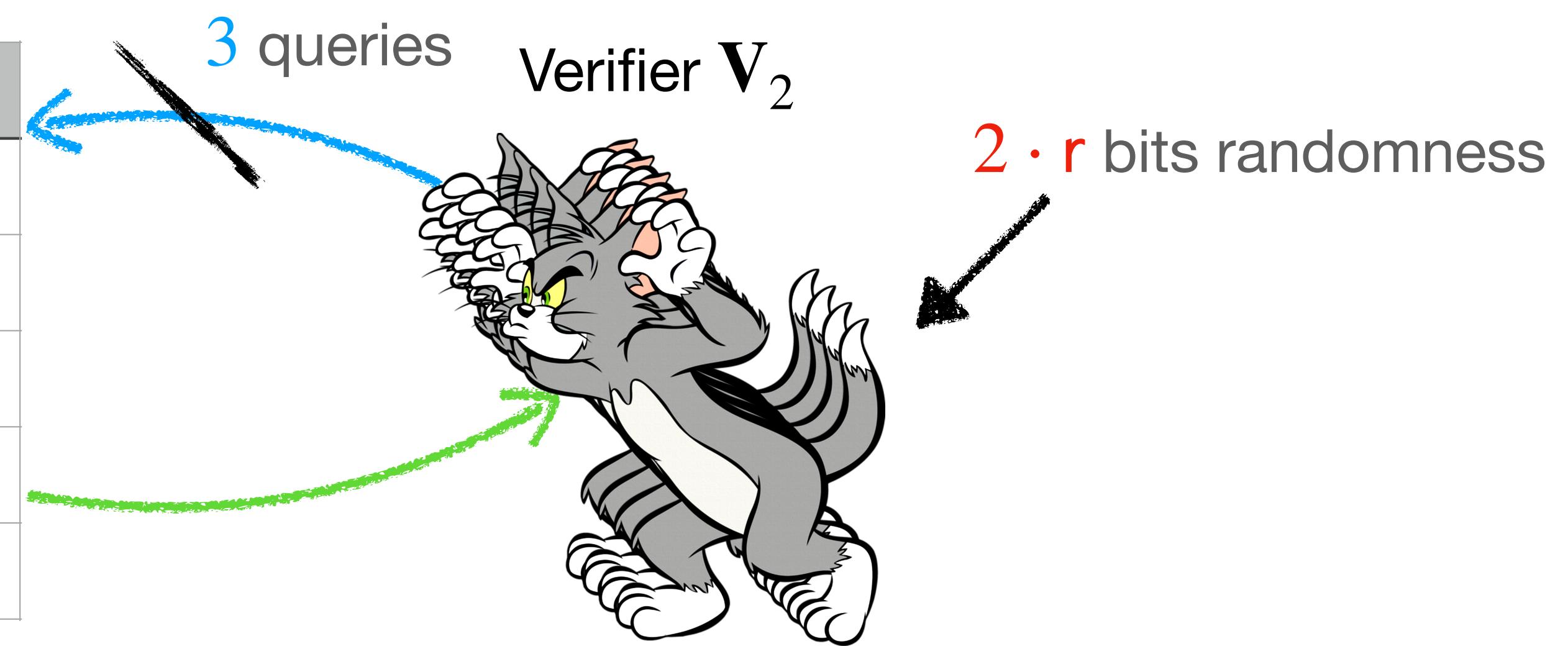
- Verifier \mathbf{V}_2 samples ρ_1 and ρ_2 for the two repetitions.
- Assume $Q_1 = (q_{1,1}, q_{1,2}, q_{1,3})$ and $Q_2 = (q_{2,1}, q_{2,2}, q_{2,3})$.
- $\mathbf{Q}_1 := (q_{1,1}, q_{2,1})$, $\mathbf{Q}_2 := (q_{1,2}, q_{2,2})$ and $\mathbf{Q}_3 := (q_{1,3}, q_{2,3})$.

$$\pi = (a, b, c, d, e)$$

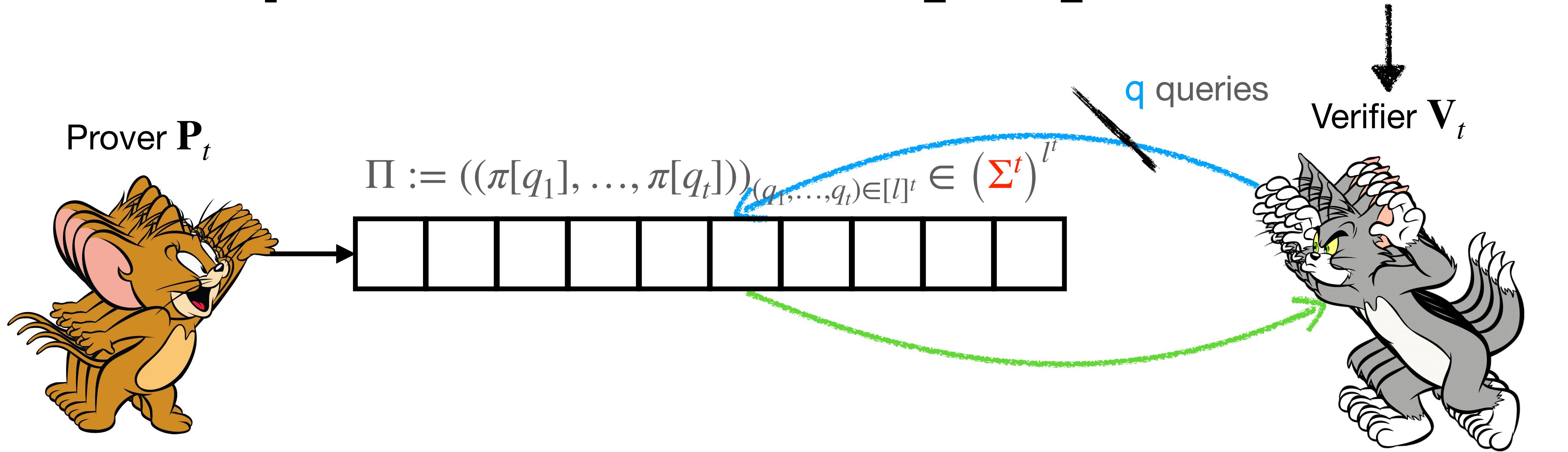
First position
in \mathbf{V}_2 's query

Π	1	2	3	4	5
1	(a, a)	(a, b)	(a, c)	(a, d)	(a, e)
2	(b, a)	(b, b)	(b, c)	(b, d)	(b, e)
3	(c, a)	(c, b)	(c, c)	(c, d)	(c, e)
4	(d, a)	(d, b)	(d, c)	(d, d)	(d, e)
5	(e, a)	(e, b)	(e, c)	(e, d)	(e, e)

Second position
in \mathbf{V}_2 's query



Parallel repetition for PCPs [3/3]



Query complexity $q \mapsto q \checkmark$

Alphabet size $\Sigma \mapsto \Sigma^t$

Proof length $l \mapsto l^t$

Verifier randomness complexity $r \mapsto t \cdot r$

What is the soundness error?

- Let β_t be the soundness error of the parallel repetition of PCP.
- What is β_t as a function of β and t ?

Our results

Result 1. Parallel repetition for PCP **doesn't** work: For a wide range of NP-complete languages, parallel repetition brings the limit of soundness error to 1.

Result 2. Parallel repetition for a PCP **works** if and only if the **MIP projection of the PCP** has non-trivial soundness.

Result 3. Rate of decay of parallel repetition for some PCPs cannot be better than that for MIPs.

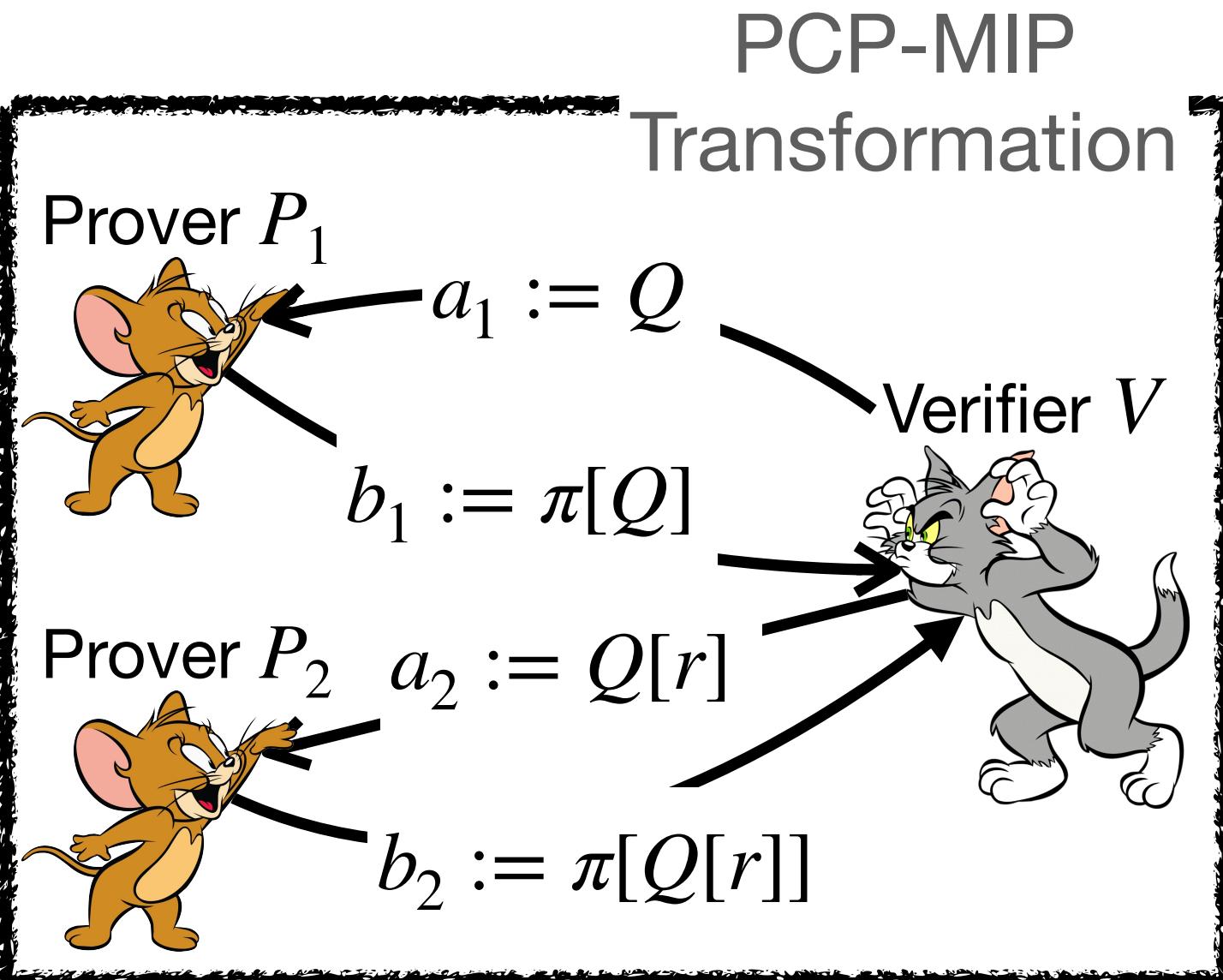
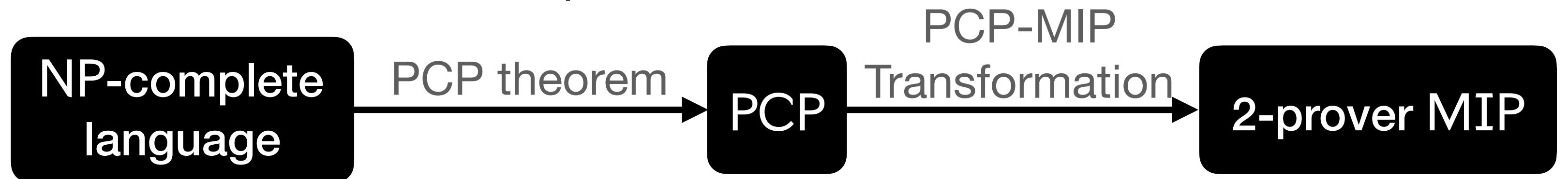
Result 4. Consistent parallel repetition (a variant of parallel repetition that we defined) for PCPs work as expected with exponential rate of decay.

Isn't parallel repetition for PCP used previously?

e.g. Hardness of approximation

Too expensive! Soundness error $\beta \mapsto 1 - \frac{1 - \beta}{q}$

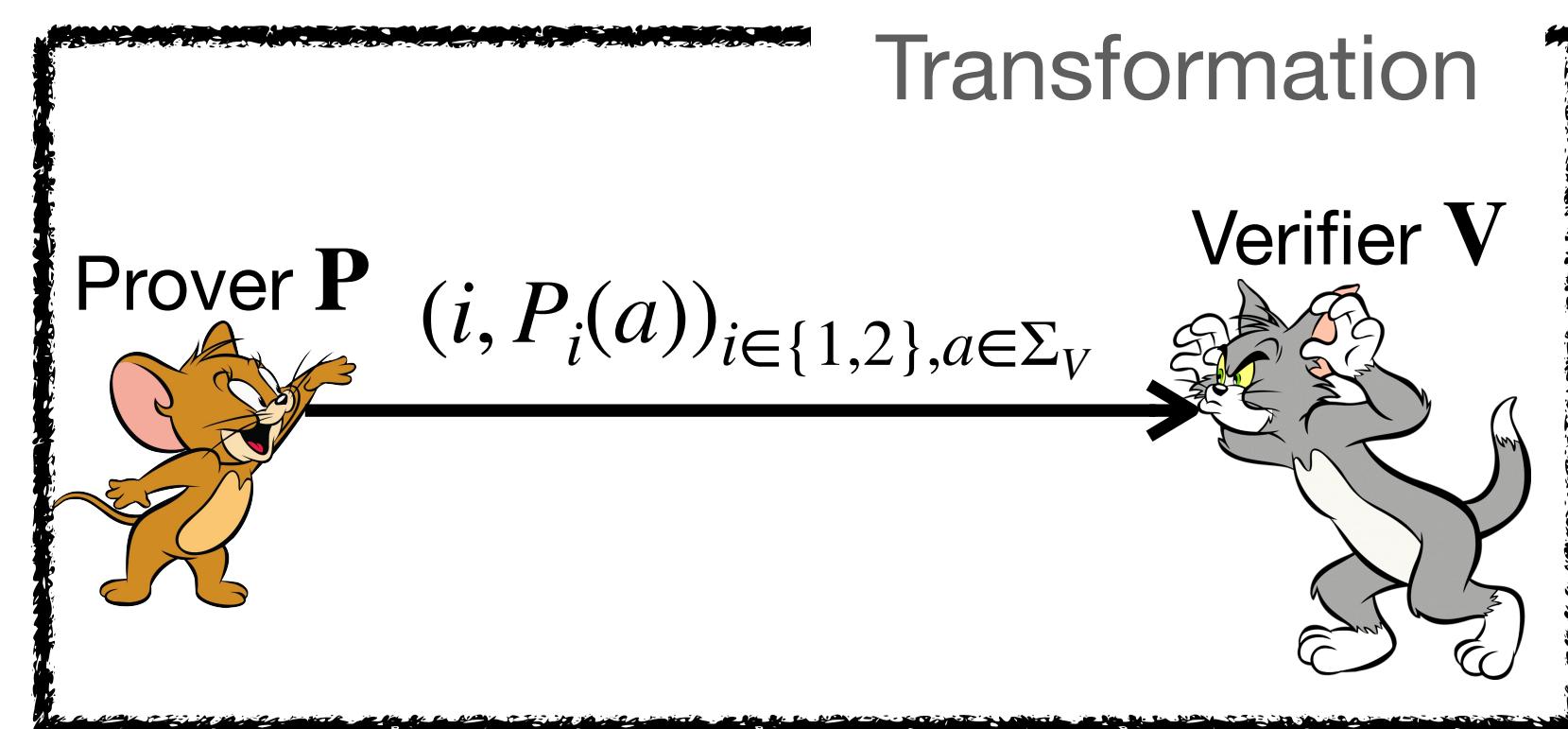
Step 1. Transform a PCP to a 2-prover MIP.



Step 2. Parallel repeat the 2-prover MIP to reduce soundness error.



Step 3. Convert the repeated MIP back to a PCP.



Parallel repetition for PCPs fails



Parallel repetition for PCPs fails

Theorem 1.

2-query PCP
for NP-complete language L
soundness error $\beta < 1$

t-wise
parallel repetition

2-query PCP for L
soundness error β_t

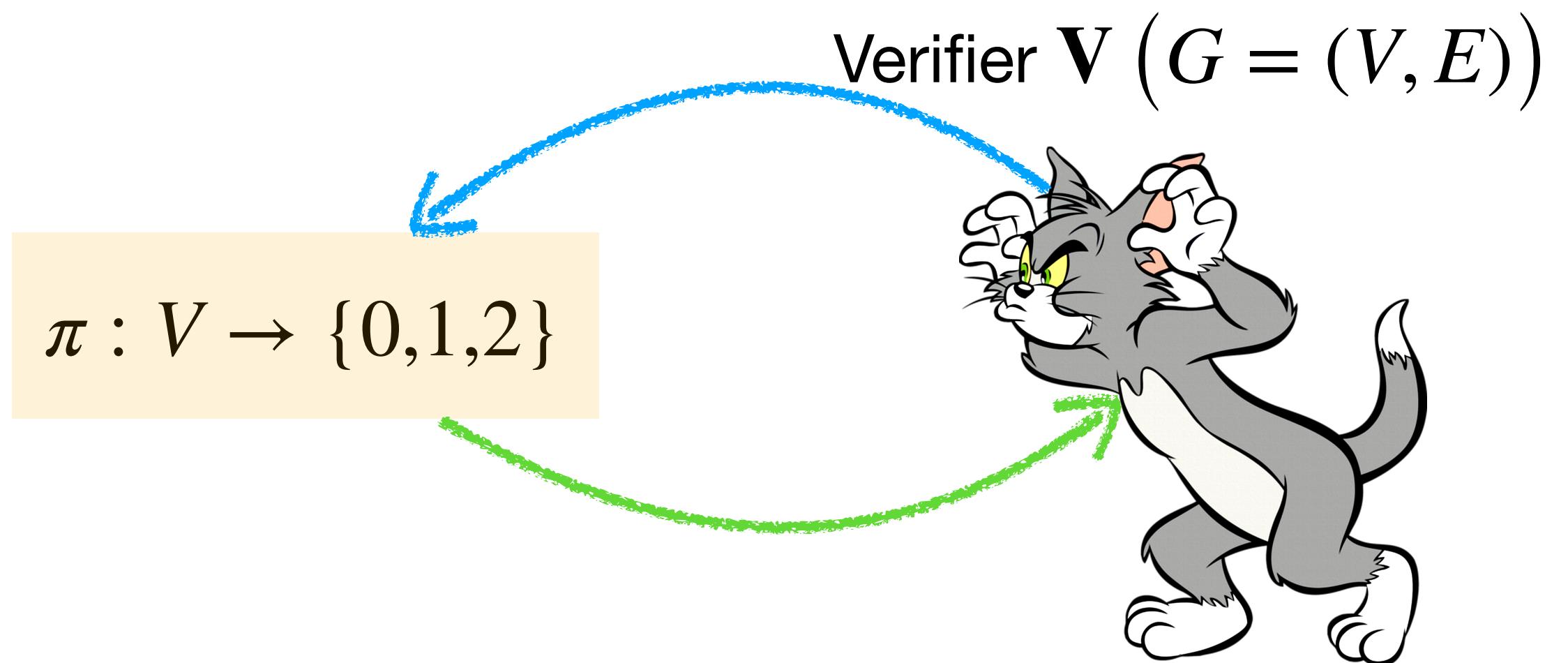
for every $x \notin L$, $\lim_{t \rightarrow \infty} \beta_t = 1$



In particular, $\beta(x)^t \leq \beta_t(x) \leq \beta(x)$ does not hold.

PCP for 3COL

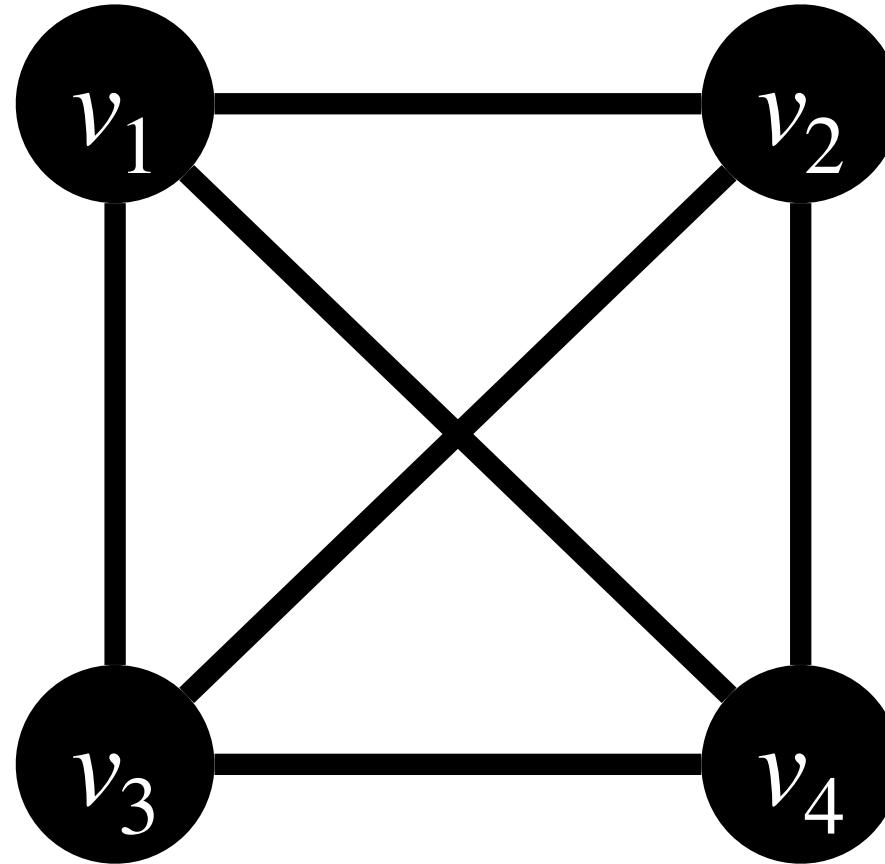
- $3\text{COL} := \{G : G \text{ has a 3-coloring}\}$
- $\text{PCP} = (\mathbf{P}, \mathbf{V})$ for 3COL



1. Sample $\{u, v\} \leftarrow E$. (Assume $u < v$.)
2. Query π at u and v , and check that $\pi[u] \neq \pi[v]$.

- Perfect completeness: \mathbf{V} always accepts for every $G \in 3\text{COL}$.
- Soundness: $\beta(G) \leq \frac{|E| - 1}{|E|}$ for every $G \notin 3\text{COL}$.

Parallel repetition for PCP for 3COL fails [1/2]



First position
in \mathbf{V}_2 's query

Second position
in \mathbf{V}_2 's query

$\tilde{\Pi}$	v_1	v_2	v_3	v_4
v_1	(0,0)	(0,0)	(0,0)	(0,0)
v_2	(0,0)	(1,1)	(1,1)	(1,1)
v_3	(0,0)	(1,1)	(1,1)	(1,1)
v_4	(0,0)	(1,1)	(1,1)	(1,1)



- \mathbf{V}_2 rejects if and only if answers to both queries are (1,1):
 - Why can't it happen when both answers are (0,0)?
 - Both answers are (1,1) if and only if v_1 is not queried.
- Soundness error: $\beta_2(K_4) \geq 1 - \left(\frac{3}{6}\right)^2 = \frac{3}{4}$.

- \mathbf{V} 's query lists: $Q_1 = (\textcolor{green}{u}_1, w_1), Q_2 = (\textcolor{green}{u}_2, w_2)$.
- \mathbf{V}_2 's queries: $\mathbf{Q}_1 = (\textcolor{green}{u}_1, \textcolor{blue}{u}_2), \mathbf{Q}_2 = (\textcolor{blue}{w}_1, w_2)$.
 - $\textcolor{green}{u}_1 < w_1$ and $\textcolor{green}{u}_2 < w_2$.
 - Answer to \mathbf{Q}_2 cannot be (0,0).

Parallel repetition for PCP for 3COL fails [2/2]

Malicious prover strategy

For every possible query (q_1, q_2) of \mathbf{V}_2 :

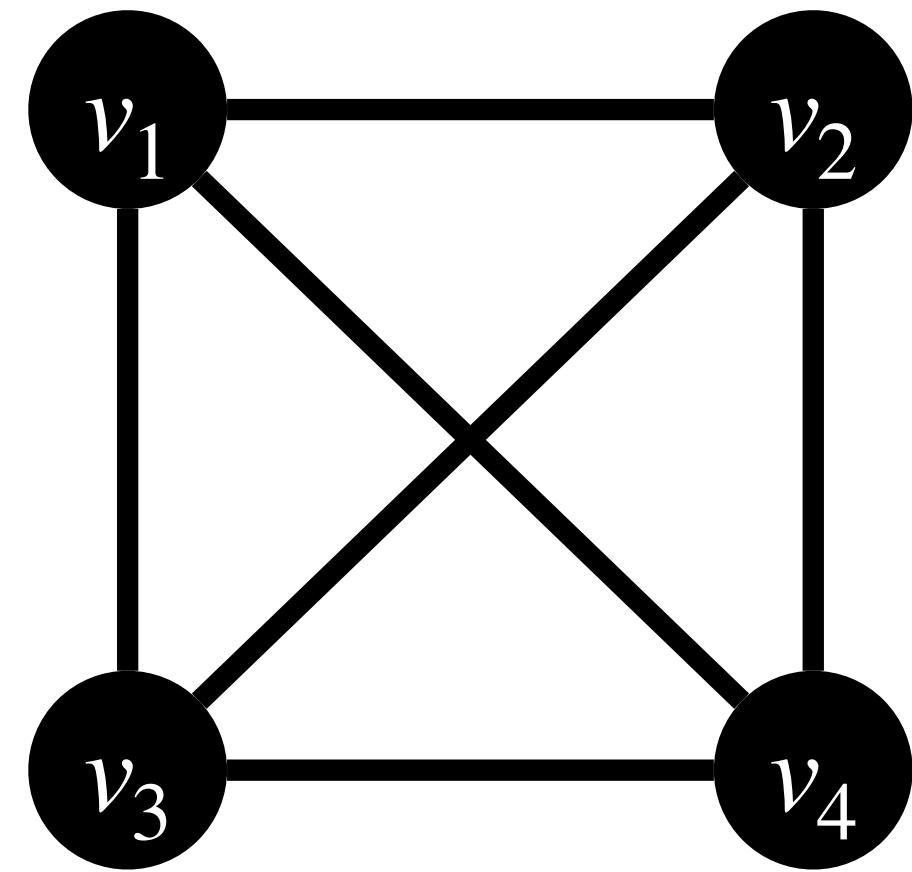
- If at least one of (q_1, q_2) is the **smallest non-isolated vertex in G** : Set $\tilde{\Pi}[(q_1, q_2)] = (0,0)$.
- Otherwise, Set $\tilde{\Pi}[(q_1, q_2)] = (1,1)$.

$$\implies \beta_2(G) \geq 1 - \left(\frac{|E| - 1}{|E|} \right)^2.$$

t-wise parallel repetition: $\beta_t(G) \geq 1 - \left(\frac{|E| - 1}{|E|} \right)^t$

$$\implies \lim_{t \rightarrow \infty} \beta_t(G) = 1.$$

Parallel repetition for PCP increases soundness error



- $\beta(K_4) \leq \frac{5}{6}$
- $\beta_2(K_4) \geq \frac{3}{4}$
- $\beta_2(K_4) > \beta(K_4)$

In general, we can show that there are **infinitely many** instances $G \notin \text{3COL}$ such that $\beta_t(G) > \beta_{t-1}(G)$.

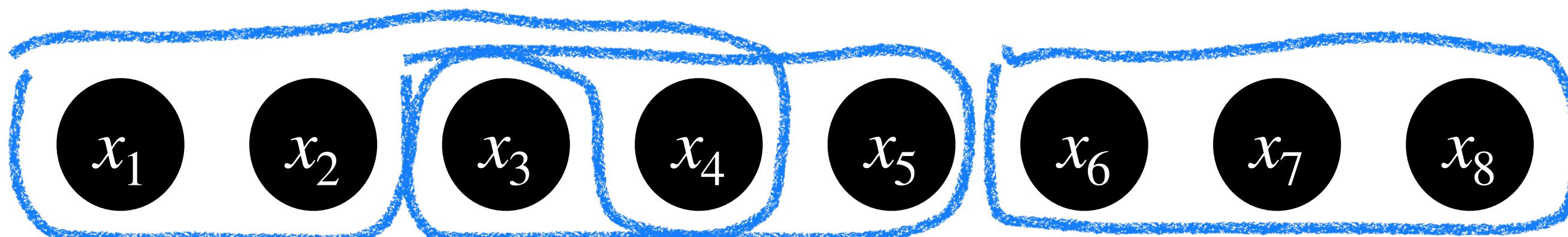
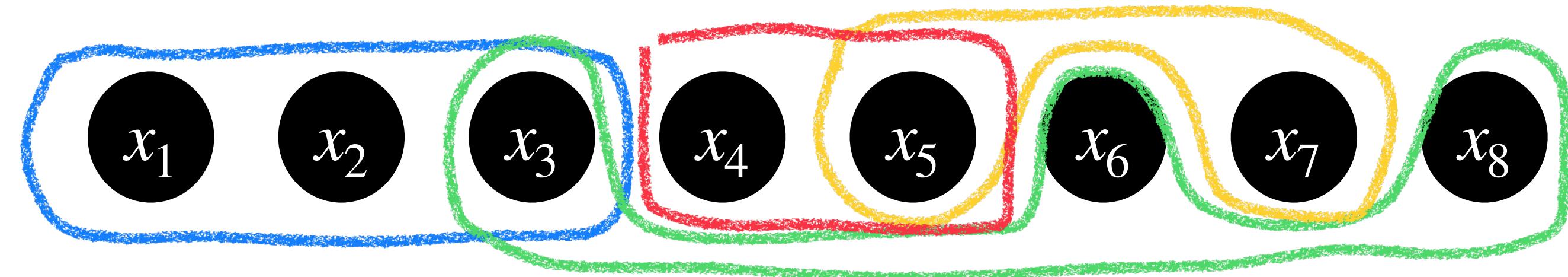
Generalization to symmetric CSPs [1/2]

Constraint satisfaction problem (CSP):

- A list ϕ of constraints over variables in X .
- Each constraint checks a predicate f over some variables.
- ϕ is satisfiable if and only if there is an assignment to the variables that satisfies all constraints.

⇒ 3COL is a CSP: each constraint is over an edge and checking the vertex colors.

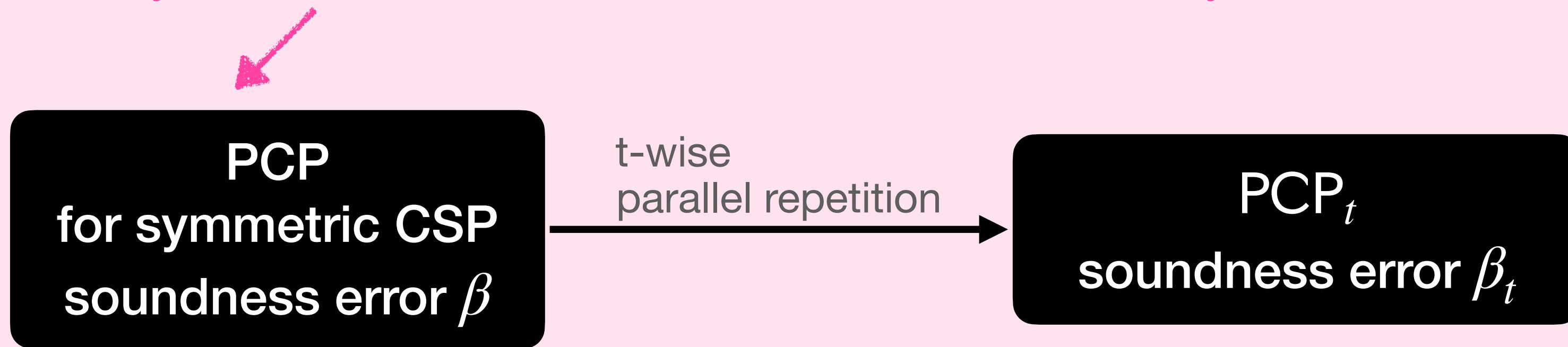
3COL is a **symmetric CSP**: the predicate for each constraint is the same.



Generalization to symmetric CSPs [2/2]

Lemma 1.

randomly selects a constraint and check its satisfiability



$$\text{for every } t \in \mathbb{N}, \beta_{t+1} \geq \beta_t \text{ and } \beta > 0 \implies \lim_{t \rightarrow \infty} \beta_t > 0$$

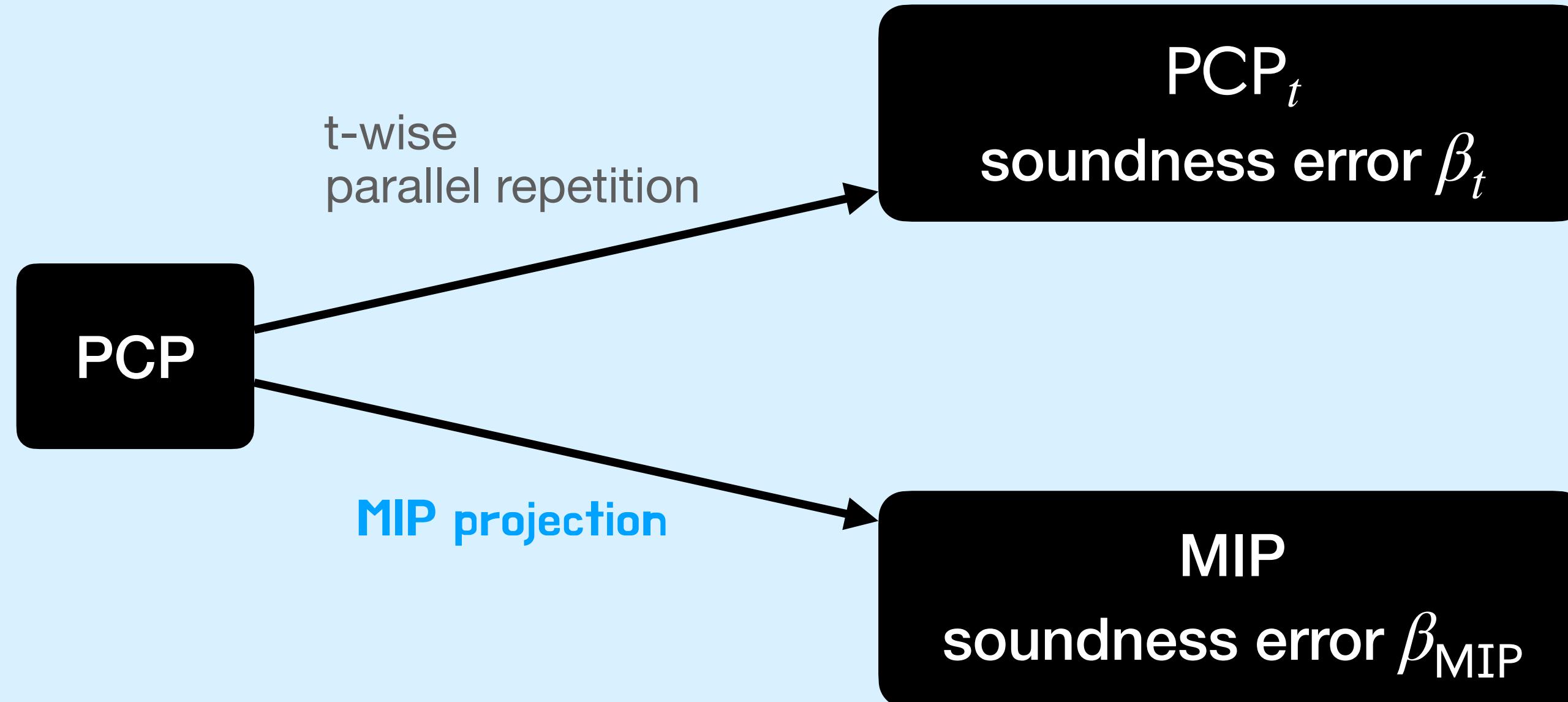
Note: Lemma 1 does not extend to non-symmetric CSPs. e.g. 3SAT is a non-symmetric CSP, we show that for some instances for 3SAT, $\beta > 0$ and $\lim_{t \rightarrow \infty} \beta_t = 0$.

A characterization result



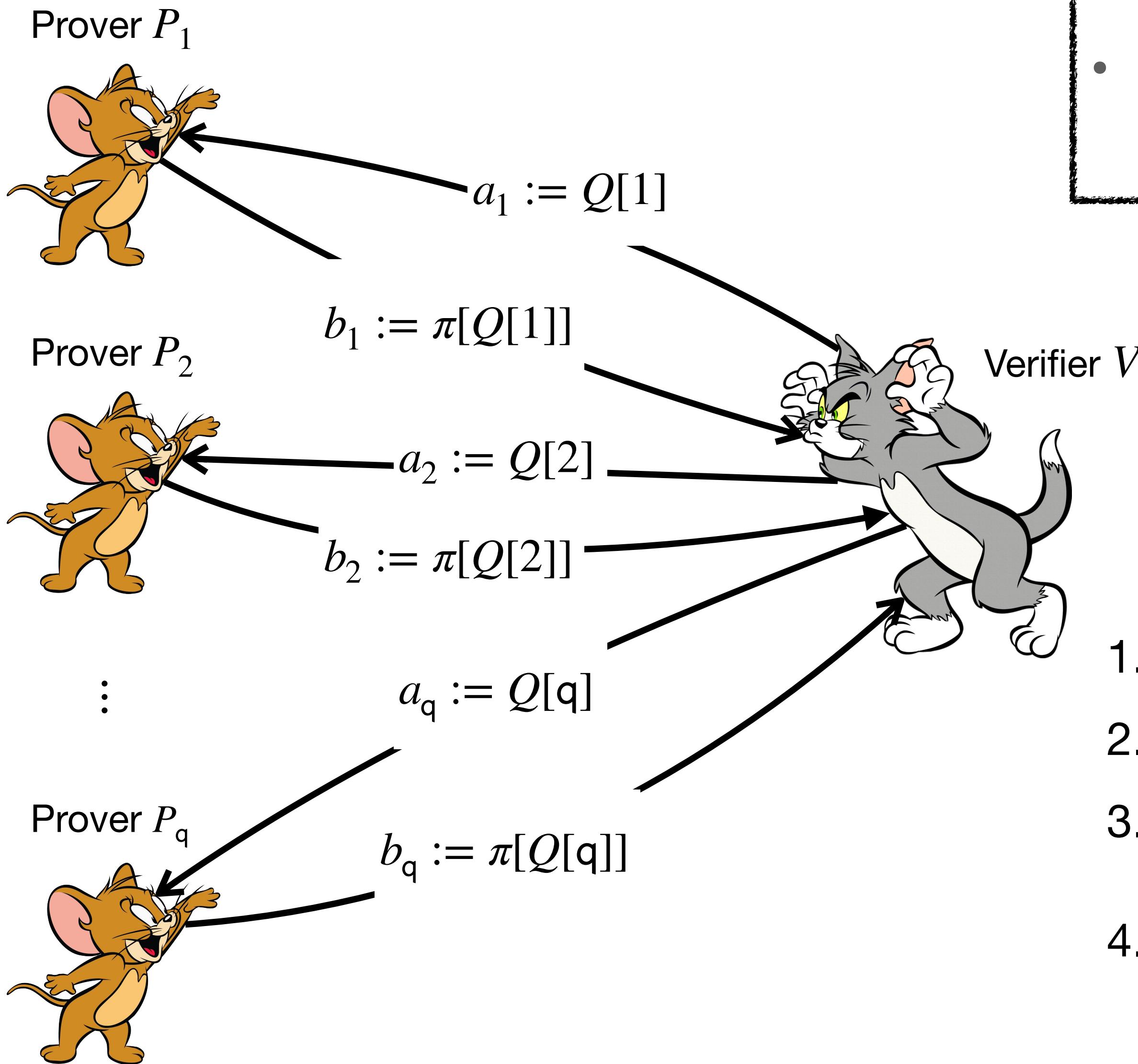
The characterization result

Theorem 2.



$$\text{for every } x \notin L, \lim_{t \rightarrow \infty} \beta_t = 0 \iff \beta_{\text{MIP}} < 1$$

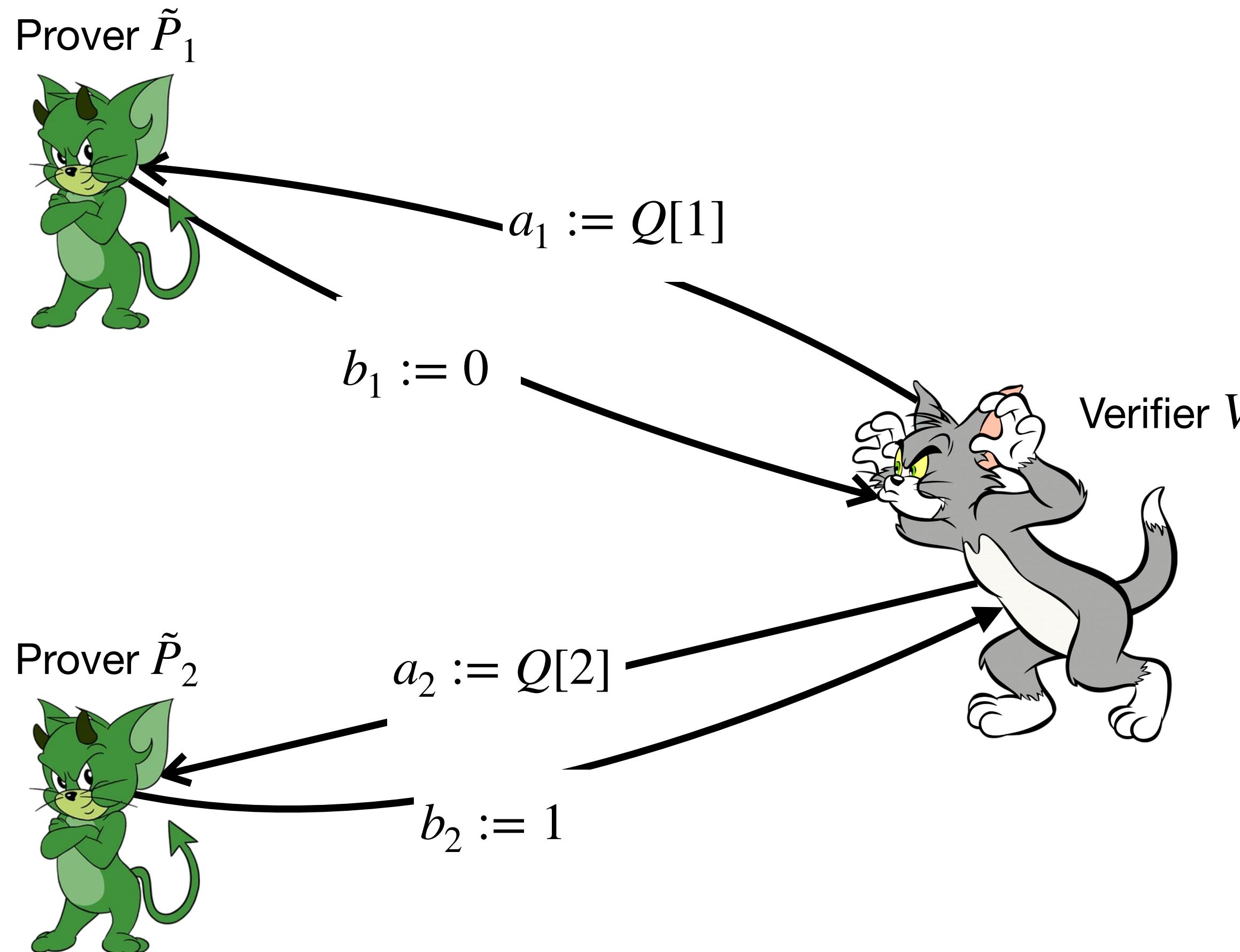
MIP projection



- Completeness of the MIP is the same as that of PCP.
- Soundness: for every $x \notin L$, $\beta_{\text{MIP}}(x) \geq \beta_{\text{PCP}}(x)$.
 - **No consistency check** \implies MIP might not be secure.

1. Sample a randomness for \mathbf{V} : $\rho \leftarrow \{0,1\}^r$.
2. Compute query lists of \mathbf{V} : $Q := \mathbf{V}_q(x; \rho)$.
3. Send the i -th query to the i -th prover P_i and get their replies.
4. Check that \mathbf{V} accept: $\mathbf{V}_d \left(x, \rho, (b_i)_{i \in [q]} \right)$.

Revisit: parallel repetition for PCP for 3COL



Theorem 2. $\lim_{t \rightarrow \infty} \beta_t = 0 \iff \beta_{\text{MIP}} < 1$

$\Rightarrow \beta_{\text{MIP}} = 1$ for 3COL.

- First malicious MIP prover always send 0.
- Second malicious MIP prover always send 1.

Proof of Theorem 2 [1/2]

$$\beta_{\text{MIP}} = 1 \implies \lim_{t \rightarrow \infty} \beta_t \geq \frac{1}{2^r} > 0$$

	ρ_1	ρ_2	\dots	ρ_t
\mathbf{Q}_1	$Q_1[1]$	$Q_2[1]$	\dots	$Q_t[1]$
\mathbf{Q}_2	$Q_1[2]$	$Q_2[2]$	\dots	$Q_t[2]$
\vdots				\vdots
\mathbf{Q}_q	$Q_1[q]$	$Q_2[q]$	\dots	$Q_t[q]$

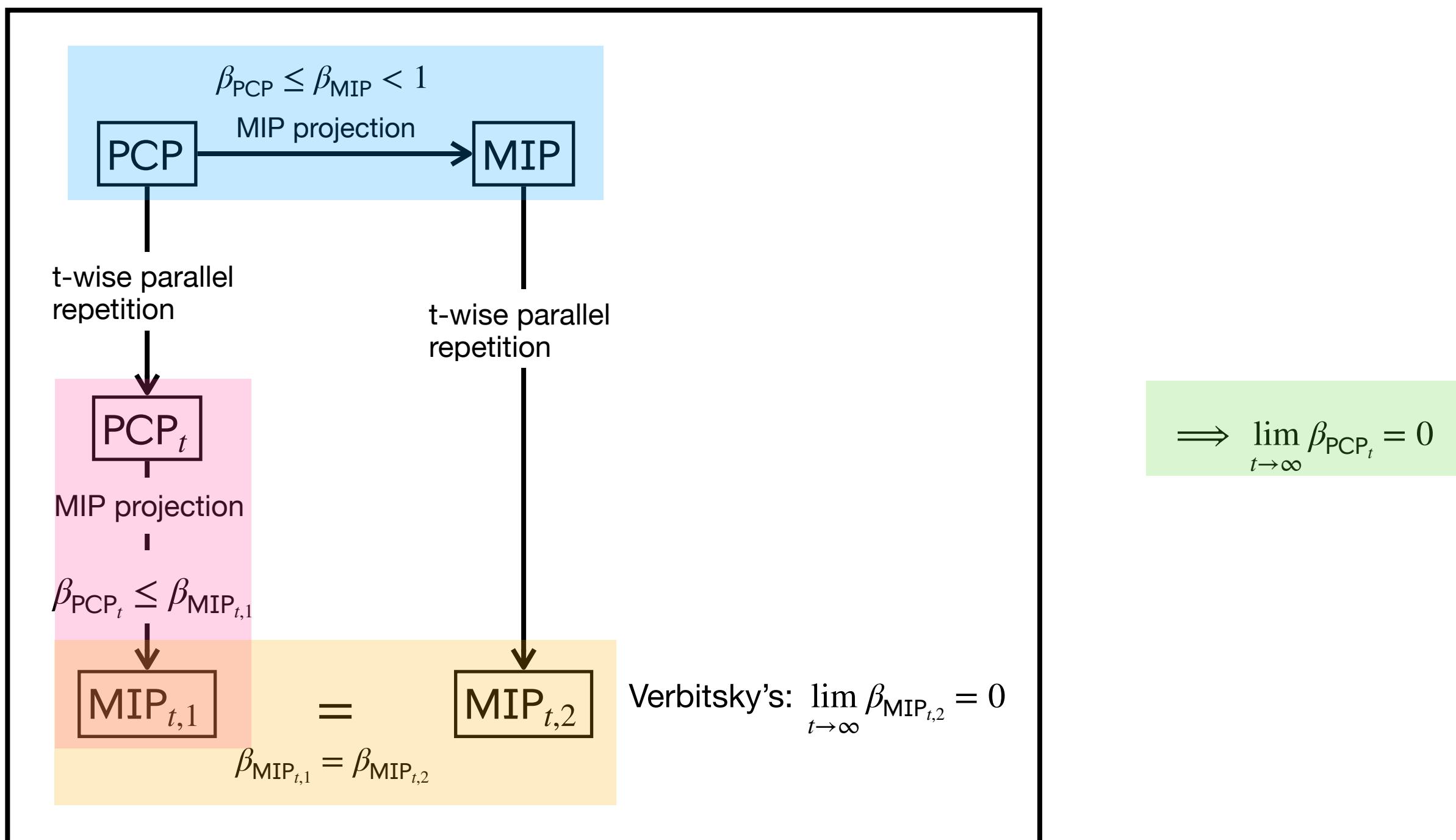
1. Consider an arbitrary PCP verifier randomness $\rho^\star \in \{0,1\}^r$.
2. Consider a set of randomness for \mathbf{V}_t : $W_{t,\rho^\star} := \left\{ \rho \in (\{0,1\}^r)^t : \rho[t] = \rho^\star \right\}$.
3. Construct a PCP string $\tilde{\Pi}$ for parallel repetition for PCP using the optimal malicious MIP provers:
 - For every $\rho \in W_{t,\rho^\star}$, fill in corresponding query positions by the answers of the MIP provers.
 - No position is filled more than once with different answers:
 - For every $i \neq j$, $Q_{\rho^\star}[i] \neq Q_{\rho^\star}[j]$. (Q_{ρ^\star} is the query list of \mathbf{V} with ρ^\star)
 - Hence, for every $i \neq j$, $\rho_1, \rho_2 \in W_{t,\rho^\star}$, $\mathbf{Q}_{\rho_1}[i] \neq \mathbf{Q}_{\rho_2}[j]$. (\mathbf{Q}_{ρ_1} is the list of all queries of \mathbf{V}_t with ρ_1)
 - We might have $\mathbf{Q}_{\rho_1}[i] = \mathbf{Q}_{\rho_2}[i]$, but the i -th query of \mathbf{V}_t is always answered by the i -th MIP prover.
4. $\beta_t(x) \geq \frac{|W_{t,\rho^\star}|}{|(\{0,1\}^r)^t|} = \frac{(2^r)^{t-1}}{(2^r)^t} = \frac{1}{2^r} \implies \lim_{t \rightarrow \infty} \beta_t(x) = \frac{1}{2^r}$.

Note: We show the above analysis is tight by giving examples of PCPs whose limits attain $\frac{c}{2^r}$ for every $c \in [1,2^r]$.

Proof of Theorem 2 [2/2]

$$\beta_{\text{MIP}} < 1 \implies \lim_{t \rightarrow \infty} \beta_t = 0$$

- Key observation: MIP projection and parallel repetition **commutes**.
- i.e. The MIP projection of the parallel repetition for PCP is equivalent to the parallel repetition of the MIP projection of the PCP.

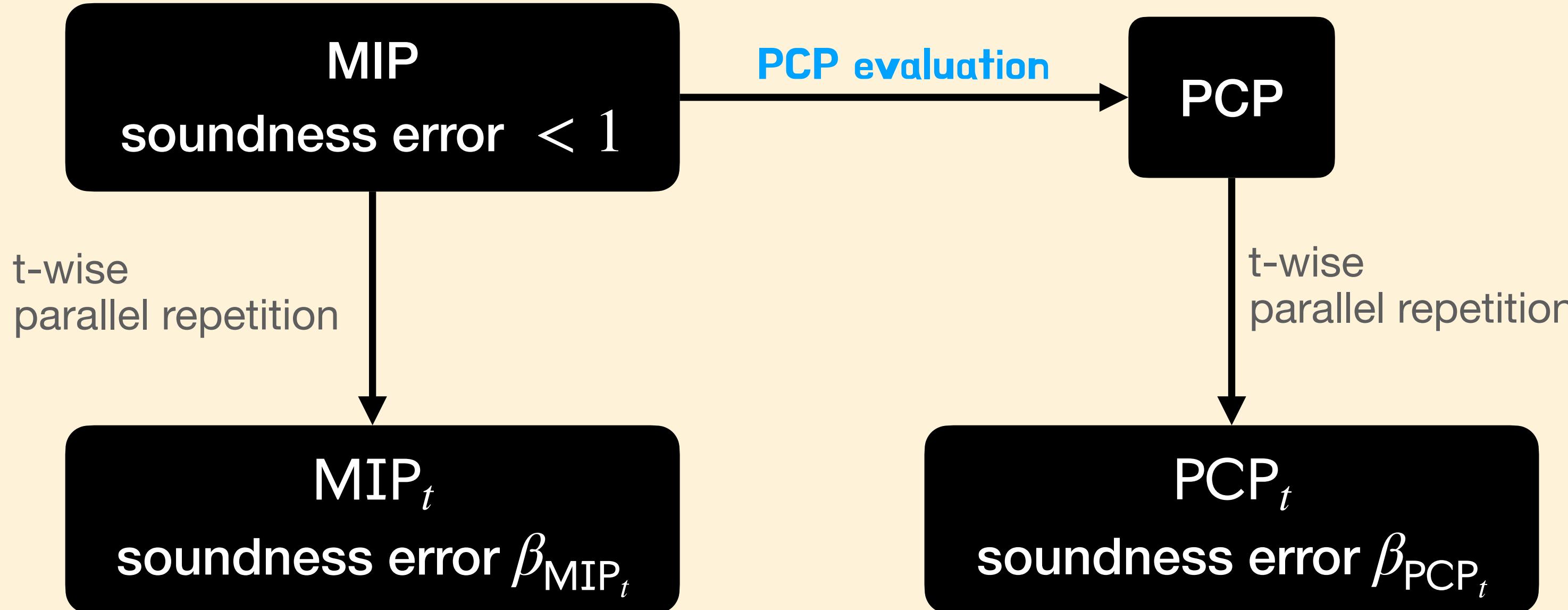


Rate of decay of parallel repetition



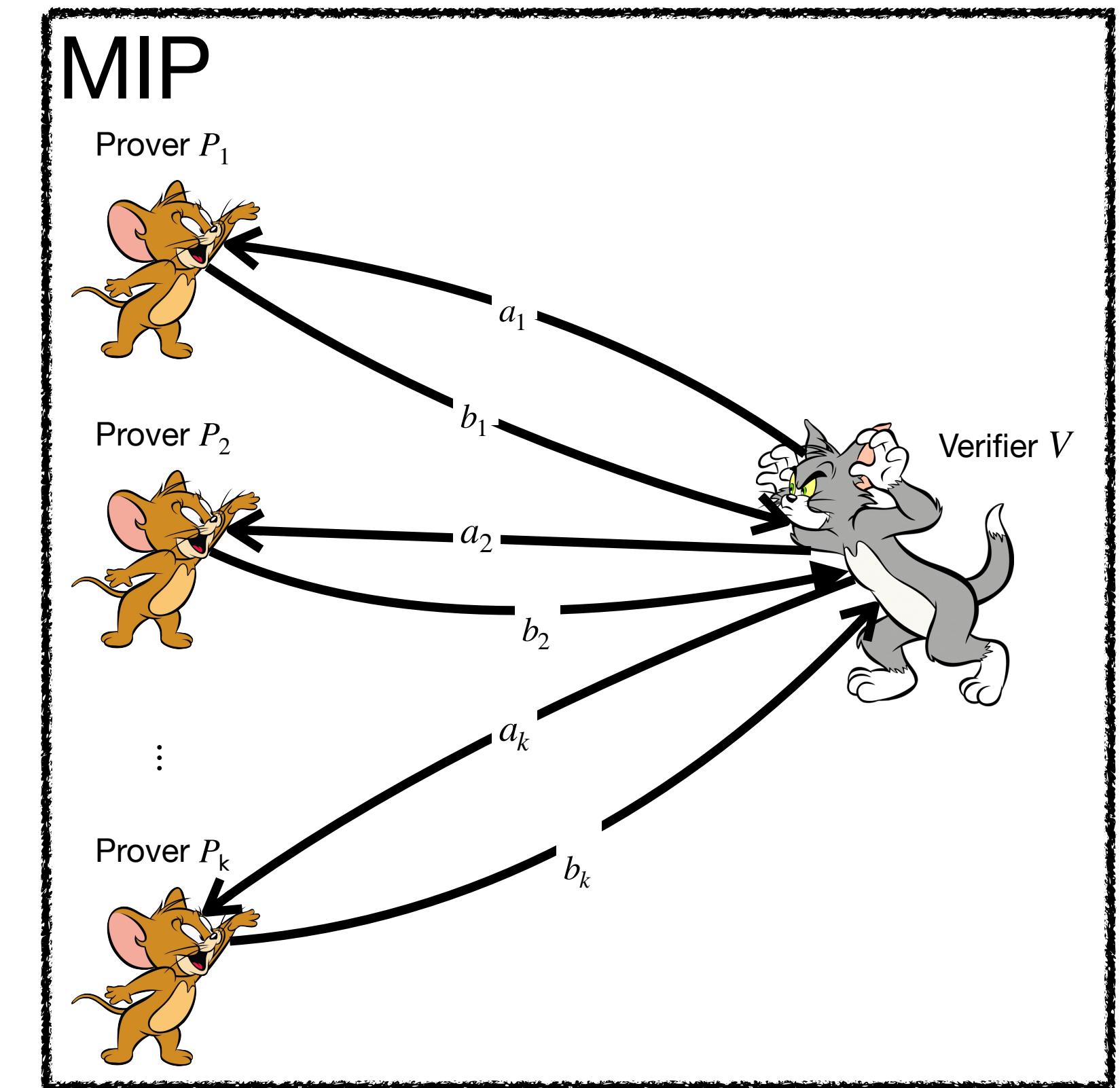
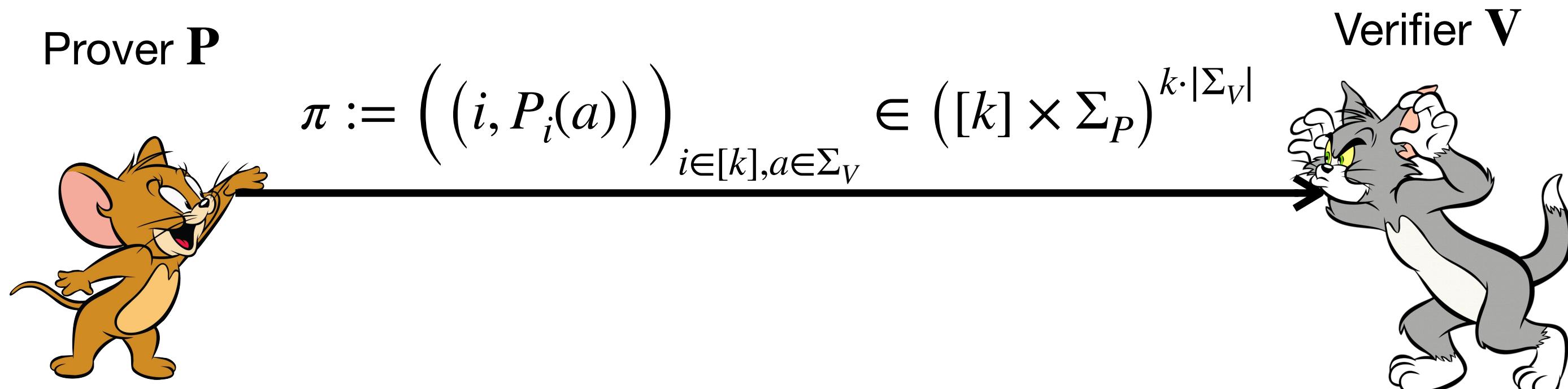
Rate of decay of parallel repetition

Lemma 2.



for every $x \notin L$ and $t \in \mathbb{N}$, $\beta_{\text{PCP}_t}(x) = \beta_{\text{MIP}_t}(x) < 1$

PCP evaluation



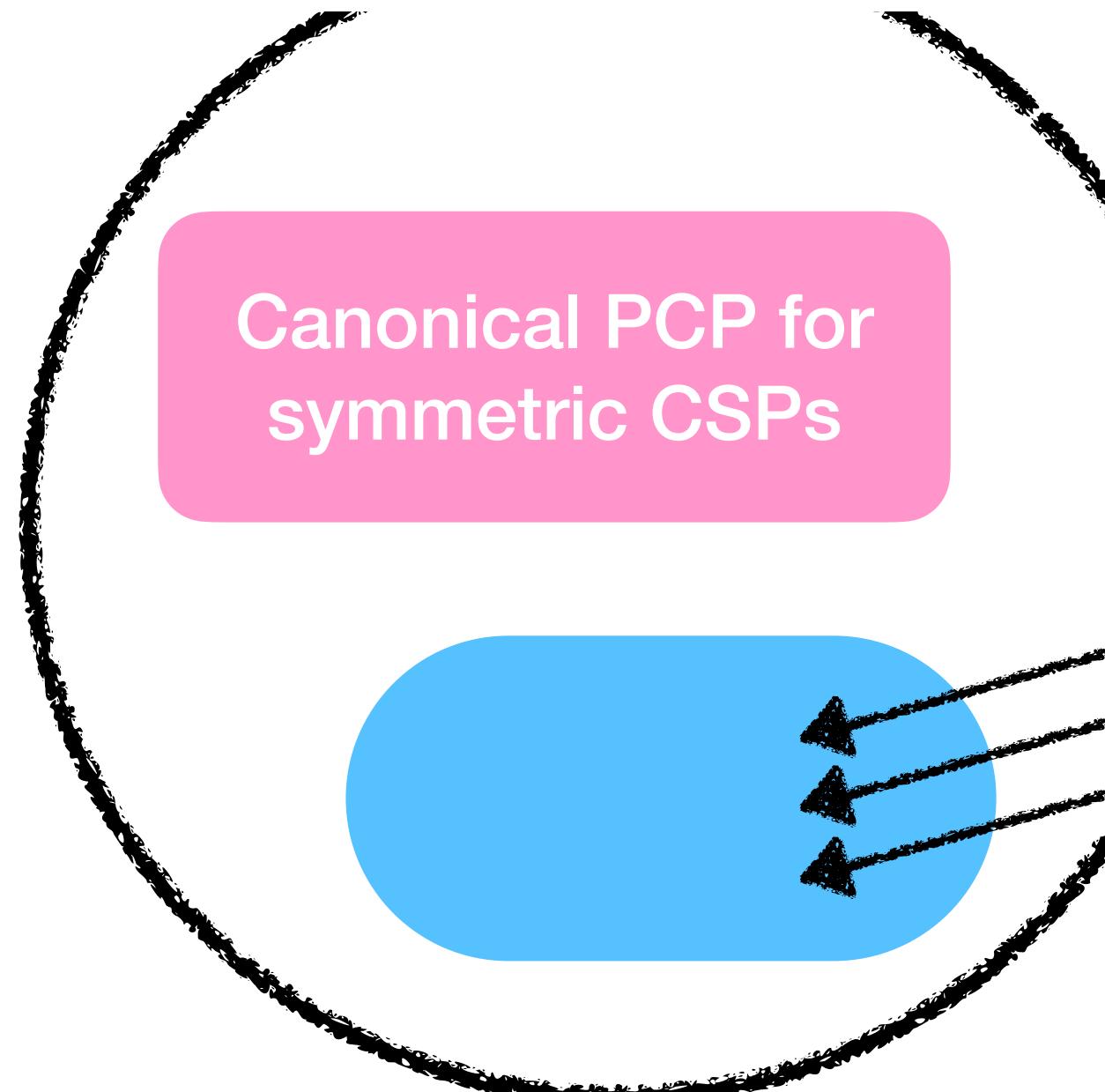
Completeness and soundness of the PCP are the same as that of the MIP.

Theorem 2 (characterization) tells us: if $\beta_{\text{MIP}} < 1$, parallel repetition works for its PCP evaluation!

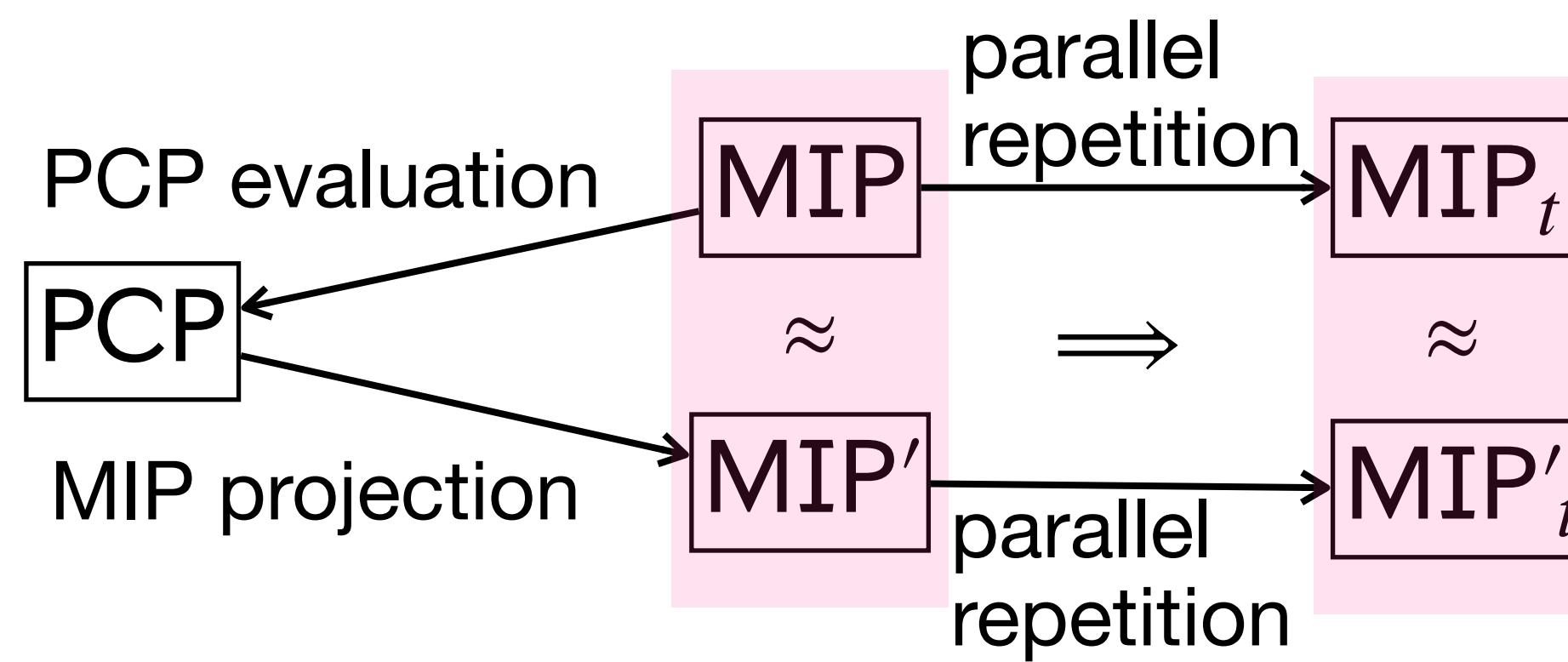
Idea behind Lemma 2

The set of all MIPs with nontrivial soundness

The set of all PCPs



PCP evaluations



$$\beta_{\text{PCP}_t} \leq \beta_{\text{MIP}_t} < 1$$

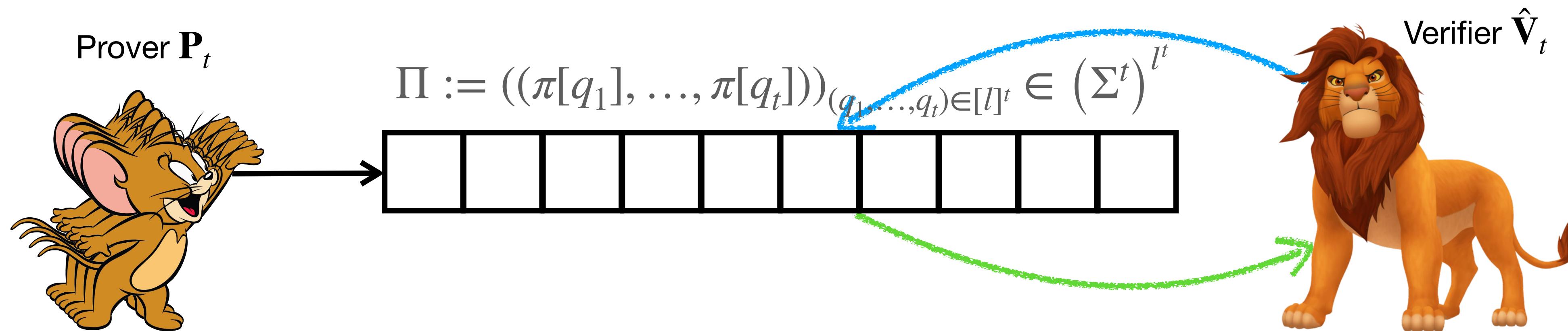
$\beta_{\text{PCP}_t} \geq \beta_{\text{MIP}_t}$ (proved by construct malicious PCP strategy from MIP strategy)

$$\beta_{\text{PCP}_t} = \beta_{\text{MIP}_t} < 1$$

Consistent parallel repetition works



Solution: consistent parallel repetition [1/3]



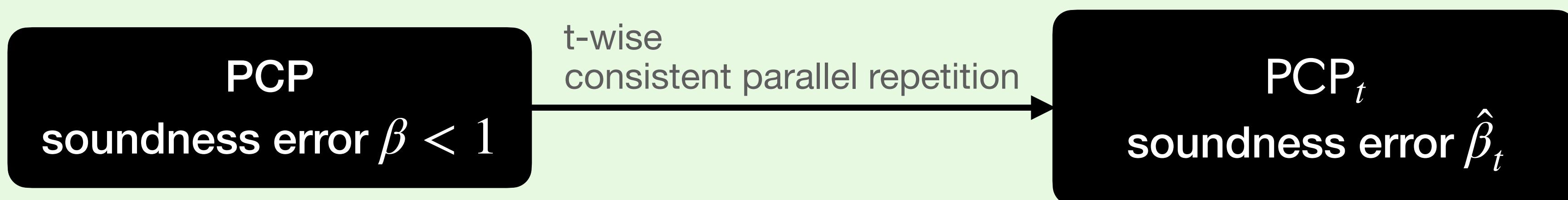
No additional queries or randomness compare to parallel repetition!

1. Sample t randomness for \mathbf{V} : $(\rho_i)_{i \in [t]} \leftarrow (\{0,1\}^r)^t$.
2. Compute query lists of \mathbf{V} : $Q_i := \mathbf{V}_q(x; \rho_i)$.
3. Compute query lists of $\hat{\mathbf{V}}_t$: $\mathbf{Q}_i := \left(Q_j[i] \right)_{j \in [t]}$.
4. Query the PCP string Π : $\mathbf{ans}_i := \Pi[\mathbf{Q}_i]$.
5. Check that for every repetition $i \in [t]$: $\mathbf{V}_d \left(x, \rho_i, (\mathbf{ans}_j[i])_{j \in [q]} \right)$.
6. For every query $q \in [l]$ made by $\hat{\mathbf{V}}_t$, if it is queried more than once, check that all answers to q are the same.



Solution: consistent parallel repetition [2/3]

Theorem 3.



for every $x \notin L$ and $t \in \mathbb{N}$, $\hat{\beta}_t(x) \leq O_x(1) \cdot \beta(x)^t$

$$O_x(1) \leq \binom{2^r}{\beta(x) \cdot 2^r}$$

Solution: consistent parallel repetition [3/3]

$O_x(1)$ is a large constant that doesn't depend on t .

- Derived from a counting problem:

$$\mathcal{K}(\Sigma, n, m) := \left| \left\{ s = (s_1, \dots, s_n) \in \Sigma^n : |\{s_1, \dots, s_n\}| \leq m \right\} \right|.$$

- Bounded from the above by $\binom{|\Sigma|}{m} \cdot m^n$.
- Open problem: can $O_x(1)$ be improved?

Future directions

Question 1. Can we replace the dichotomy in the [characterization](#) result by a trichotomy?

- Three behaviors of parallel repetition: Limit doesn't go to 0, limit goes to 0, and soundness error strictly increases after each repetition.

Question 2. More precise [rate of decay of parallel repetition](#)?

- Direct analysis without mentioning MIPs?

Question 3. Is there more to say about [rate of decay of consistent parallel repetition](#)?

- Better constant?
- Another curve?

Thank you!

<https://eprint.iacr.org/2023/1714>