Correlation Intractability and SNARGs from Sub-exponential DDH

Arka Rai Choudhuri
NTT Research


Sanjam Garg
UC Berkeley and NTT Research


Abhishek Jain
Johns Hopkins University and NTT Research


Zhengzhong Jin
MIT


Jiaheng Zhang
UC Berkeley

Succinct Non-Interactive Arguments (SNARGs)

$\boxed{\mathcal{M}}, x$

$\boxed{\mathcal{M}}, x$

$x \longrightarrow \boxed{\mathcal{M}} \longrightarrow$ accept

within T steps

Succinct Non-Interactive Arguments (SNARGs)

$\boxed{\mathcal{M}}, x$

$\boxed{\mathcal{M}}, x$

$x \longrightarrow \boxed{\mathcal{M}} \longrightarrow$ accept

within T steps

 wants to delegate computation to 

Succinct Non-Interactive Arguments (SNARGs)

$\mathcal{M}$, x

$$\xrightarrow{\quad \Pi \quad}$$

$\mathcal{M}$, x

$x \longrightarrow \boxed{\mathcal{M}} \longrightarrow$ accept

within T steps

Succinct Non-Interactive Arguments (SNARGs)

Common Reference String (CRS)

$\mathcal{M}$, x

Π

$\mathcal{M}$, x

$x \longrightarrow \boxed{\mathcal{M}} \longrightarrow$ accept

within T steps

Succinct Non-Interactive Arguments (SNARGs)

Common Reference String (CRS)

$\mathcal{M}$, x

Π

$\mathcal{M}$, x

Π is publicly verifiable

$x \longrightarrow \boxed{\mathcal{M}} \longrightarrow$ accept

within T steps

Succinct Non-Interactive Arguments (SNARGs)

Common Reference String (CRS)

$\mathcal{M}$, x

$\xleftarrow{\quad}$ $\text{polylog}(T)$ $\xrightarrow{\quad}$

Π

$\mathcal{M}$, x

Verifier running time: $\text{polylog}(T)$

Π is publicly verifiable

$x \longrightarrow \boxed{\mathcal{M}} \longrightarrow$ accept

within T steps

Succinct Non-Interactive Arguments (SNARGs)

Common Reference String (CRS)

$\mathcal{M}$, x

$\longleftarrow$ $\text{polylog}(T)$ $\longrightarrow$

Π

$\mathcal{M}$, x

Verifier running time: $\text{polylog}(T)$

Π is publicly verifiable

$x \longrightarrow \boxed{\mathcal{M}} \longrightarrow$ accept

within T steps

No PPT  can produce accepting Π if

$x \longrightarrow \boxed{\mathcal{M}} \not\longrightarrow$ accept

within T steps

Succinct Non-Interactive Arguments (SNARGs)

Common Reference String (CRS)

$\mathcal{M}$, x

$\longleftarrow$ $\mathrm{polylog}(T)$ $\longrightarrow$

Π

$\mathcal{M}$, x

Verifier running time: $\mathrm{polylog}(T)$

Π is publicly verifiable

$$x \longrightarrow \boxed{\mathcal{M}} \longrightarrow \text{accept}$$

within T steps

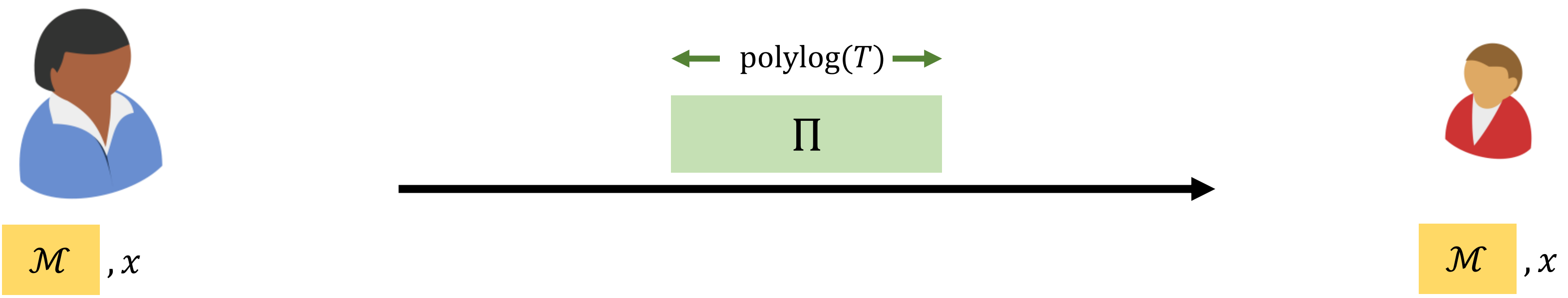
No PPT  can produce accepting x, Π if

$$x \longrightarrow \boxed{\mathcal{M}} \not\longrightarrow \text{accept}$$

within T steps

Succinct Non-Interactive Arguments (SNARGs)

Common Reference String (CRS)



Verifier running time: polylog(T)

Π is publicly verifiable

What kind of computation can we hope to delegate based on standard assumptions?

x

Succinct Non-Interactive Arguments (SNARGs)

Common Reference String (CRS)

$\mathcal{M}$, x

$\leftarrow$ polylog(T) $\rightarrow$

Π

$\mathcal{M}$, x

Verifier running time: polylog(T)

Π is publicly verifiable

x

What kind of computation can we hope to delegate based on standard assumptions?

Nondeterministic polynomial-time computation (NP)? Unlikely! [Gentry-Wichs'11]

SNARGs for Batch NP (or BARGs)

CRS

$C, x_1, \cdots, x_k$

$C, x_1, \cdots, x_k$

$\text{SAT} = \{(C, x) \mid \exists w \ s.t. \ C(x, w) = 1\}$

$\forall i \in [k], (C, x_i) \in \text{SAT}$

SNARGs for Batch NP (or BARGs)

CRS

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SNARGs for Batch NP (or BARGs)

CRS

Π

$C, x_1, \cdots, x_k$

$C, x_1, \cdots, x_k$

Π is publicly verifiable

No PPT  can produce accepting Π if

$\exists i^* \in [k], (C, x_{i^*}) \notin \mathrm{SAT}$

$\mathrm{SAT} = \{(C, x) \mid \exists w \ s.t. \ C(x, w) = 1\}$

$\forall i \in [k], (C, x_i) \in \mathrm{SAT}$

SNARGs for Batch NP (or BARGs)

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SNARGs for Batch NP (or BARGs)

CRS

$C, x_1, \cdots, x_k$

$w_1, \ldots, w_k$

$C, x_1, \cdots, x_k$

Π is publicly verifiable

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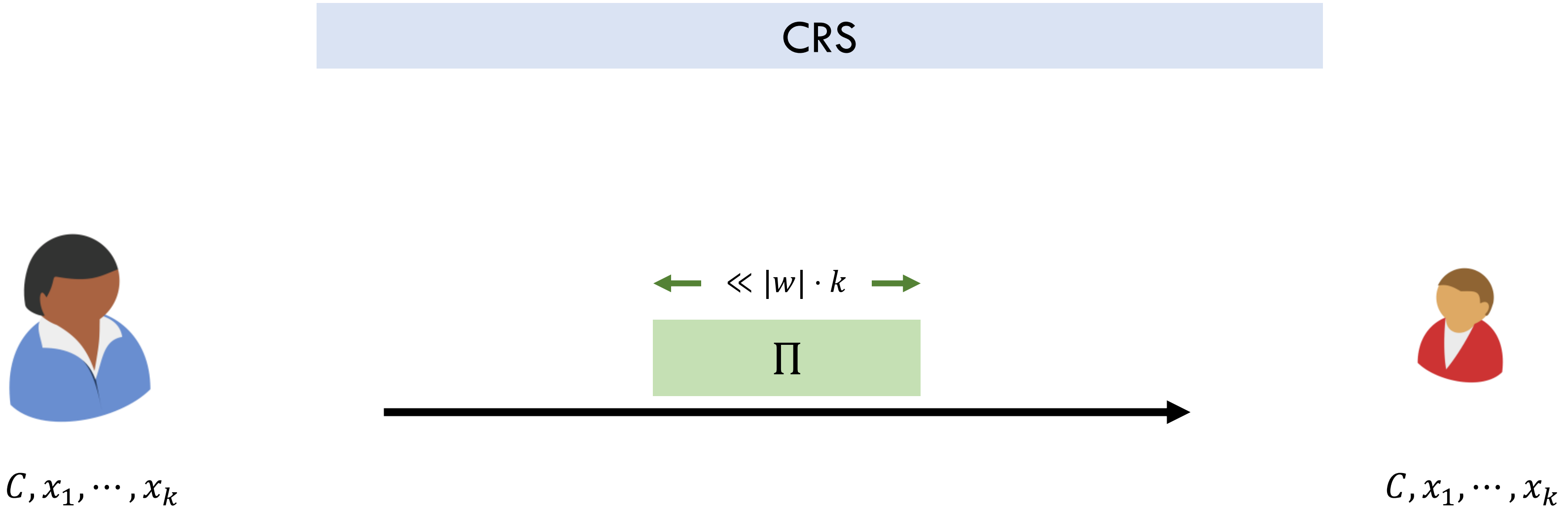
SNARGs for Batch NP (or BARGs)



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SNARGs for Batch NP (or BARGs)

CRS

$C, x_1, \cdots, x_k$

$\ll |w| \cdot k$

Π

$C, x_1, \cdots, x_k$

Verifier running time:
$k \cdot |x| + |\Pi|$

Π is publicly verifiable

$$\text{SAT} = \{(C, x) \mid \exists w \; s.t. \; C(x, w) = 1\}$$

$$\forall i \in [k], (C, x_i) \in \text{SAT}$$

Usefulness of BARGs

BARGs

Usefulness of BARGs

SNARGs for P

[C-Jain-Jin'21, Kalai-Vaikuntanathan-Zhang'21]

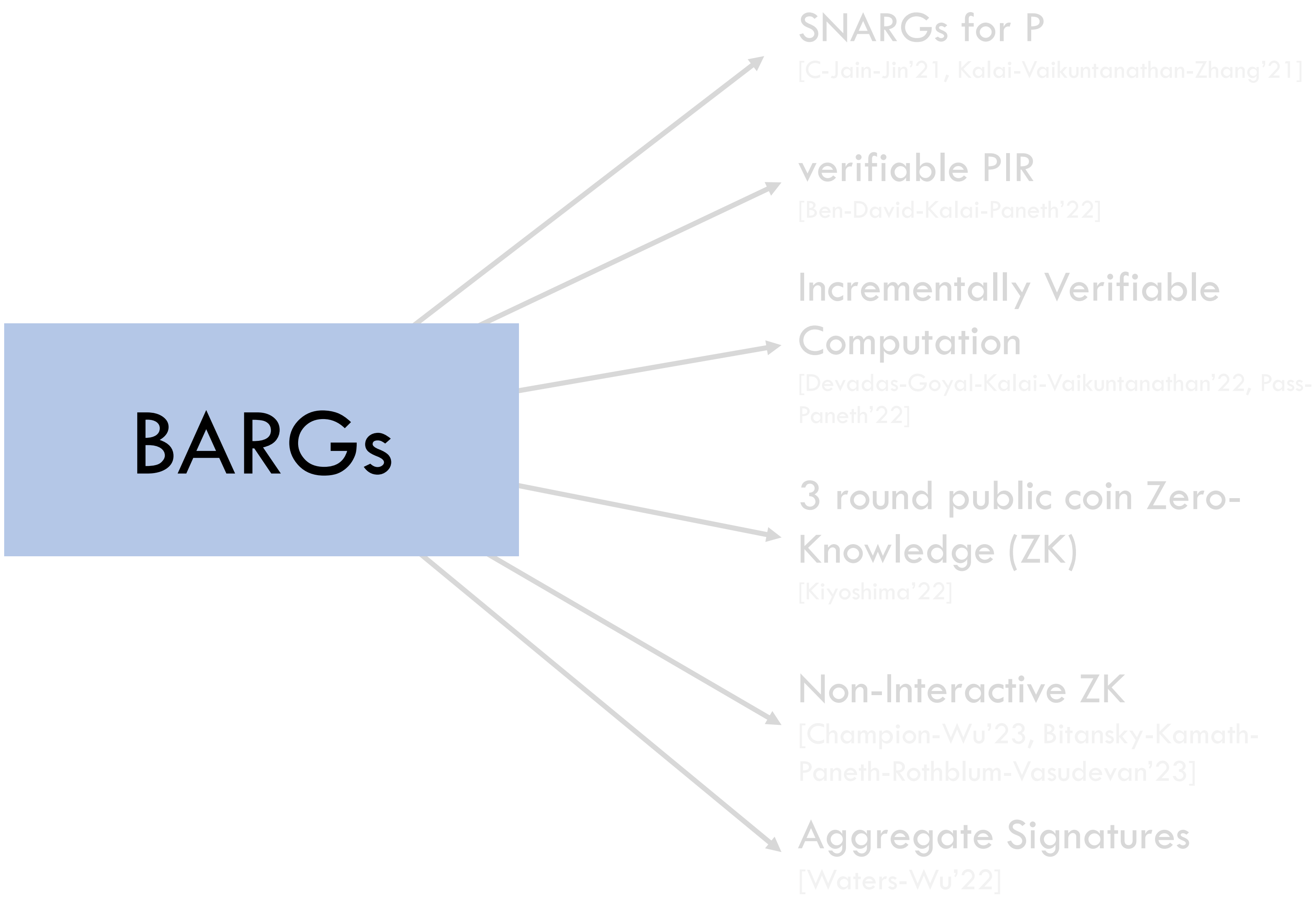
BARGs

Usefulness of BARGs

BARGs

- SNARGs for P
  [C-Jain-Jin'21, Kalai-Vaikuntanathan-Zhang'21]
- verifiable PIR
  [Ben-David-Kalai-Paneth'22]
- Incrementally Verifiable Computation
  [Devadas-Goyal-Kalai-Vaikuntanathan'22, Pass-Paneth'22]
- 3 round public coin Zero-Knowledge (ZK)
  [Kiyoshima'22]
- Non-Interactive ZK
  [Champion-Wu'23, Bitansky-Kamath-Paneth-Rothblum-Vasudevan'23]
- Aggregate Signatures
  [Waters-Wu'22]

Construction of BARGs



Construction of BARGs

LWE
[C-Jain-Jin'21]

DLIN
[Waters-Wu'22]

Sub-exp DDH
+ QR
[C-Jain-Jin'21a, Hulett-Jawale-Khurana-Srinivasan'22]

BARGs

SNARGs for P
[C-Jain-Jin'21, Kalai-Vaikuntanathan-Zhang'21]

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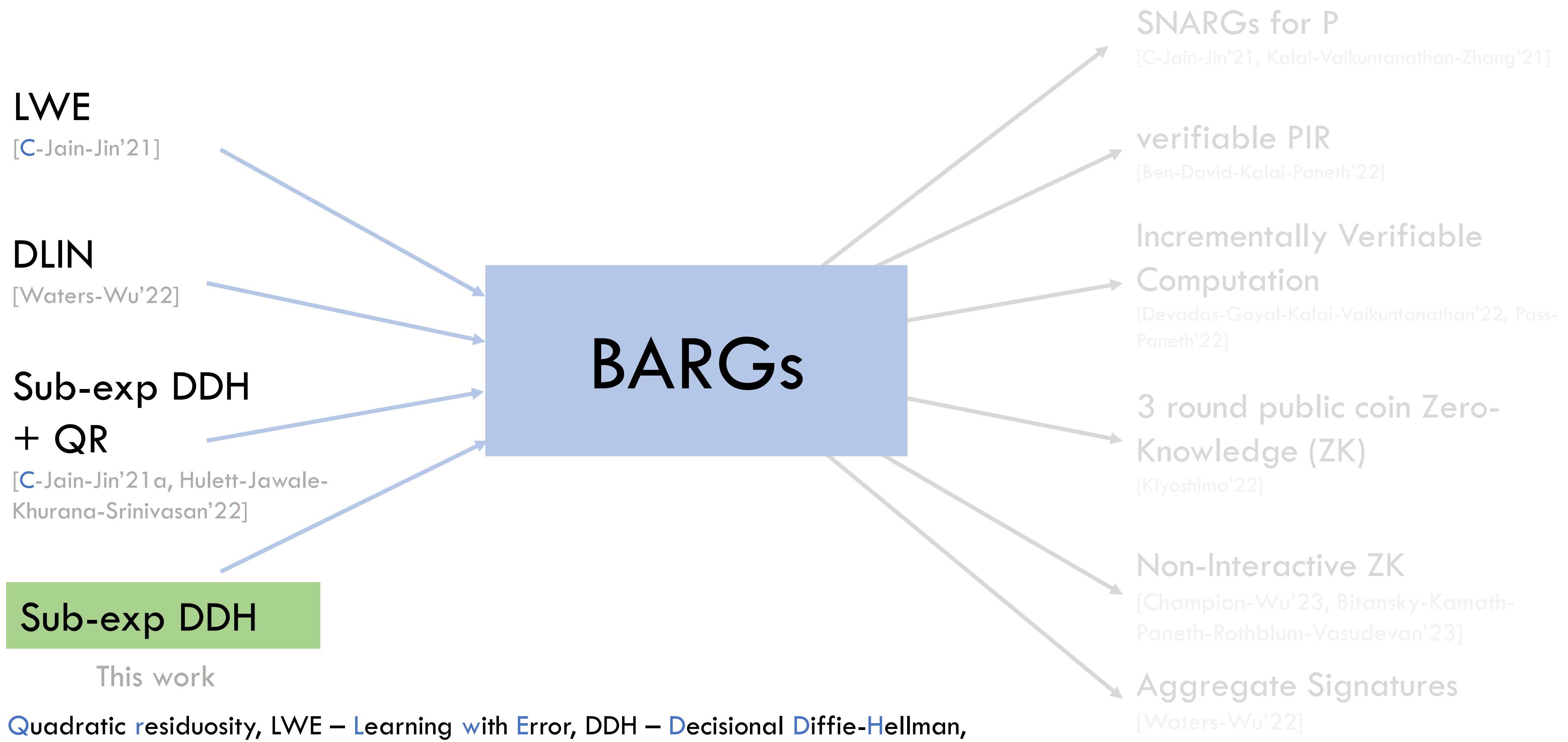
Aggregate Signatures
[Waters-Wu'22]

QR – Quadratic residuosity, LWE – Learning with Error, DDH – Decisional Diffie-Hellman,
DLIN – Decisional Linear Assumption over Bilinear Maps.

Construction of BARGs



QR – Quadratic residuosity, LWE – Learning with Error, DDH – Decisional Diffie-Hellman, DLIN – Decisional Linear Assumption over Bilinear Maps.

Our Results

Theorem 1

Assuming sub-exponential hardness of DDH, there exists SNARGs for batch NP where

$$|\Pi| = \mathrm{poly}(\log k, |C|)$$

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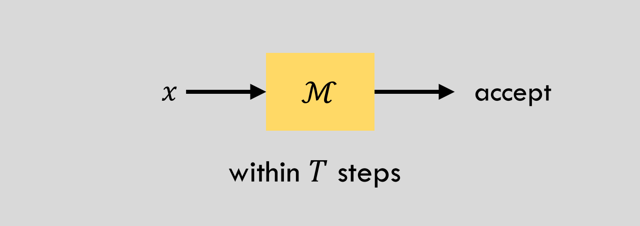
Our Results



Theorem 2

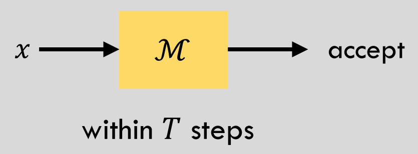
Assuming sub-exponential hardness of DDH, there exists SNARGs for P where

$$|\mathsf{CRS}|, |\Pi|, |\;| = \mathrm{polylog}(T)$$

Our Results

Recent concurrent work [Kalai-Lombardi-Vaikuntanathan'23]:

SNARGs for bounded depth circuits assuming sub-exponential hardness of DDH.



Theorem 2

Assuming sub-exponential hardness of DDH, there exists SNARGs for P where

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Our Results

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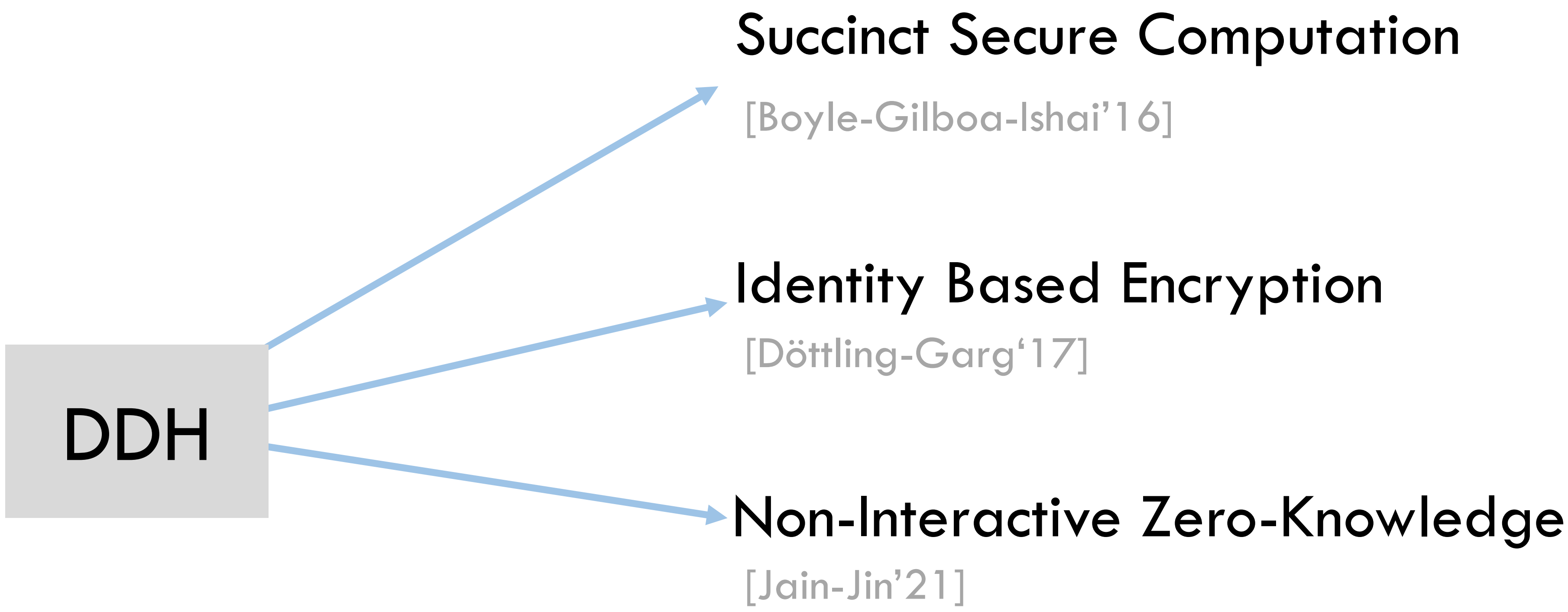
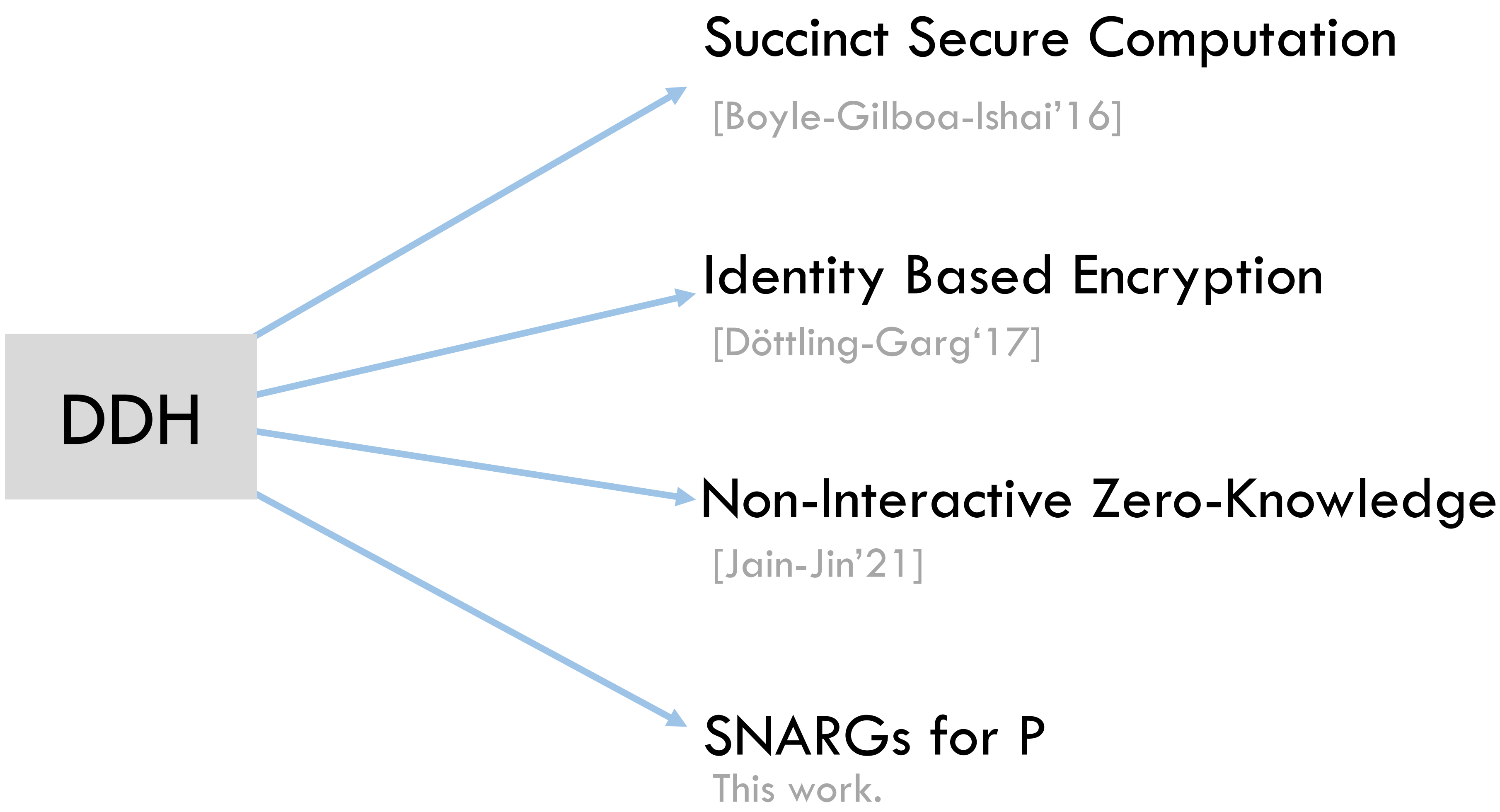
Meta View: Advanced Primitives from DDH

DDH

Meta View: Advanced Primitives from DDH

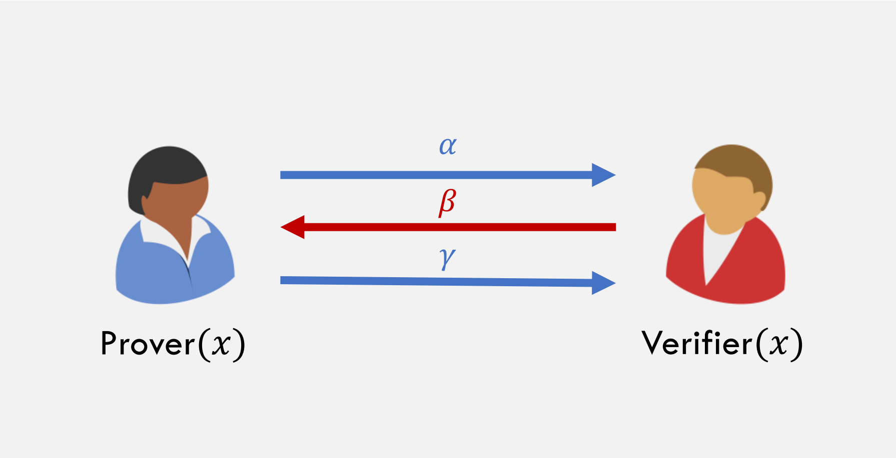


Meta View: Advanced Primitives from DDH



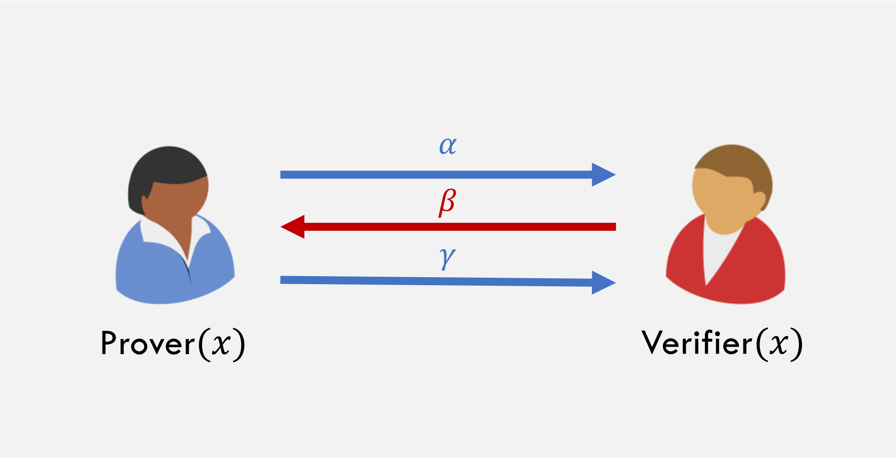
Tools and Techniques

Fiat-Shamir (FS) Methodology: Recipe for Success

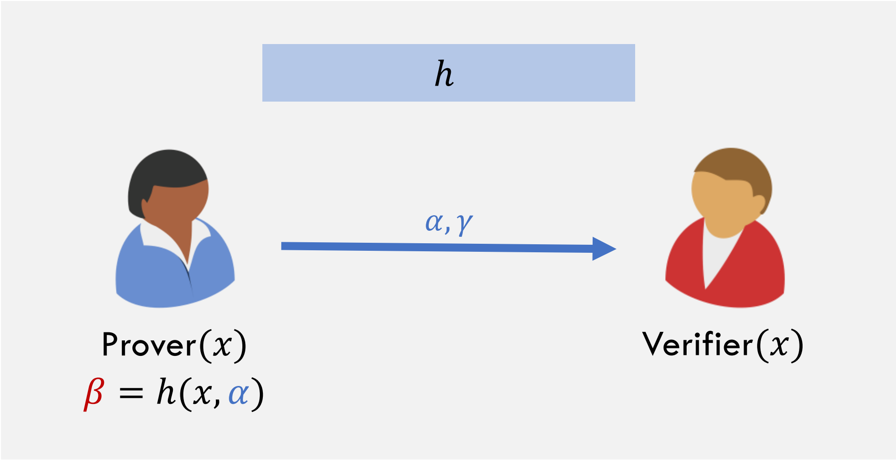


β is a random string

Fiat-Shamir (FS) Methodology



[Fiat-Shamir'86]



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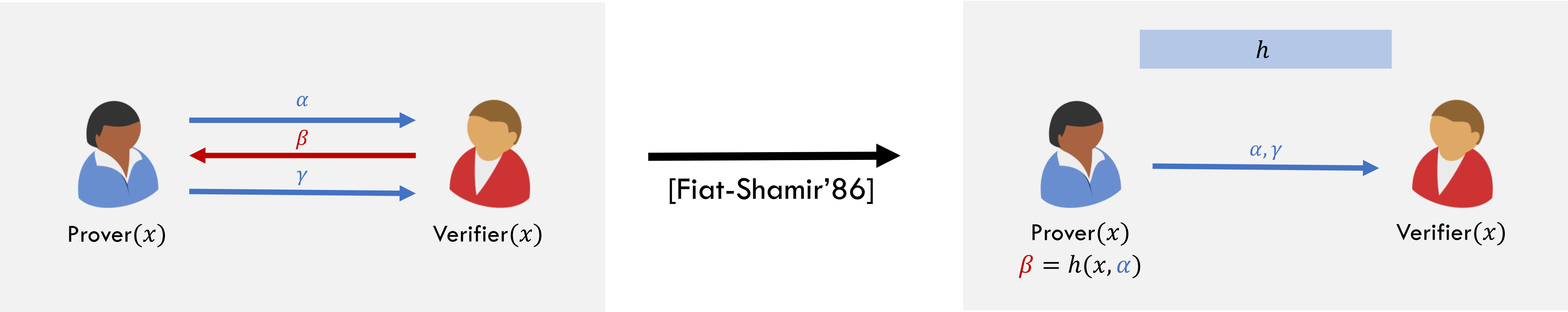
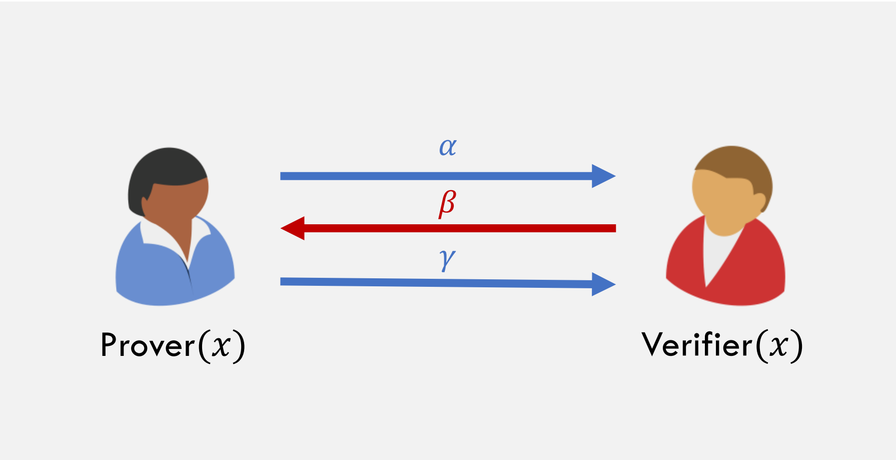


β is a random string

$\forall\, x \notin \mathcal{L}$

$$\mathrm{BAD}_{x,\alpha} = \{\beta \mid \exists \gamma \text{ s.t. Verifier accepts } (\alpha, \beta, \gamma)\}$$

Fiat-Shamir (FS) Methodology



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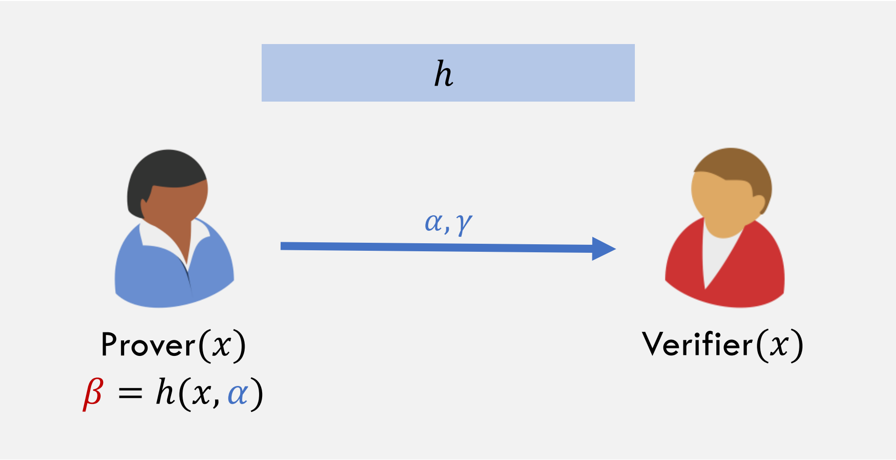

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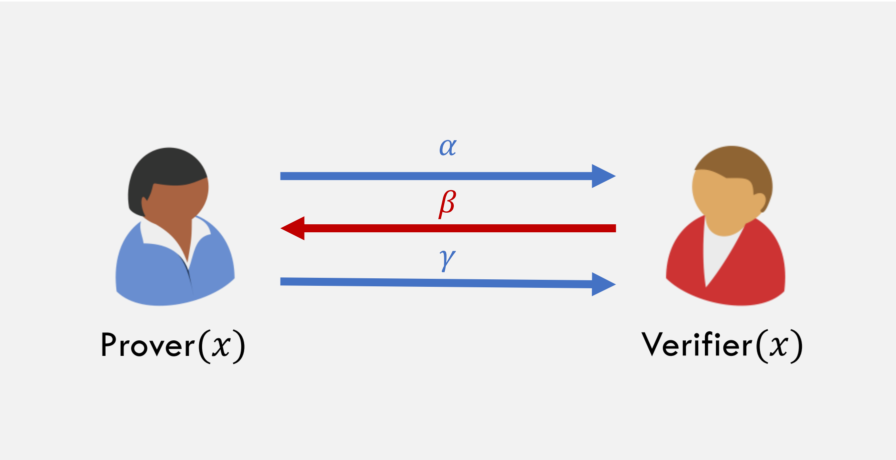
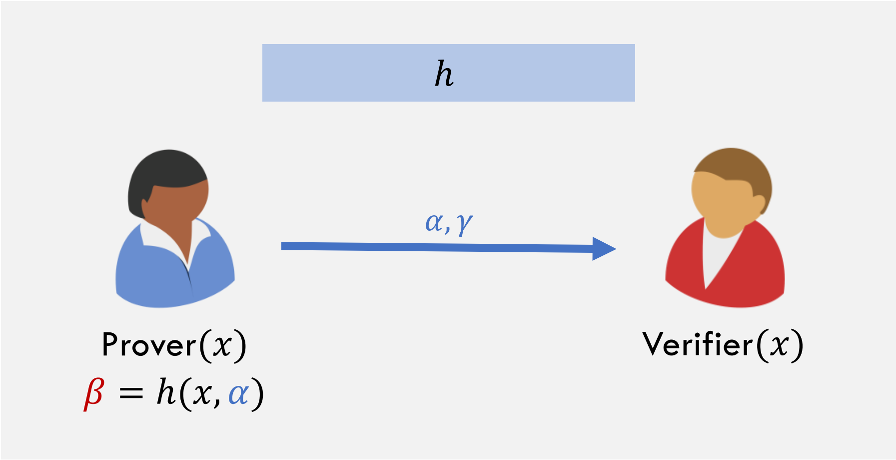
If $x \notin \mathcal{L}$, no PPT  can find α such that

$h(x, \alpha) \in \mathrm{BAD}_{x,\alpha}$

Correlation Intractability [Canetti-Goldreich-Halevi'98]



[Fiat-Shamir'86]



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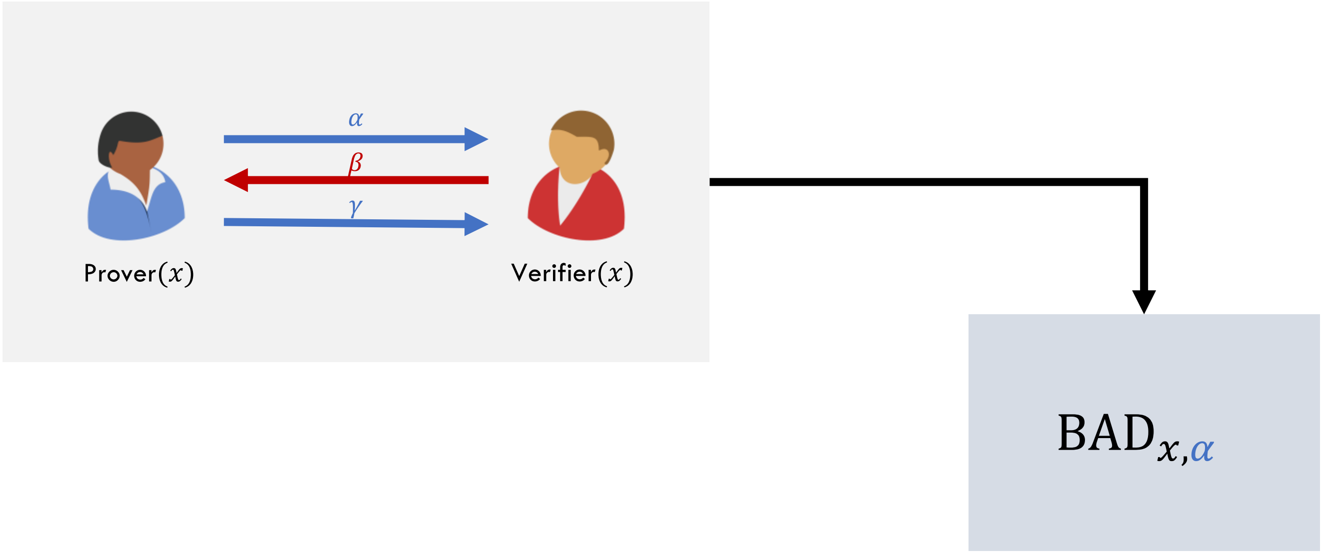
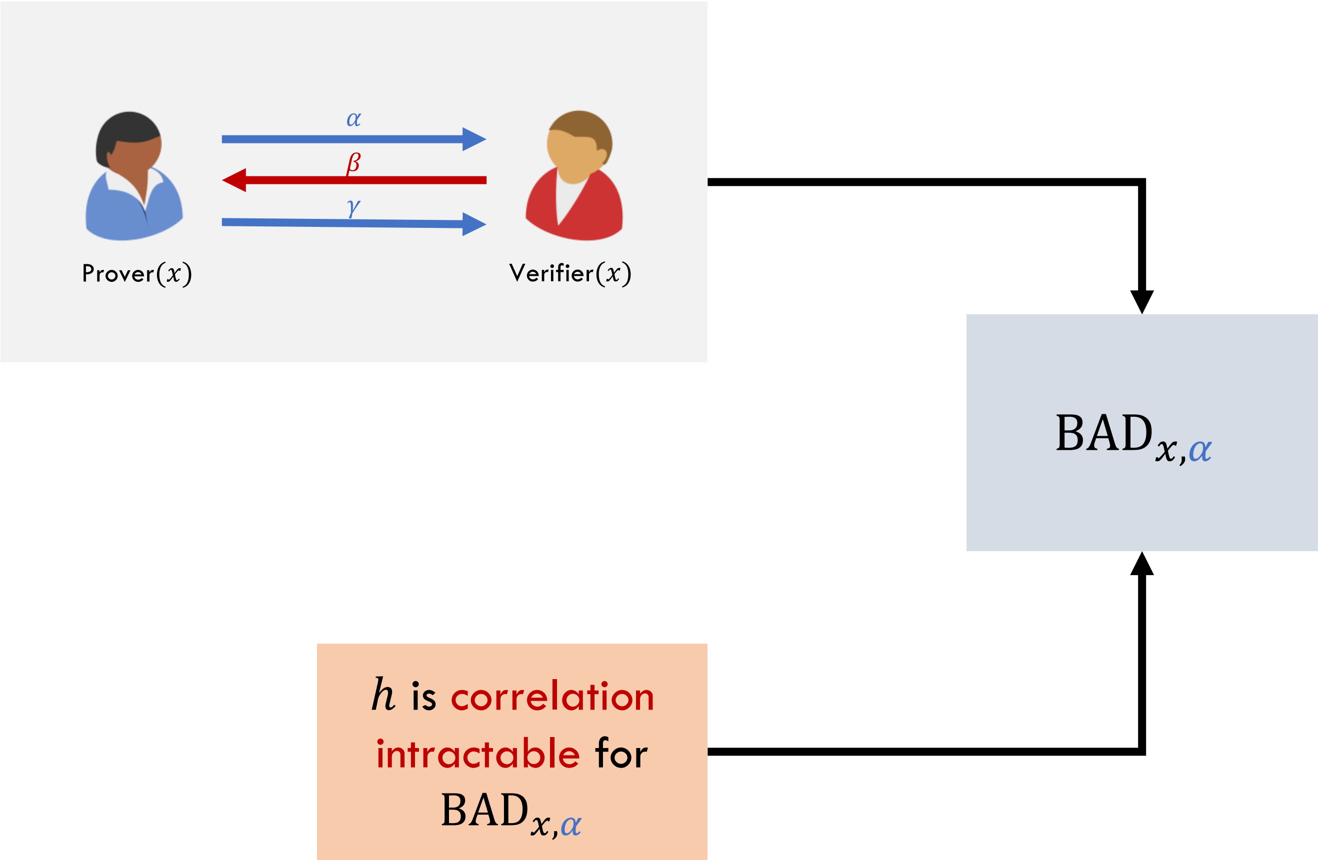
h is correlation intractable (CI) for $\mathrm{BAD}_{x,\alpha}$

Instantiating the FS Transform



Instantiating the FS Transform



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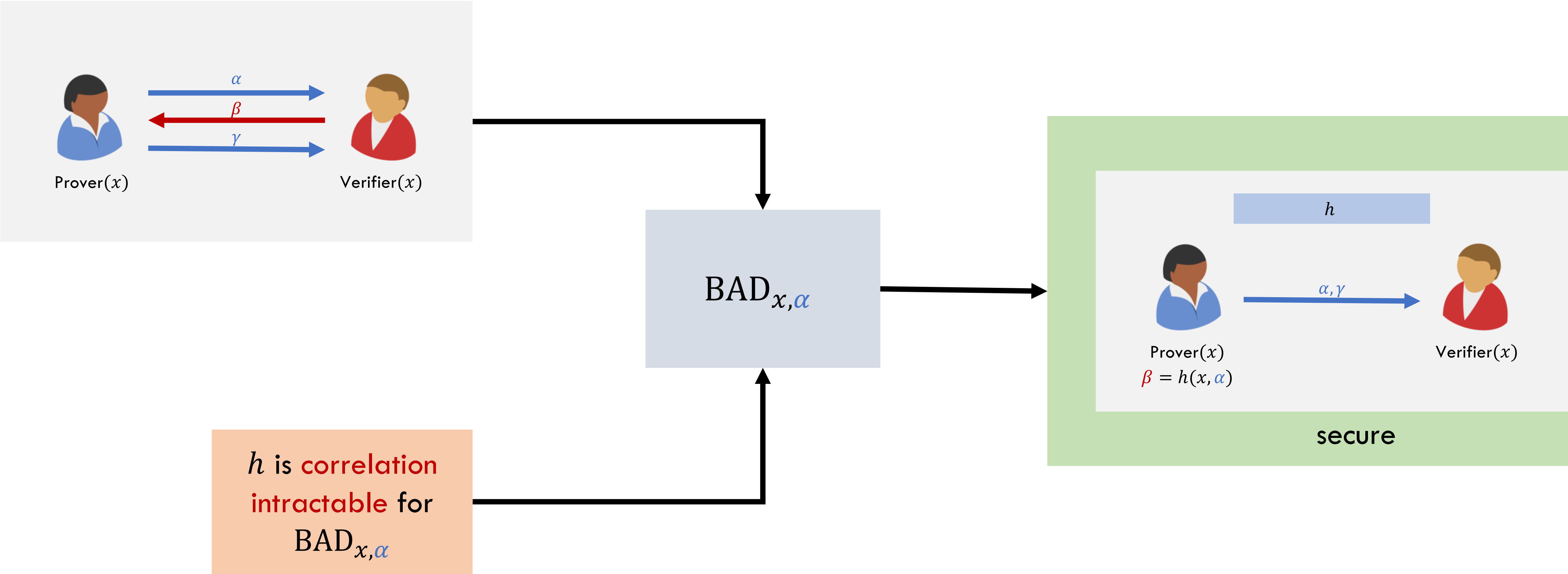
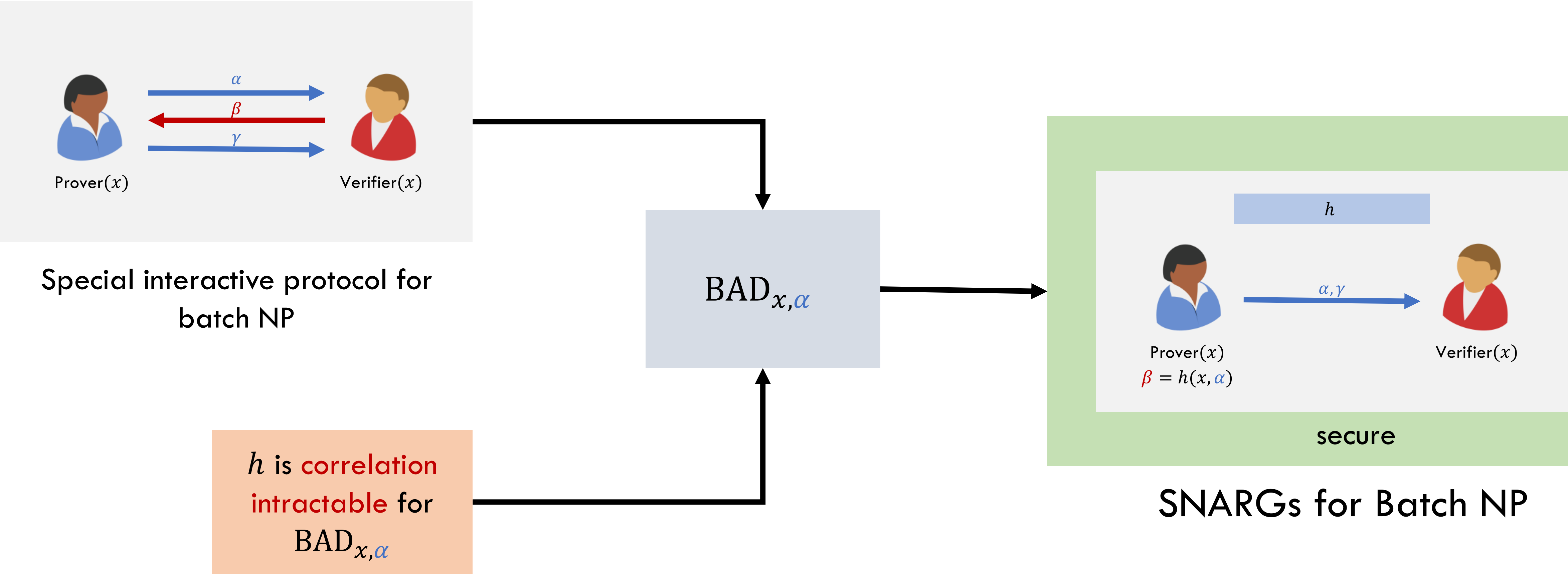


[C-Jain-Jin'21] Methodology



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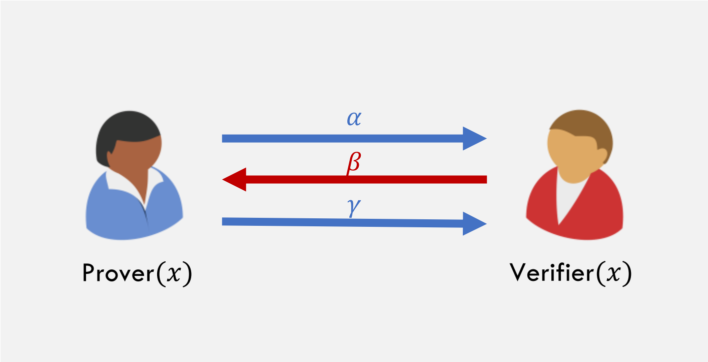
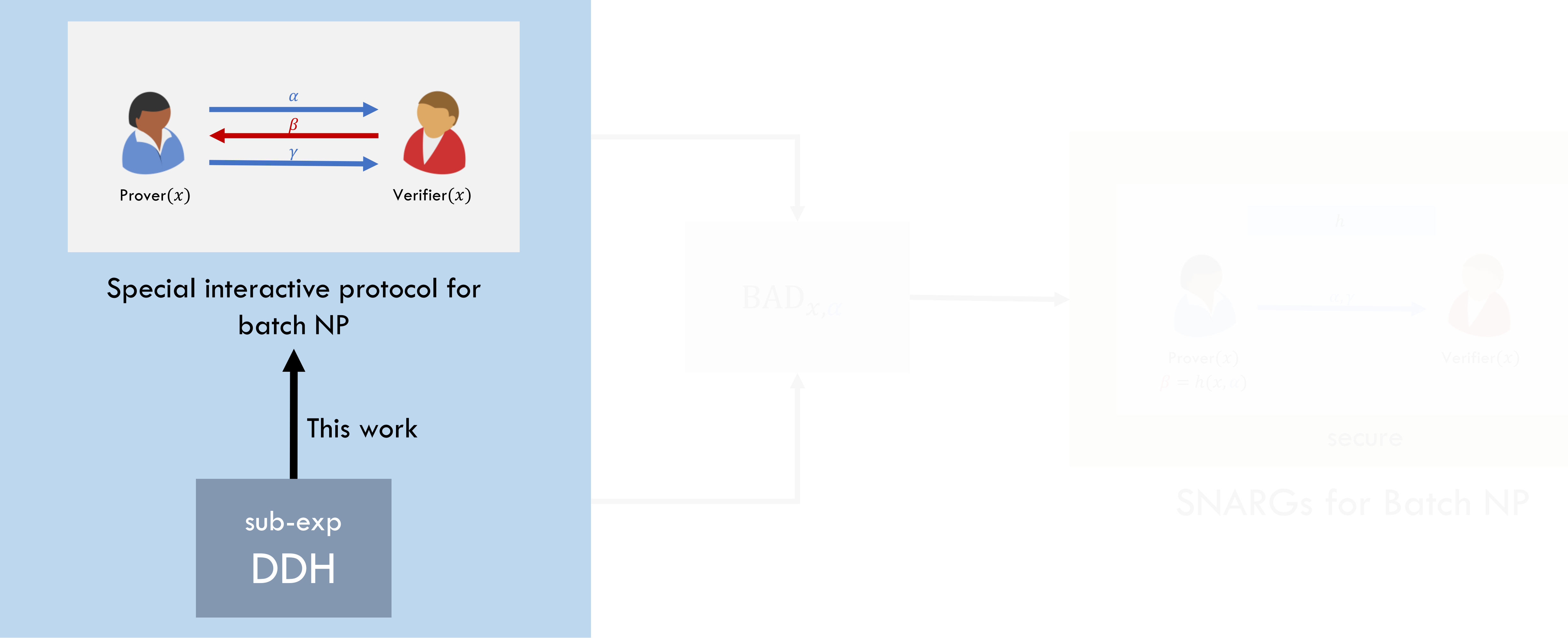


Special interactive protocol for batch NP

h is correlation intractable for $\mathrm{BAD}_{x,\alpha}$

SNARGs for Batch NP

[C-Jain-Jin'21] Methodology



see paper for details

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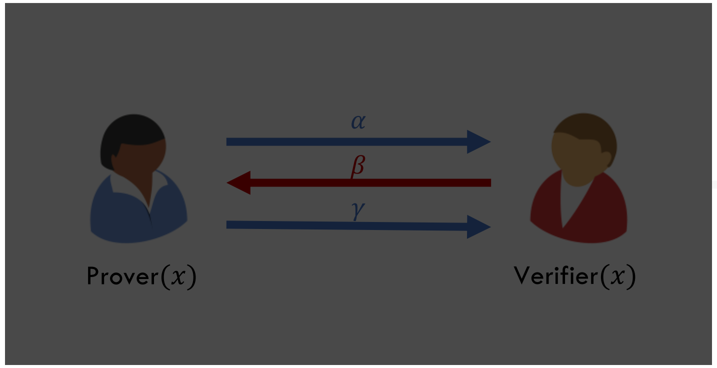

Magic Box

Special interactive protocol for batch NP

see paper for details

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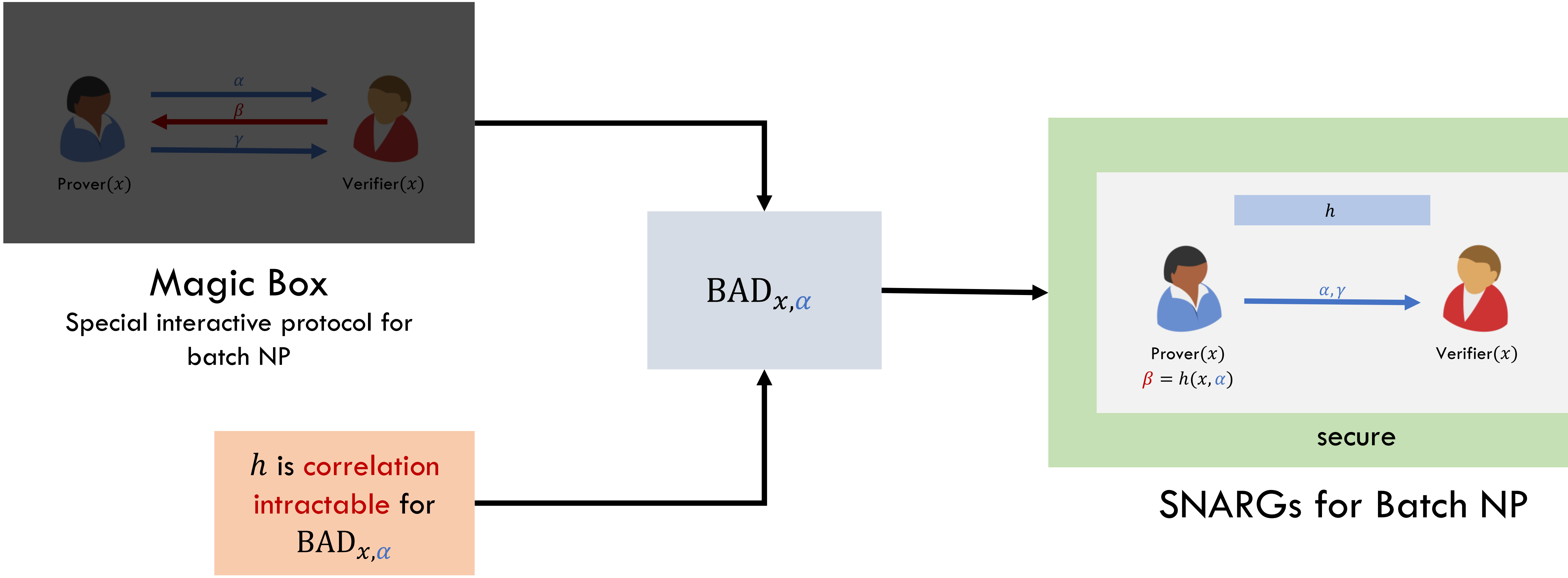

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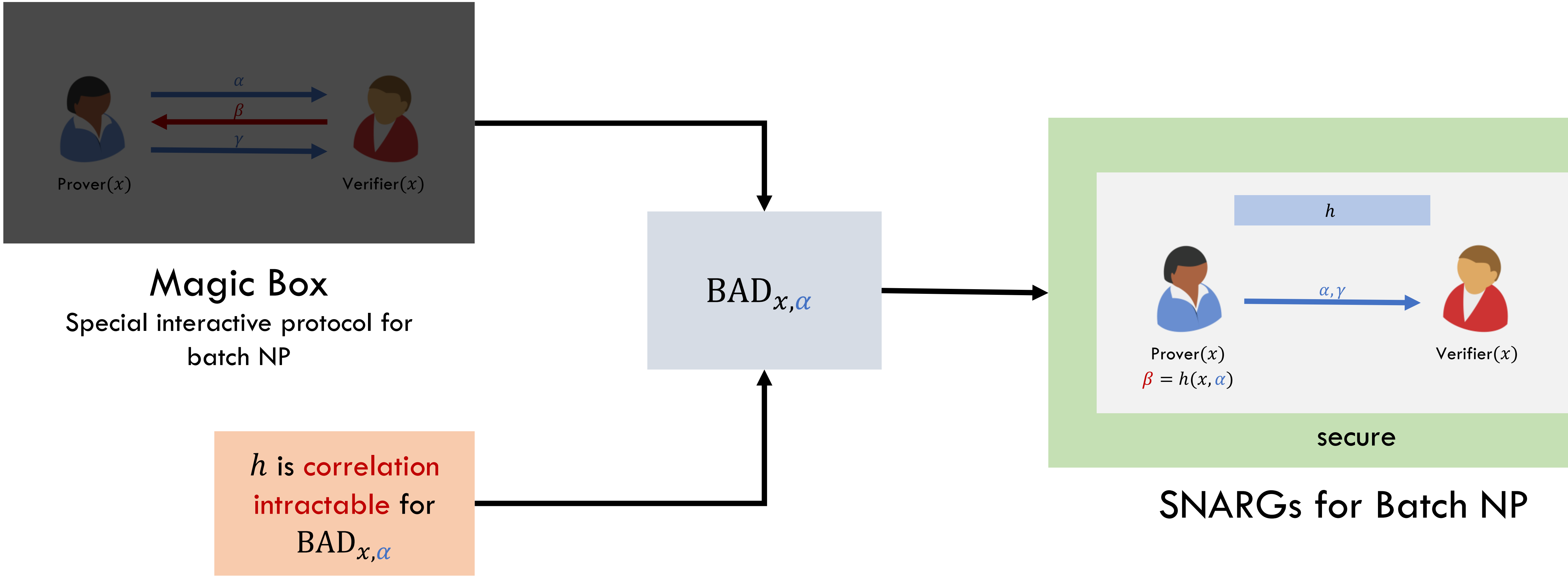

What properties does $\mathrm{BAD}_{x,\alpha}$ have?

see paper for details

Properties of $\mathrm{BAD}_{x,\alpha}$

$\mathrm{BAD}_{x,\alpha}$ is product verifiable.

$\forall\, x \notin \mathcal{L}$

$$\mathrm{BAD}_{x,\alpha} = \{\beta \mid \exists \gamma \text{ s.t. Verifier accepts } (\alpha, \beta, \gamma)\}$$

Properties of $\mathrm{BAD}_{x,\alpha}$

$$\mathrm{BAD}_{x,\alpha} = \mathrm{BAD}_{x,\alpha}^{(1)} \times \mathrm{BAD}_{x,\alpha}^{(2)} \times \mathrm{BAD}_{x,\alpha}^{(3)} \times \mathrm{BAD}_{x,\alpha}^{(4)}$$

$\mathrm{BAD}_{x,\alpha}$ is product verifiable.

$\forall\, x \notin \mathcal{L}$

$$\mathrm{BAD}_{x,\alpha}^{(j)} = \{\beta \mid \exists \gamma \text{ s.t. Verifier accepts } (\alpha, \beta, \gamma)\}$$

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$\mathrm{BAD}_{x,\alpha}^{(j)} = \{\beta \mid \exists\gamma \text{ s.t. Verifier accepts } (\alpha,\beta,\gamma)\}$

Exponentially many bad challenges even when β sampled from polynomial size challenge space.

Properties of $\mathrm{BAD}_{x,\alpha}$

$\mathrm{BAD}_{x,\alpha} = \mathrm{BAD}_{x,\alpha}^{(1)} \times \mathrm{BAD}_{x,\alpha}^{(2)} \times \mathrm{BAD}_{x,\alpha}^{(3)} \times \mathrm{BAD}_{x,\alpha}^{(4)}$

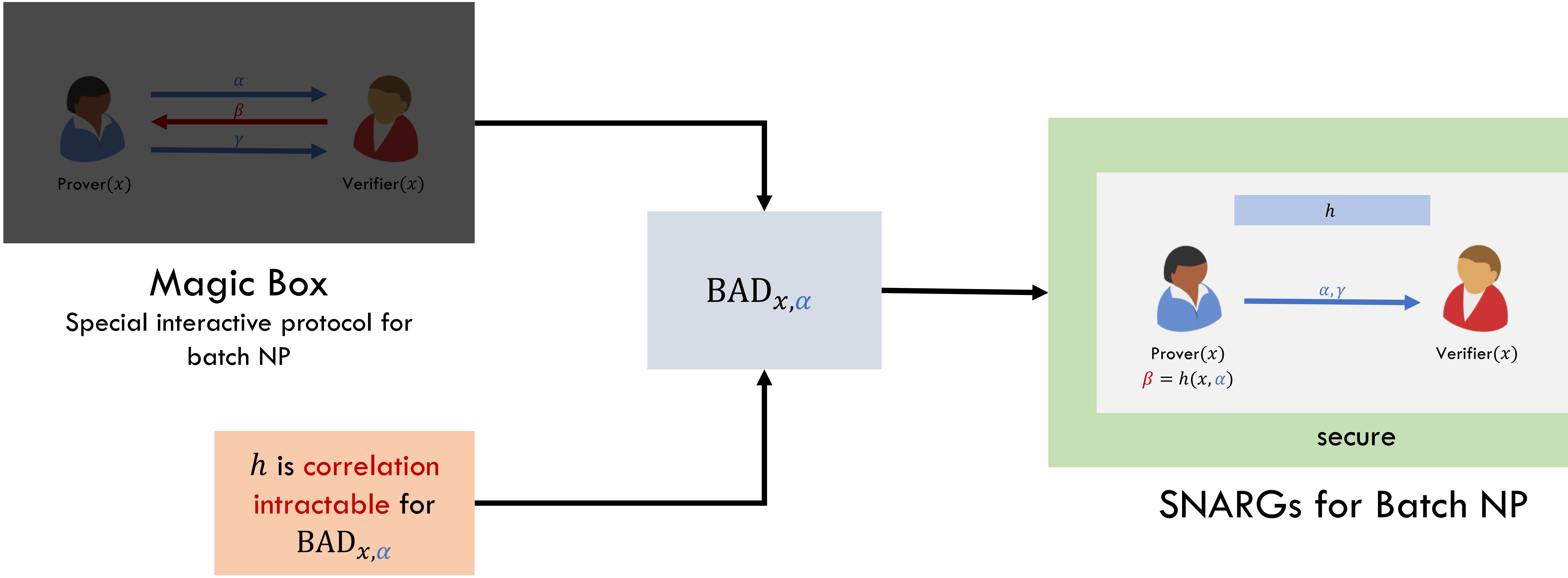
$\mathrm{BAD}_{x,\alpha}$ is product verifiable.

Each $\mathrm{BAD}_{x,\alpha}^{(i)}$ is efficiently verifiable

$\forall\, x \notin \mathcal{L}$

$\mathrm{BAD}_{x,\alpha}^{(j)} = \{\beta \mid \exists \gamma$ s.t. Verifier accepts $(\alpha, \beta, \gamma)\}$

[C-Jain-Jin'21] Methodology



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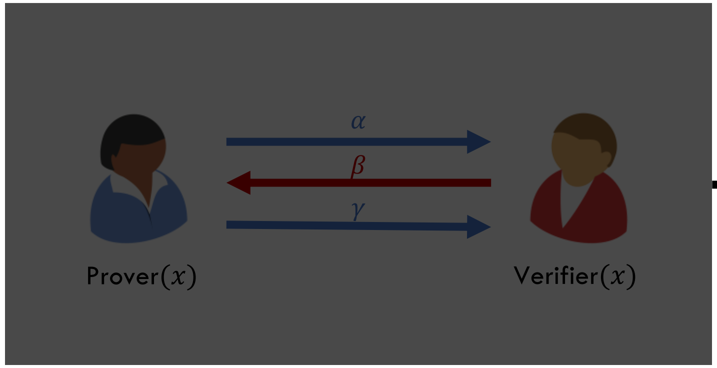

Magic Box

Special interactive protocol for batch NP

$\mathrm{BAD}_{x,\alpha}$

h is correlation intractable for $\mathrm{BAD}_{x,\alpha}$

$\mathrm{BAD}_{x,\alpha}$ properties

1. Bad challenges are a product set
2. Challenge space is of polynomial size
3. Bad challenges are product verifiable in TC^0

TC^0 - Constant depth polynomial-size threshold circuits

see paper for details

[C-Jain-Jin'21] Methodology

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TC^0 - Constant depth polynomial-size threshold circuits

[C-Jain-Jin'21] Methodology

$\mathrm{BAD'}_{x,\alpha}$ computable in TC^0

$\mathrm{BAD}_{x,\alpha}$

[Jain-Jin'21]

sub-exp DDH

h is correlation intractable for $\mathrm{BAD'}_{x,\alpha}$

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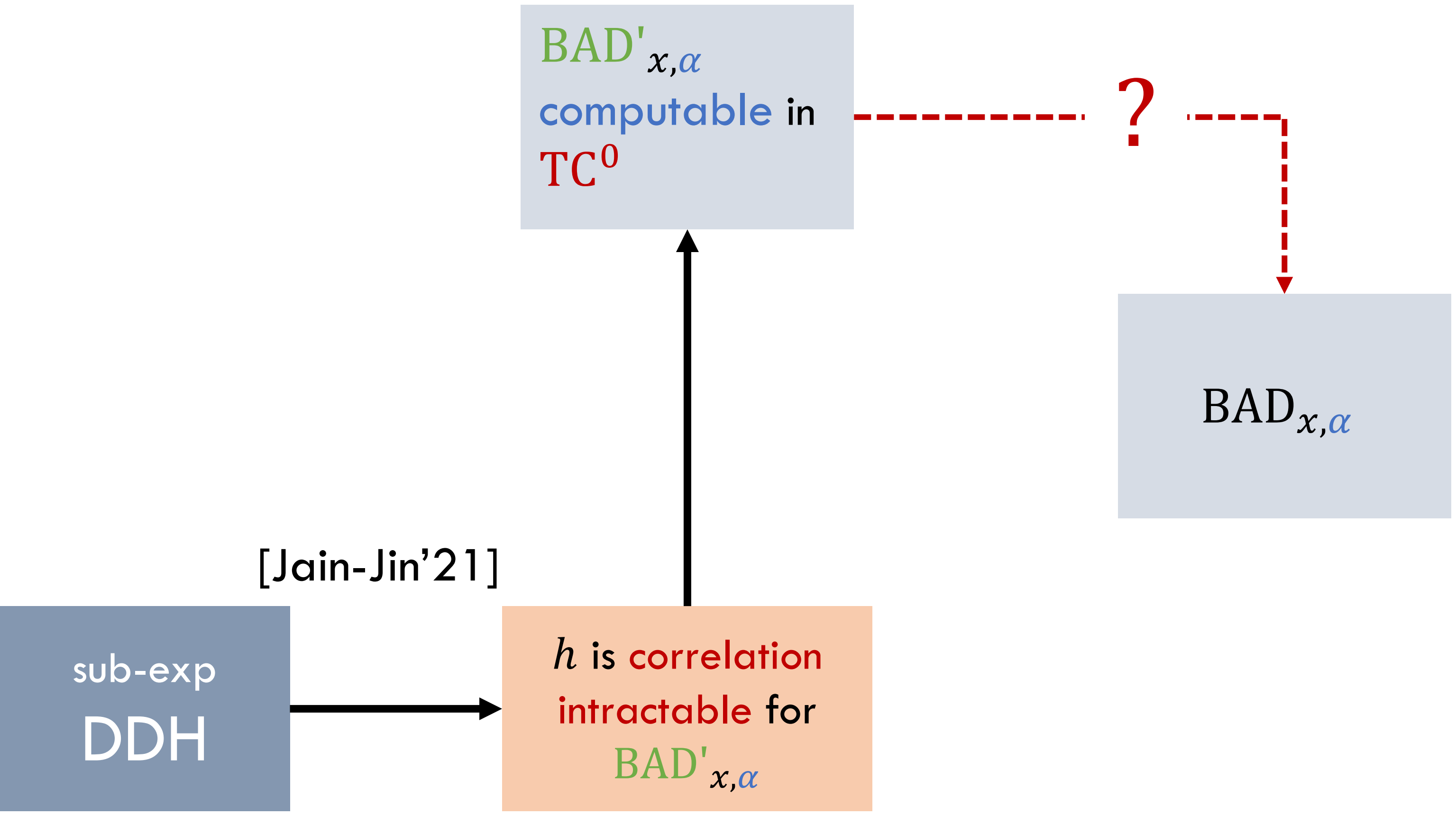

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TC^0 - Constant depth polynomial-size threshold circuits

[C-Jain-Jin'21] Methodology

$\text{BAD}'_{x,\alpha}$ computable in TC^0

?

$\text{BAD}_{x,\alpha}$

[Jain-Jin'21]

Difficulty [Holmgren-Lombardi-Rothblum'21]:

$\text{BAD}_{x,\alpha}$ has exponentially many bad challenges.

$\text{BAD}_{x,\alpha}$ properties

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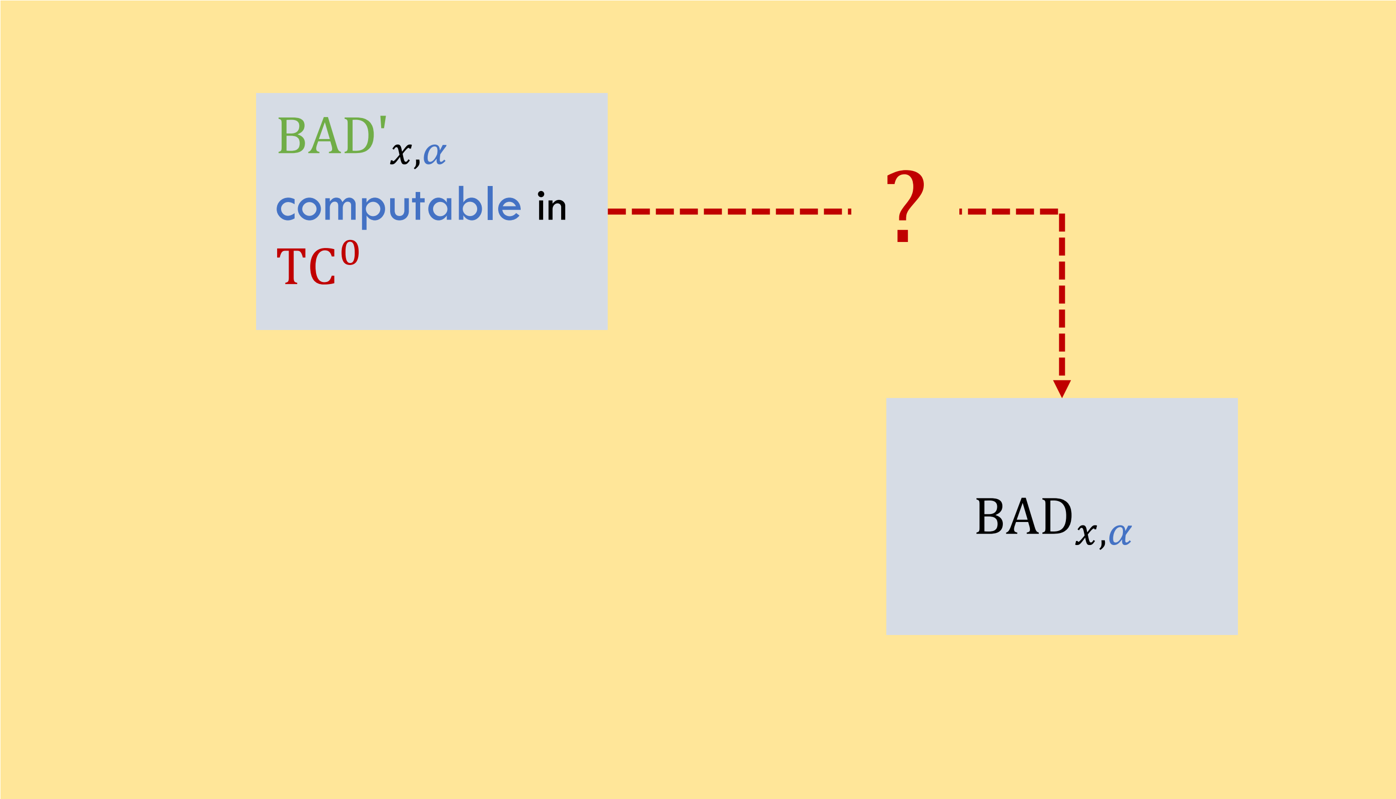
TC^0 - Constant depth polynomial-size threshold circuits

[C-Jain-Jin'21] Methodology



$\mathrm{BAD}_{x,\alpha}$ properties

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TC^0 - Constant depth polynomial-size threshold circuits

[C-Jain-Jin'21] Methodology

$\mathrm{BAD}'_{x,\alpha}$
computable in ~~TC^0~~ poly

?

$\mathrm{BAD}_{x,\alpha}$

$\mathrm{BAD}_{x,\alpha}$ properties

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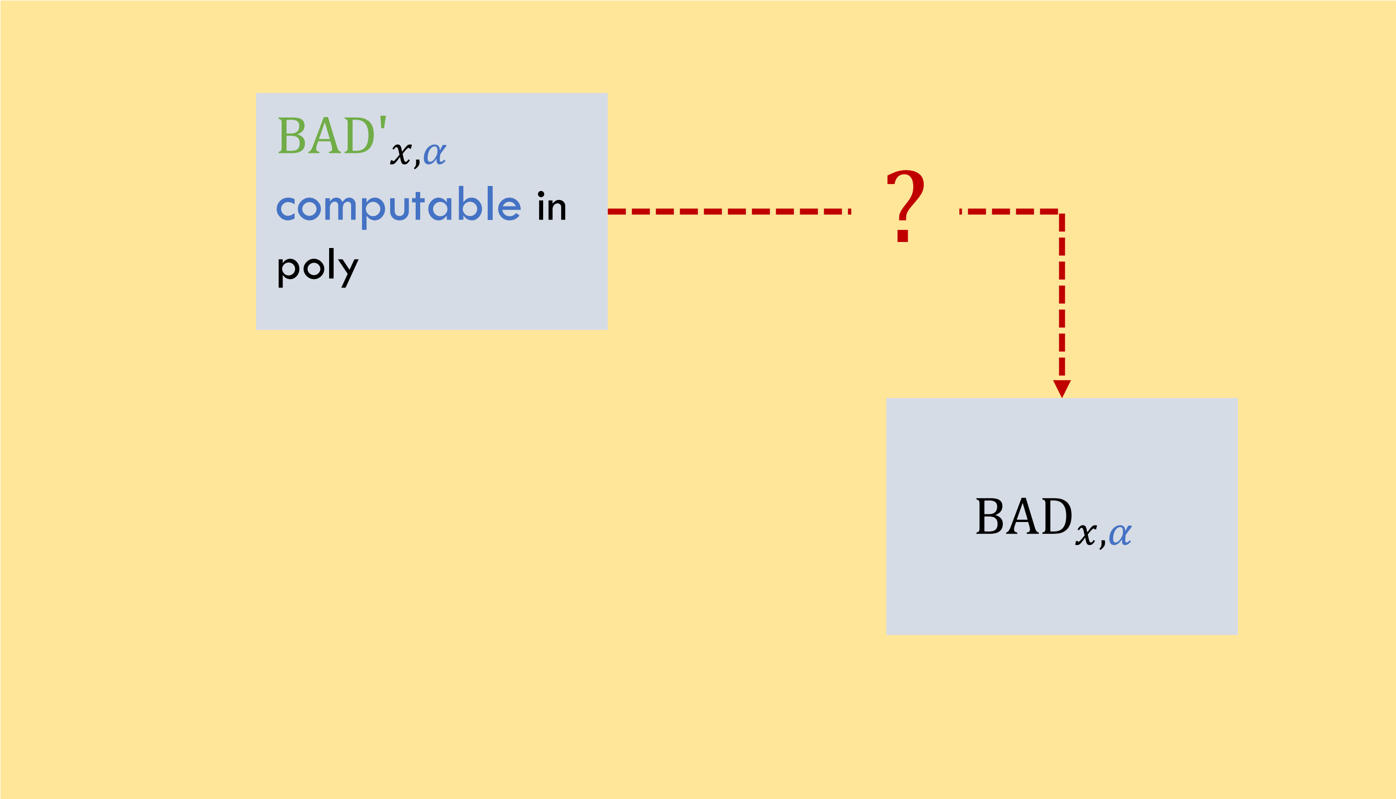
2 Challenge space is of polynomial size

3 Bad challenges are product verifiable in ~~TC^0~~ poly

TC^0 - Constant depth polynomial-size threshold circuits

For this talk

[C-Jain-Jin'21] Methodology



BAD$_{x,\alpha}$ properties

1. Bad challenges are a product set
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For this talk

Easy Case: Verifiable Unique Bad Challenge

$$\mathrm{BAD}_{x,\alpha}^{(1)}$$

Easy Case: Verifiable Unique Bad Challenge

$\mathrm{BAD}_{x,\alpha}^{(1)}$

<u>Compute Bad Challenge</u>

for $\beta \in \mathrm{ChallengeSpace}$

  if $\beta \in \mathrm{BAD}_{x,\alpha}^{(1)}$

    return β

$\mathrm{ChallengeSpace}$ polynomial size + $\mathrm{BAD}_{x,\alpha}^{(1)}$ efficiently verifiable $\Rightarrow$ $\mathrm{BAD}_{x,\alpha}^{(1)}$ efficiently computable.

Easy Case: Verifiable Unique Bad Challenge

$$\mathrm{BAD}_{x,\alpha} = \mathrm{BAD}_{x,\alpha}^{(1)} \times \mathrm{BAD}_{x,\alpha}^{(2)} \times \cdots \times \mathrm{BAD}_{x,\alpha}^{(d)}$$

Easy Case: Verifiable Unique Bad Challenge

$$\mathrm{BAD}_{x,\alpha} = \mathrm{BAD}_{x,\alpha}^{(1)} \times \mathrm{BAD}_{x,\alpha}^{(2)} \times \cdots \times \mathrm{BAD}_{x,\alpha}^{(d)}$$

<u>Compute Bad Challenge</u>

for $i \in [d]$
    for $\beta^{(i)} \in \mathrm{ChallengeSpace}$
        if $\beta^{(i)} \in \mathrm{BAD}_{x,\alpha}^{(i)}$
            store $\beta^{(i)}$
return $(\beta^{(1)}, \cdots, \beta^{(d)})$

poly repetitions + $\mathrm{ChallengeSpace}$ polynomial size + $\mathrm{BAD}_{x,\alpha}^{(i)}$ efficiently verifiable $\Rightarrow$ $\mathrm{BAD}_{x,\alpha}$ efficiently computable.

Reducing to Verifiable Unique Bad Challenge

No parallel repetition

$\longleftarrow \ell = \log_2 |\text{ChallengeSpace}| \longrightarrow$

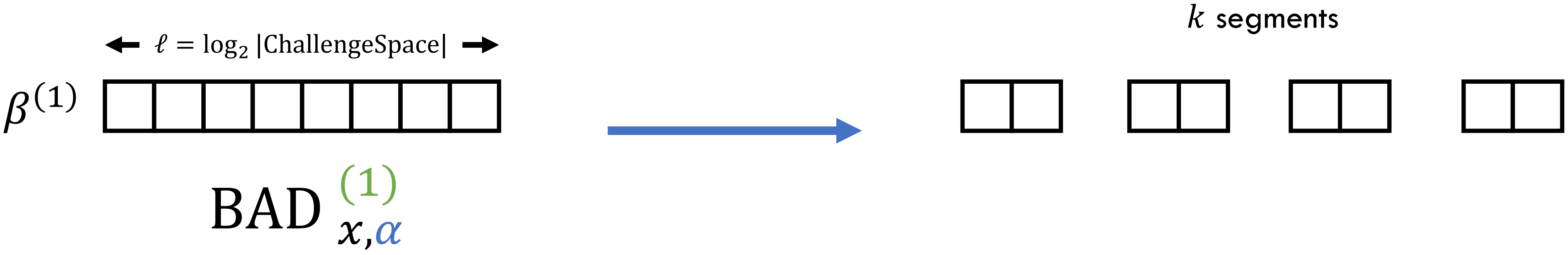
$\beta^{(1)}$ $\boxed{}\boxed{}\boxed{}\boxed{}\boxed{}\boxed{}\boxed{}\boxed{}$

$$\text{BAD}_{x,\alpha}^{(1)}$$

No restriction on number of bad challenges

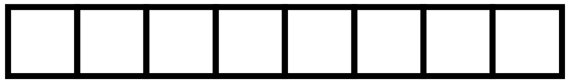
Reducing to Verifiable Unique Bad Challenge

No parallel repetition

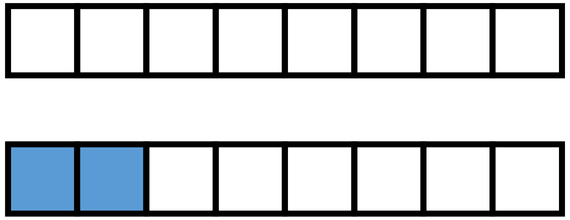


Each segment has ℓ/k bits

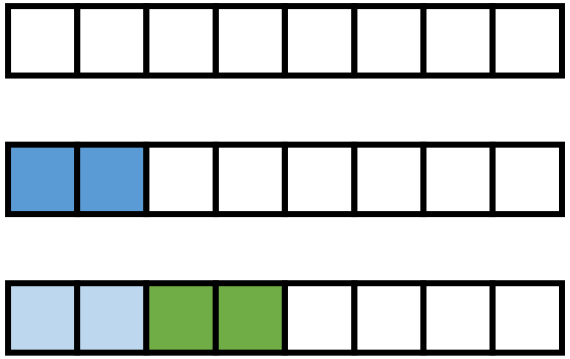
Sampling Challenges via Segments



Sampling Challenges via Segments



Sampling Challenges via Segments



Sampling Challenges via Segments

h is correlation intractable for efficiently verifiable unique bad challenge relations.

Sampling Challenges via Segments

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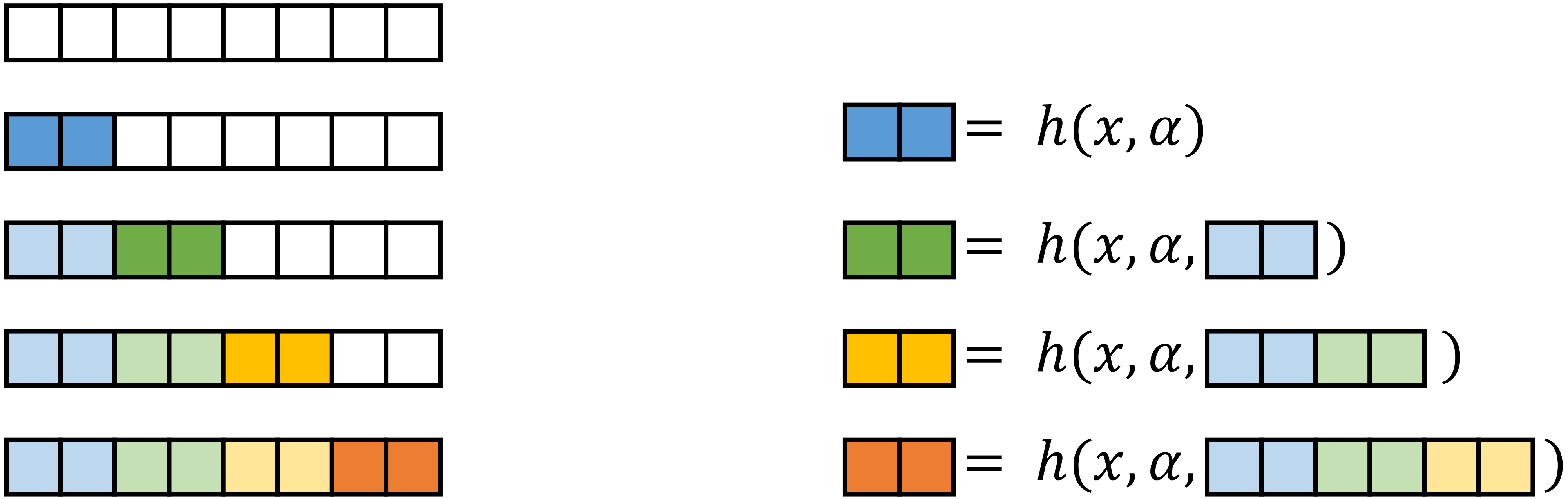
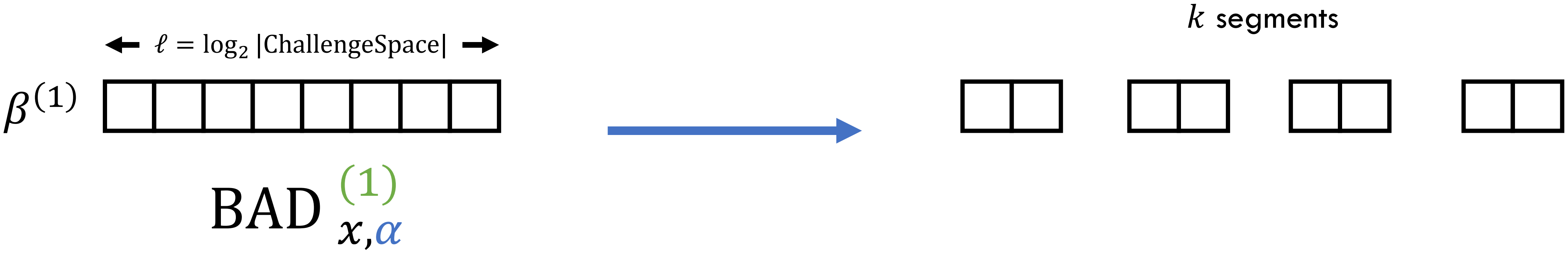
Sampling Challenges via Segments



h is correlation intractable for efficiently verifiable unique bad challenge relations.

Reducing to Verifiable Unique Bad Challenge

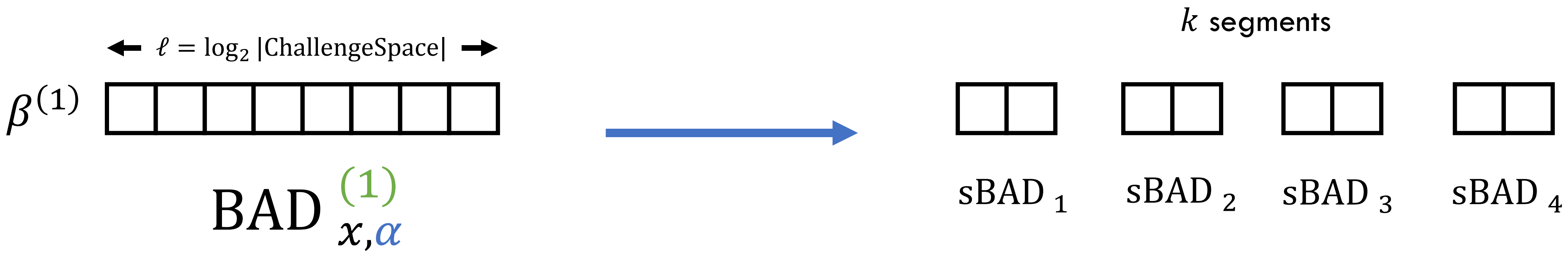
No parallel repetition



Each segment has ℓ / k bits

Reducing to Verifiable Unique Bad Challenge

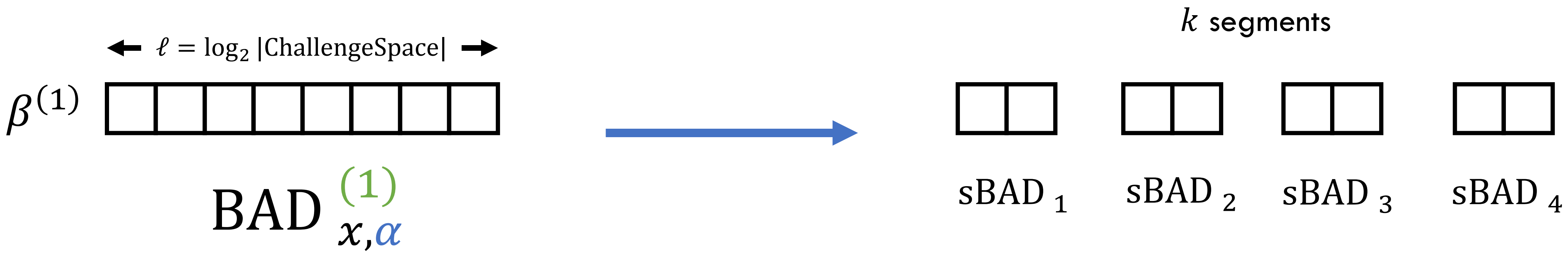
No parallel repetition



Each segment has ℓ/k bits

Reducing to Verifiable Unique Bad Challenge

No parallel repetition



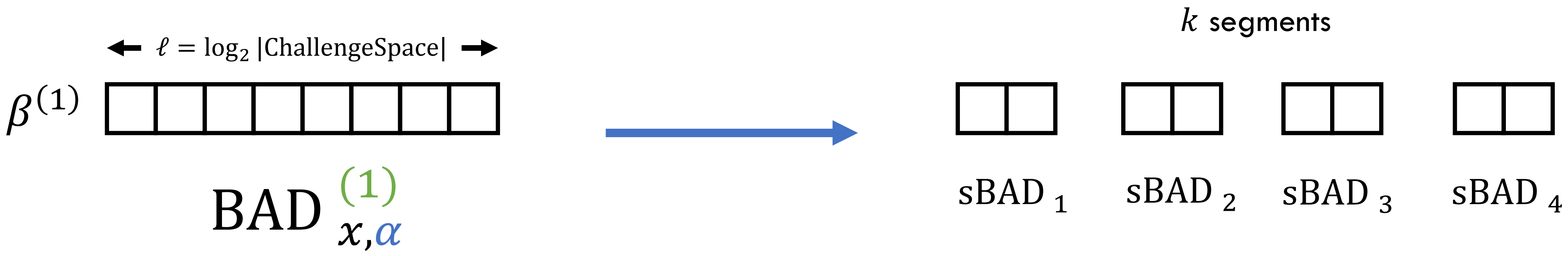
Requirements:

1. Each sBAD_j must be efficiently verifiable unique bad challenge relations.

Each segment has ℓ/k bits

Reducing to Verifiable Unique Bad Challenge

No parallel repetition

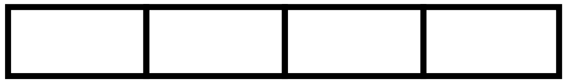


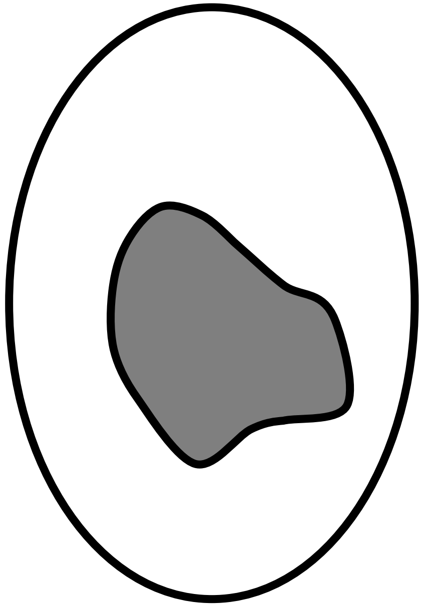
Requirements:

1. Each sBAD_j must be efficiently verifiable unique bad challenge relations.
2. If a challenge is bad, then there must exist a bad segment.

Each segment has ℓ/k bits

Defining Bad Segments

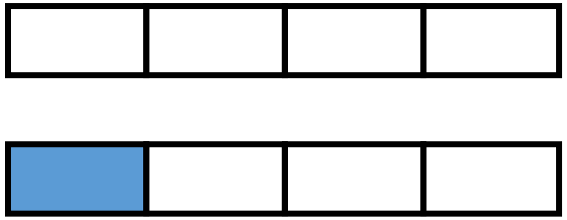


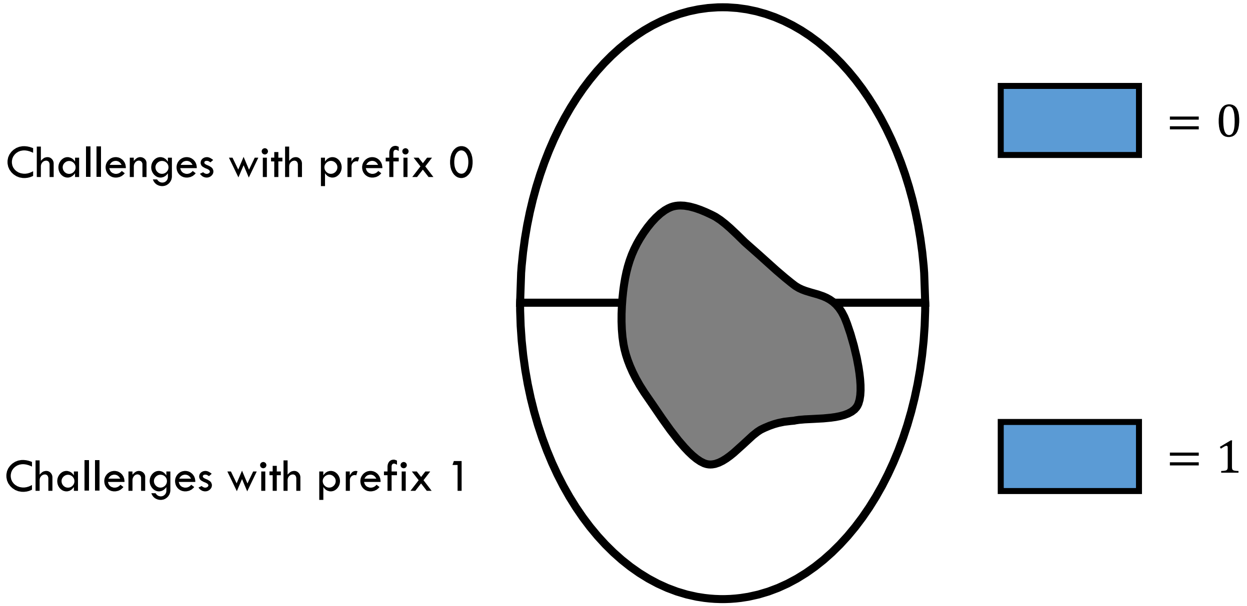


Challenge space

All bad challenges for $\mathrm{BAD}_{x,\alpha}^{(1)}$

Defining Bad Segments



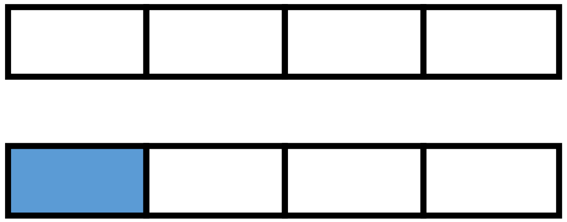


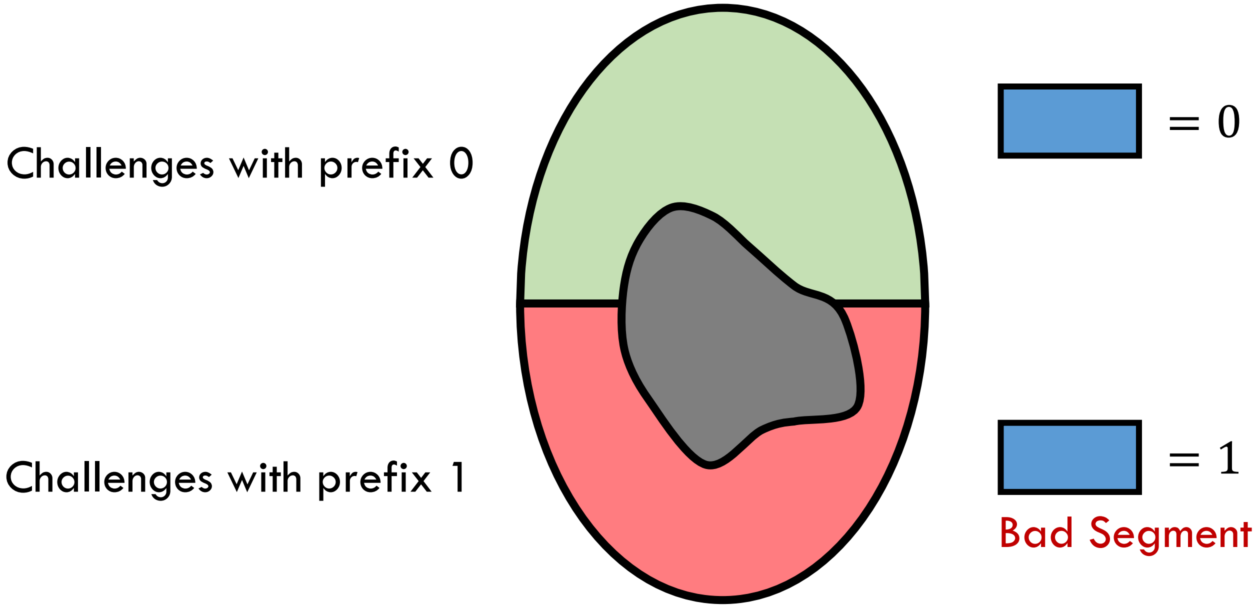
sBAD_1

is bad if

#bad challenges with prefix $>$ #bad challenges/2

Defining Bad Segments





sBAD_1

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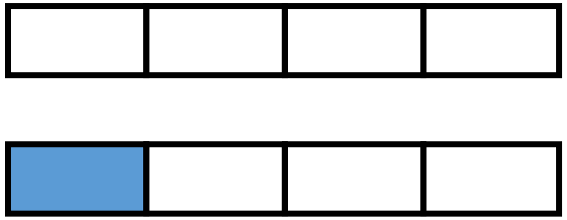
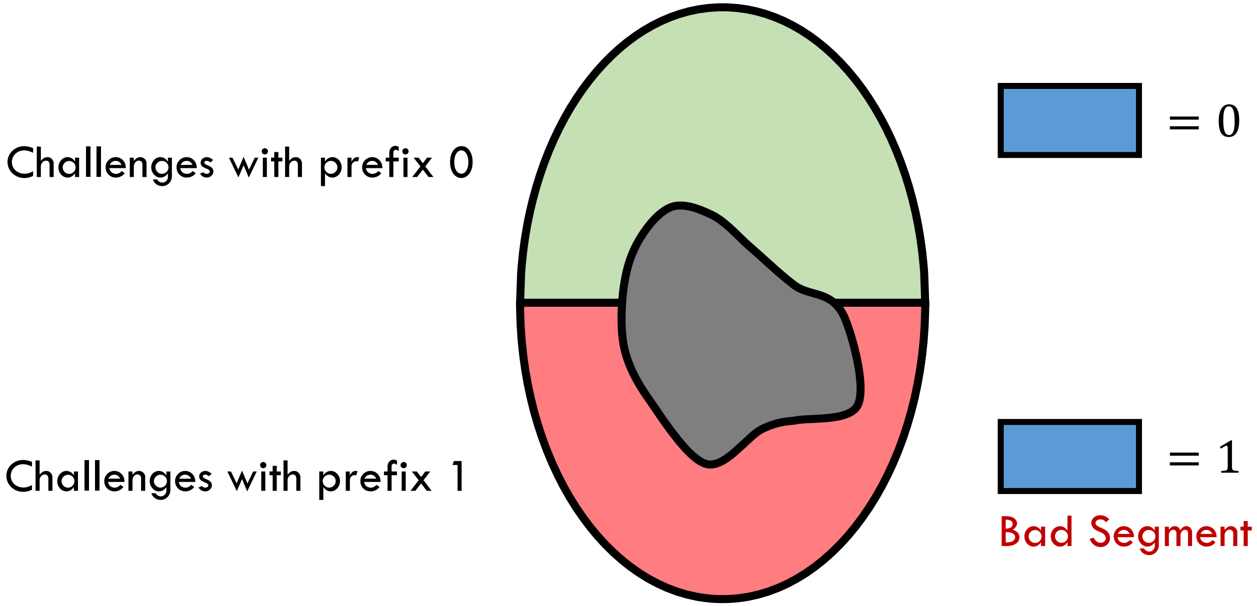
Defining Bad Segments





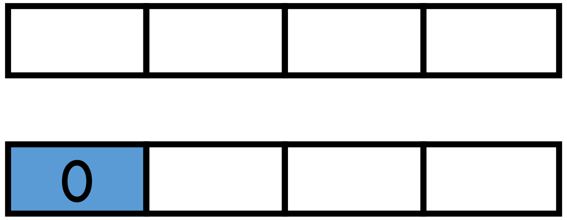
1. By pigeonhole principle, unique bad
2. ChallengeSpace polynomial size + $\mathrm{BAD}_{x,\alpha}^{(1)}$ efficiently verifiable ⇒ sBAD_1 efficiently verifiable

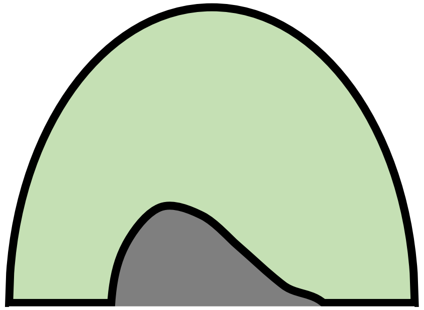
sBAD_1

is bad if

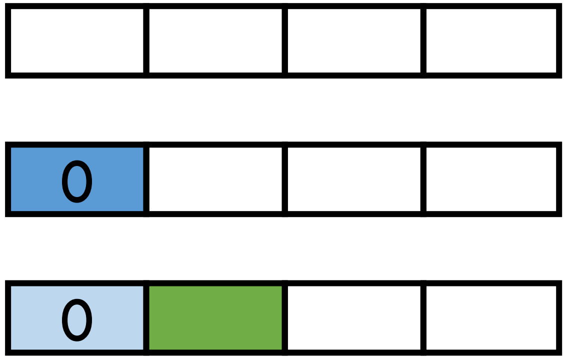
#bad challenges with prefix $>$ #bad challenges/2

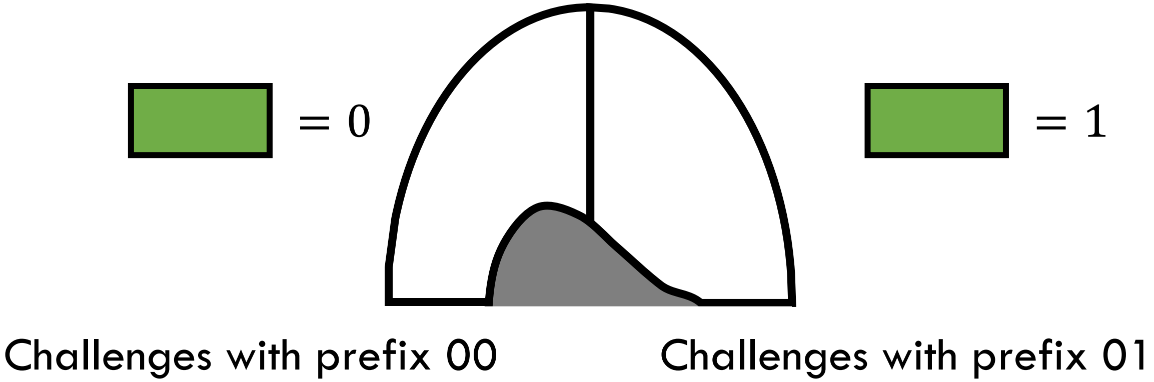
Defining Bad Segments



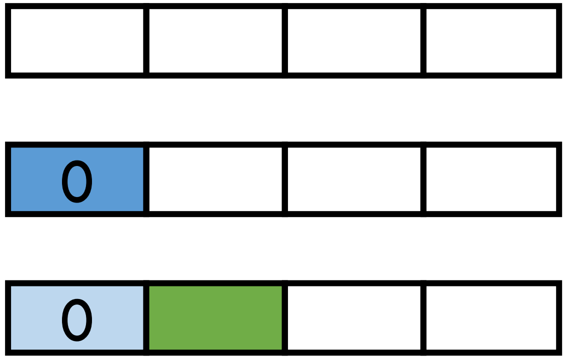


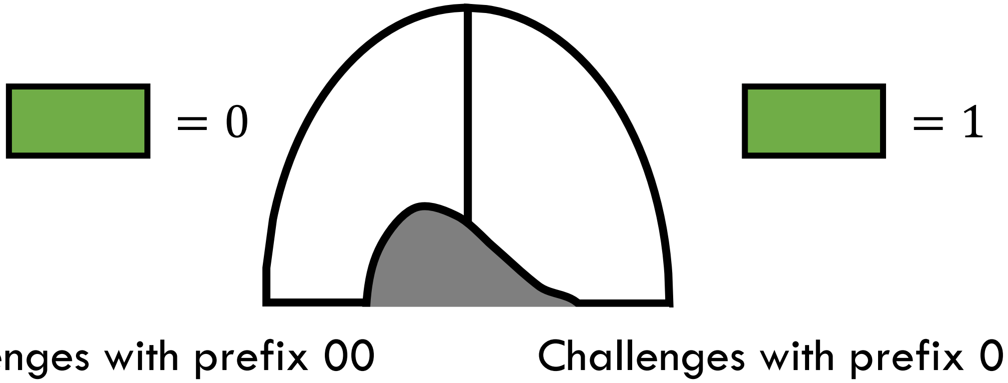
Defining Bad Segments





Defining Bad Segments

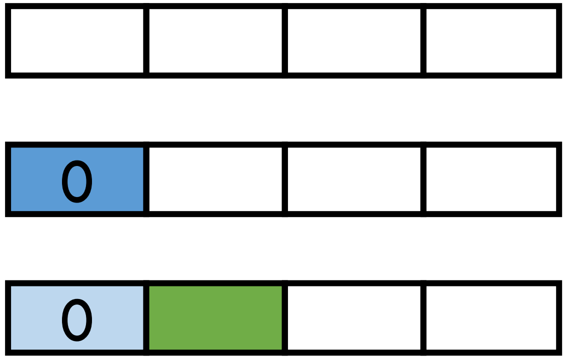


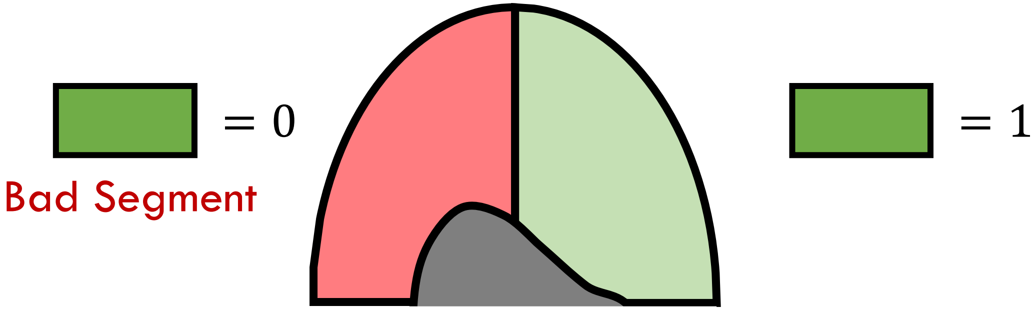


sBAD $_2$

is bad given $\boxed{0}$ if
#bad challenges with prefix $\boxed{0}$
> (#bad challenges with prefix $\boxed{0}$)/2

Defining Bad Segments





sBAD_2

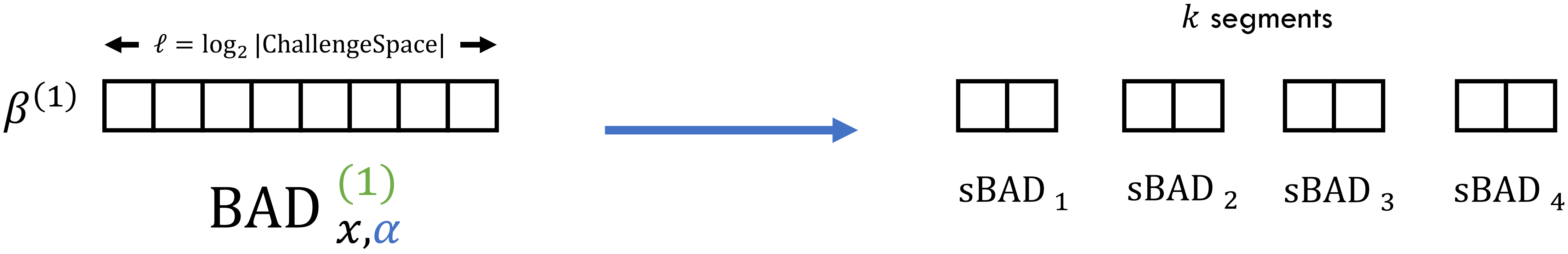
is bad given 0 if

#bad challenges with prefix 0

> (#bad challenges with prefix 0)/2

Reducing to Verifiable Unique Bad Challenge

No parallel repetition



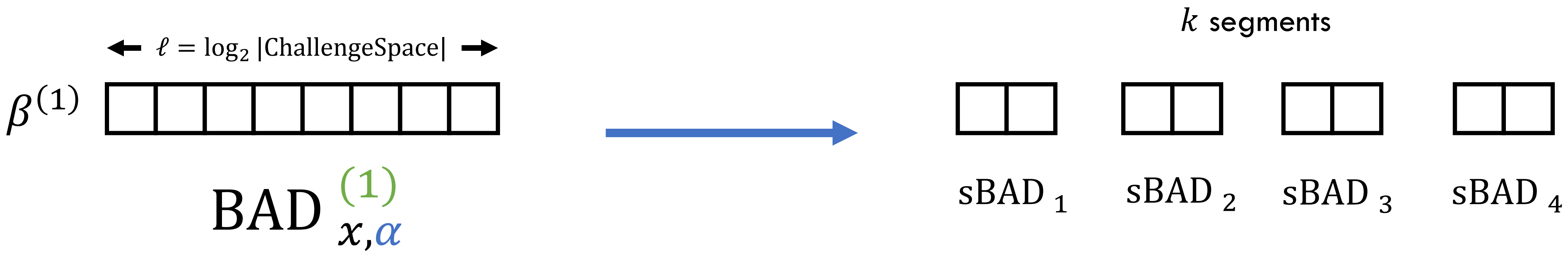
Requirements:

1. Each sBAD_j must be efficiently verifiable unique bad challenge relations.
2. If a challenge is bad, then there must exist a bad segment.

Each segment has ℓ / k bits

Reducing to Verifiable Unique Bad Challenge

No parallel repetition



Requirements:

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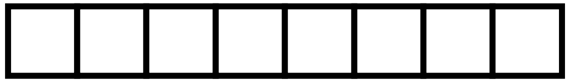
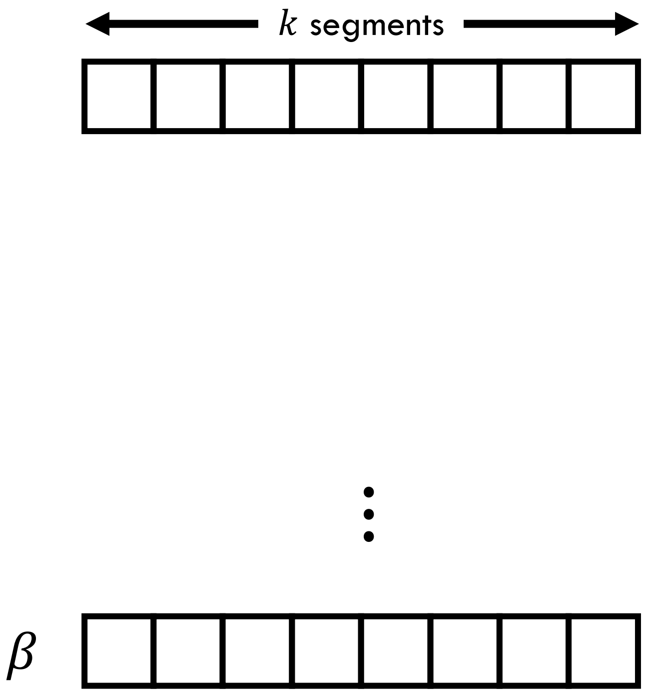
Existence of a bad segment

β



Bad challenge by assumption

Existence of a bad segment



Bad challenge by assumption

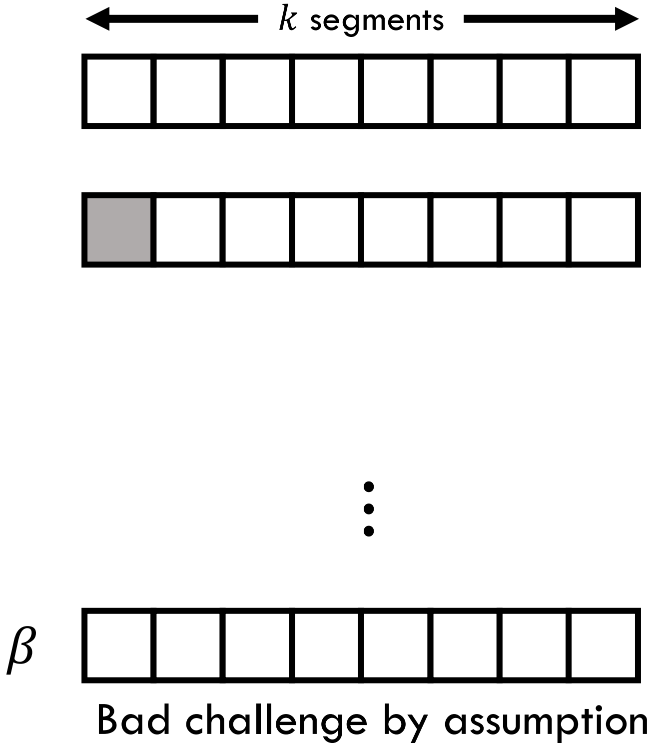
#bad challenges remaining

T

$T =$ #bad challenges $\mathrm{BAD}_{x,\alpha}^{(1)}$

k such that $2^k > T$

Existence of a bad segment



#bad challenges remaining

T

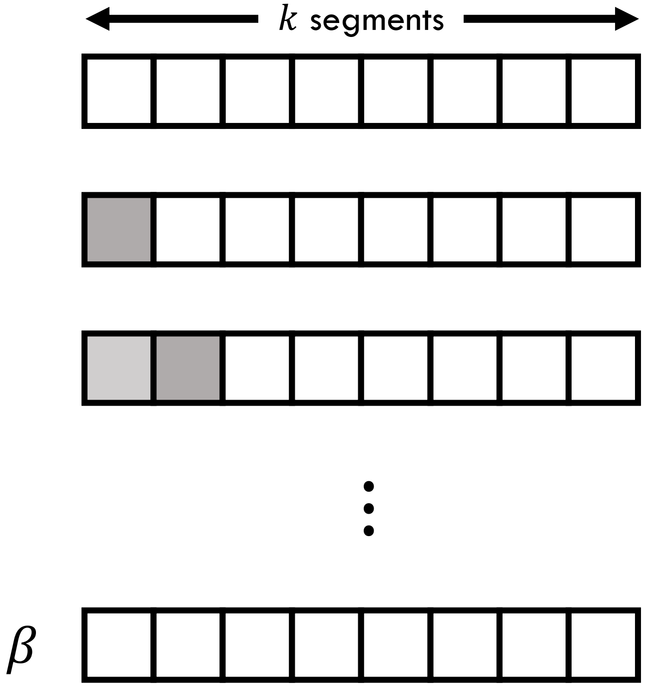
$< T/2$

If each segment is good

$T = \#\text{bad challenges } \mathrm{BAD}_{x,\alpha}^{(1)}$

k such that $2^k > T$

Existence of a bad segment



Bad challenge by assumption

#bad challenges remaining

T

$< T/2$

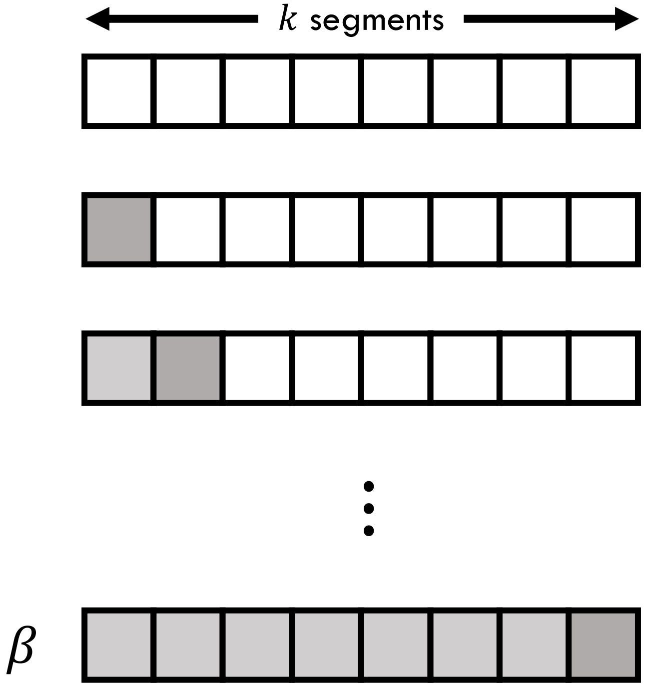
$< T/4$

If each segment is good

T = #bad challenges $\mathrm{BAD}_{x,\alpha}^{(1)}$

k such that $2^k > T$

Existence of a bad segment



Bad challenge by assumption

#bad challenges remaining

T

$< T/2$

$< T/4$

$\vdots$

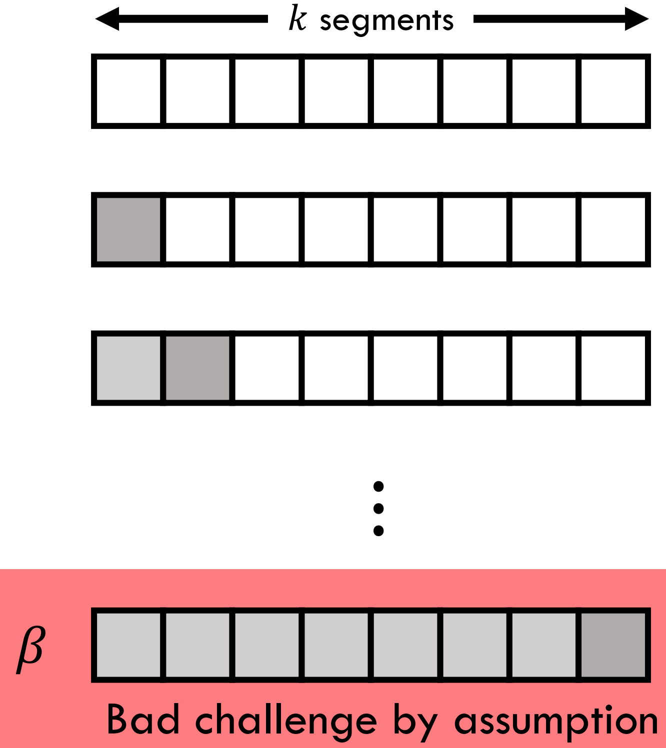
< 1

If each segment is good

$T = $ #bad challenges $\mathrm{BAD}_{x,\alpha}^{(1)}$

k such that $2^k > T$

Existence of a bad segment



#bad challenges remaining
T
$< T/2$
$< T/4$
⋮
< 1

$T = \#\text{bad challenges } \mathrm{BAD}_{x,\alpha}^{(1)}$

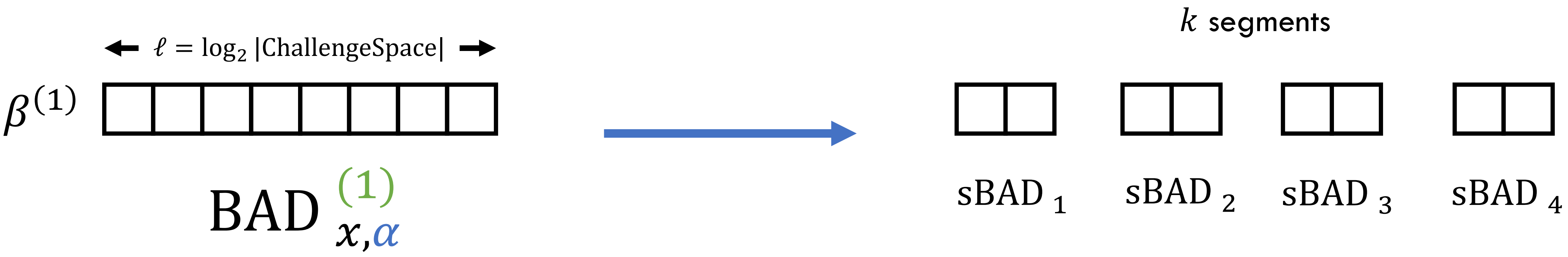
k such that $2^k > T$

contradiction

If each segment is good

Reducing to Verifiable Unique Bad Challenge

No parallel repetition



Requirements:

1. Each sBAD_j must be efficiently verifiable unique bad challenge relations.
2. If a challenge is bad, then there must exist a bad segment.

Each segment has ℓ/k bits

[C-Jain-Jin'21] Methodology

$\mathrm{BAD'}_{x,\alpha}$ computable in poly

$\mathrm{BAD}_{x,\alpha}$

No repetition

$\mathrm{BAD}_{x,\alpha}$ properties

1. Bad challenges are a product set
2. Challenge space is of polynomial size
3. Bad challenges are product verifiable in poly

Concluding Remarks

See paper for:

1. Extension to parallel repetition.
2. Choice of parameters for size of segments, number of repetitions.
3. New somewhere extractable hash scheme necessary for “Magic box”.

Recap: Our Results

Theorem 1

Assuming sub-exponential hardness of DDH, there exists SNARGs for batch NP where

$$|\Pi| = \text{poly}(\log k, |C|)$$

Theorem 2

Assuming sub-exponential hardness of DDH, there exists SNARGs for P where

$|\text{CRS}|, |\Pi|, |$$| = \text{polylog}(T)$

Thank you. Questions?

Arka Rai Choudhuri

arkarai.choudhuri@ntt-research.com

ia.cr/2022/1486