When Can We Incrementally Prove Computations of Arbitrary Depth?

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A joint work with
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(IMDEA Software Institute)

This Talk in a Nutshell

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A study of the security of
Incrementally Verifiable Computation (IVC) under
the lens of the <u>depth</u> of the proven computation.

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the lens of the depth of the proven computation.

Our main motivation:
how can we prove security (or insecurity)
when we move beyond constant depth?

Succinct Cryptographic Proofs (SNARKs)

Server (Prover)

Client (Verifier)

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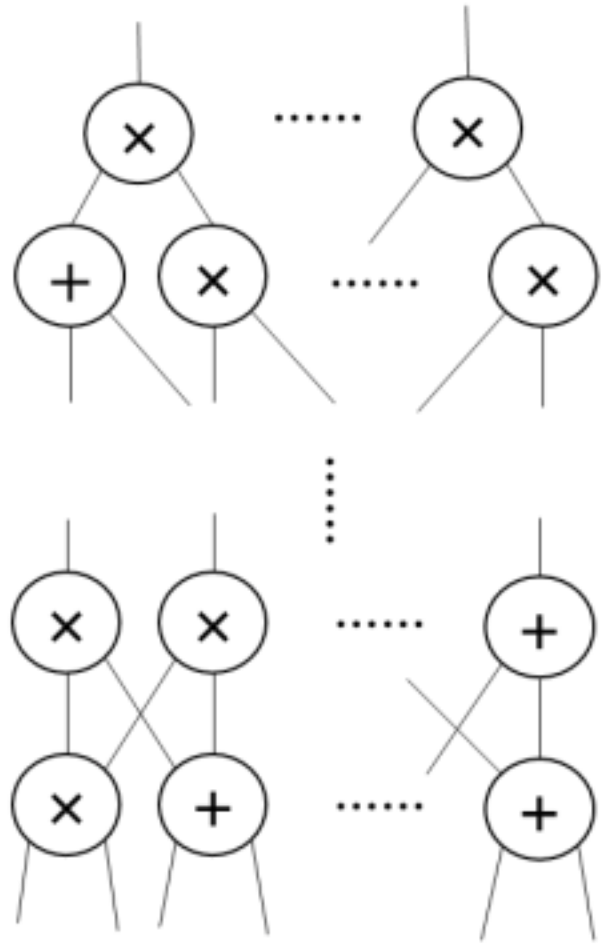
Client (Verifier)



Some program *F*

Succinct Cryptographic Proofs (SNARKs)

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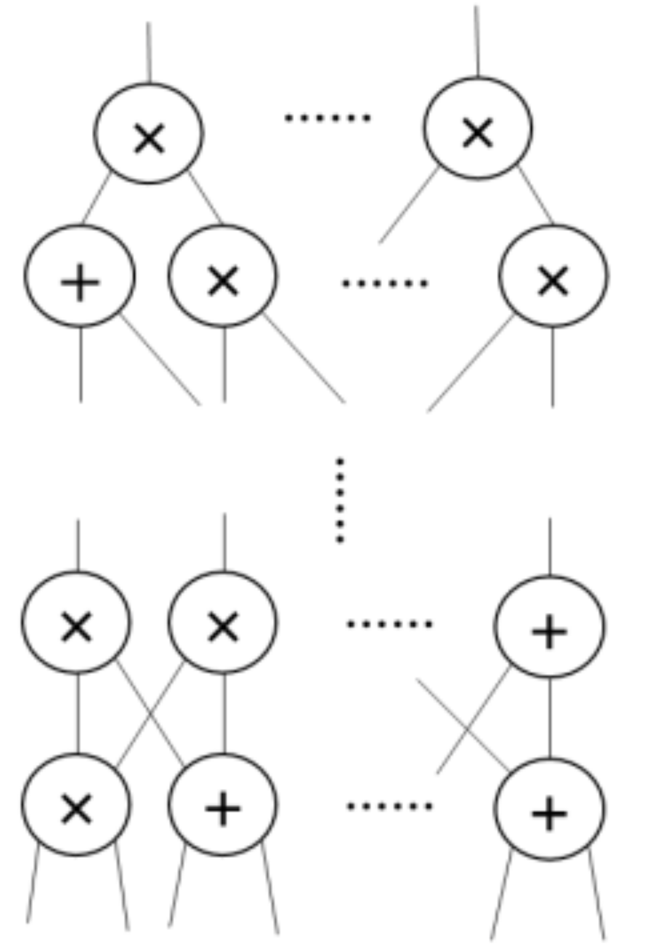

Some program *F*

Client would like to know whether $\exists w : F(\mathrm{x}, \mathrm{w}) = 1$

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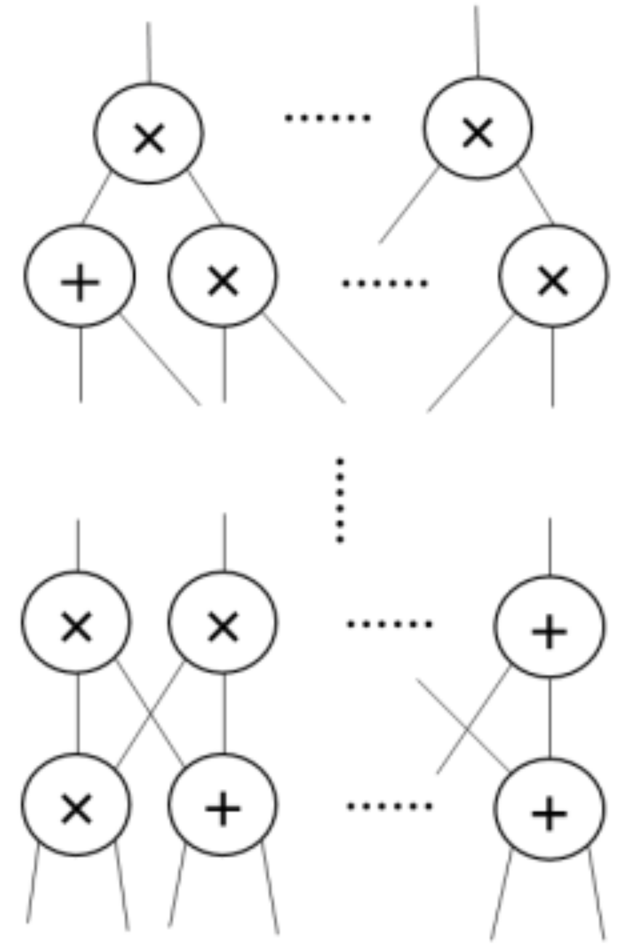
Server (Prover)

π

Client (Verifier)



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Proof that statement is true

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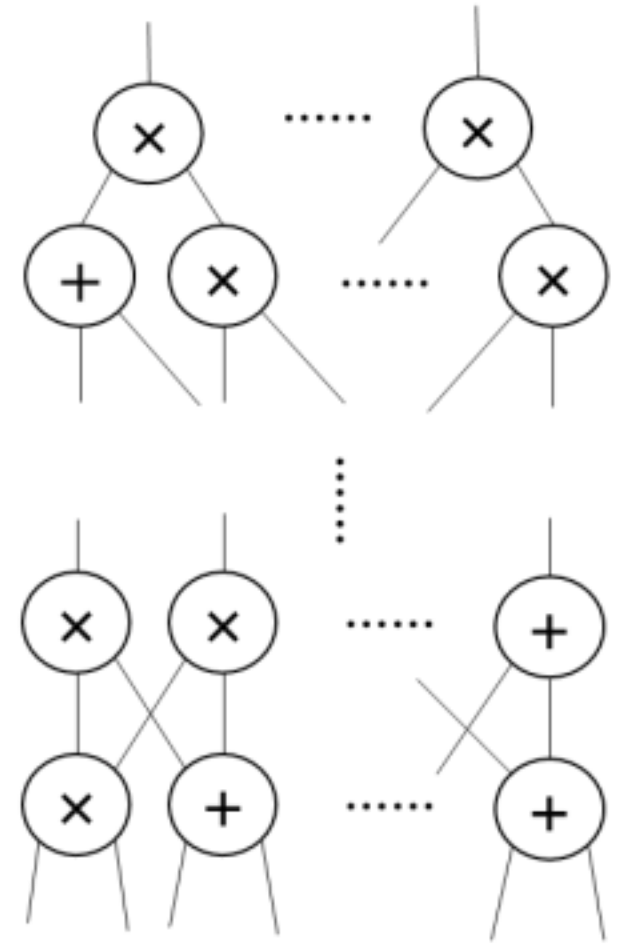

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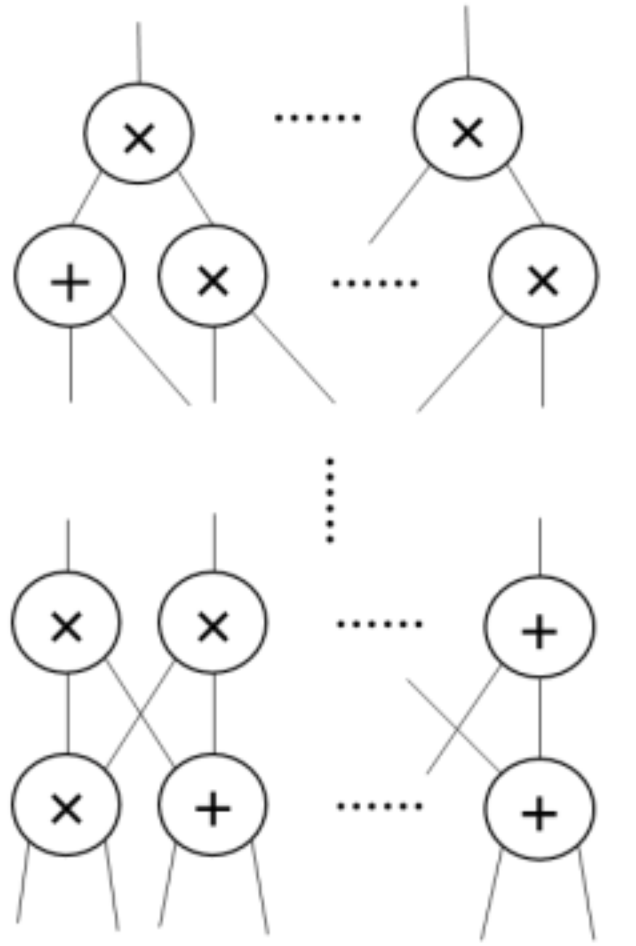
Proof that statement is true

Verify(x, π)

Client (Verifier)



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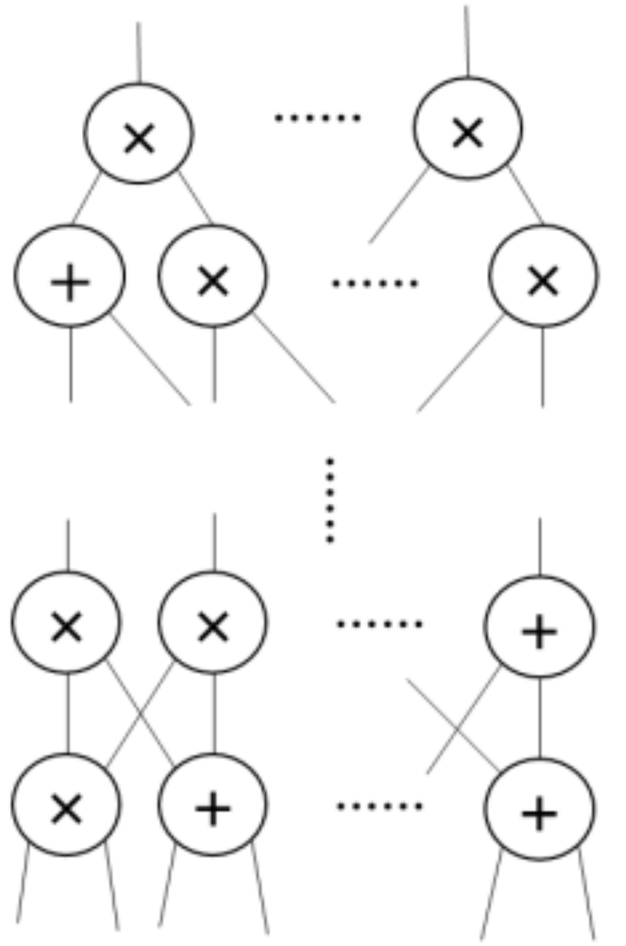

Some program *F*

Common requirement: **Succinctness**

(π is very small; Verify is very fast)

Client would like to know whether $\exists w : F(\mathrm{x}, \mathrm{w}) = 1$

Limitations of Traditional “Monolithic” Proofs

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  - whole “trace” of the computation should in principle be kept all in memory at the same time
- No pipelining
  - Must finish the computation before starting proving
  - Cannot take advantage of incremental computations (next slide)

Incremental Computations

$$z_0 \xrightarrow[w_0]{F} z_1 \xrightarrow[w_1]{F} \cdots \xrightarrow[w_{d-2}]{F} z_{d-1} \xrightarrow[w_{d-1}]{F} z_d$$

$$z_i = F(z_{i-1}, w_{i-1})$$

Incremental Computations

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Examples of natural applications:

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Examples of natural applications:

- Streaming algorithms

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Examples of natural applications:

- Streaming algorithms
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- Verifiable Delay Functions (VDF)

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- Streaming algorithms
- RAM computations
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- Recurrent neural networks

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Examples of natural applications:

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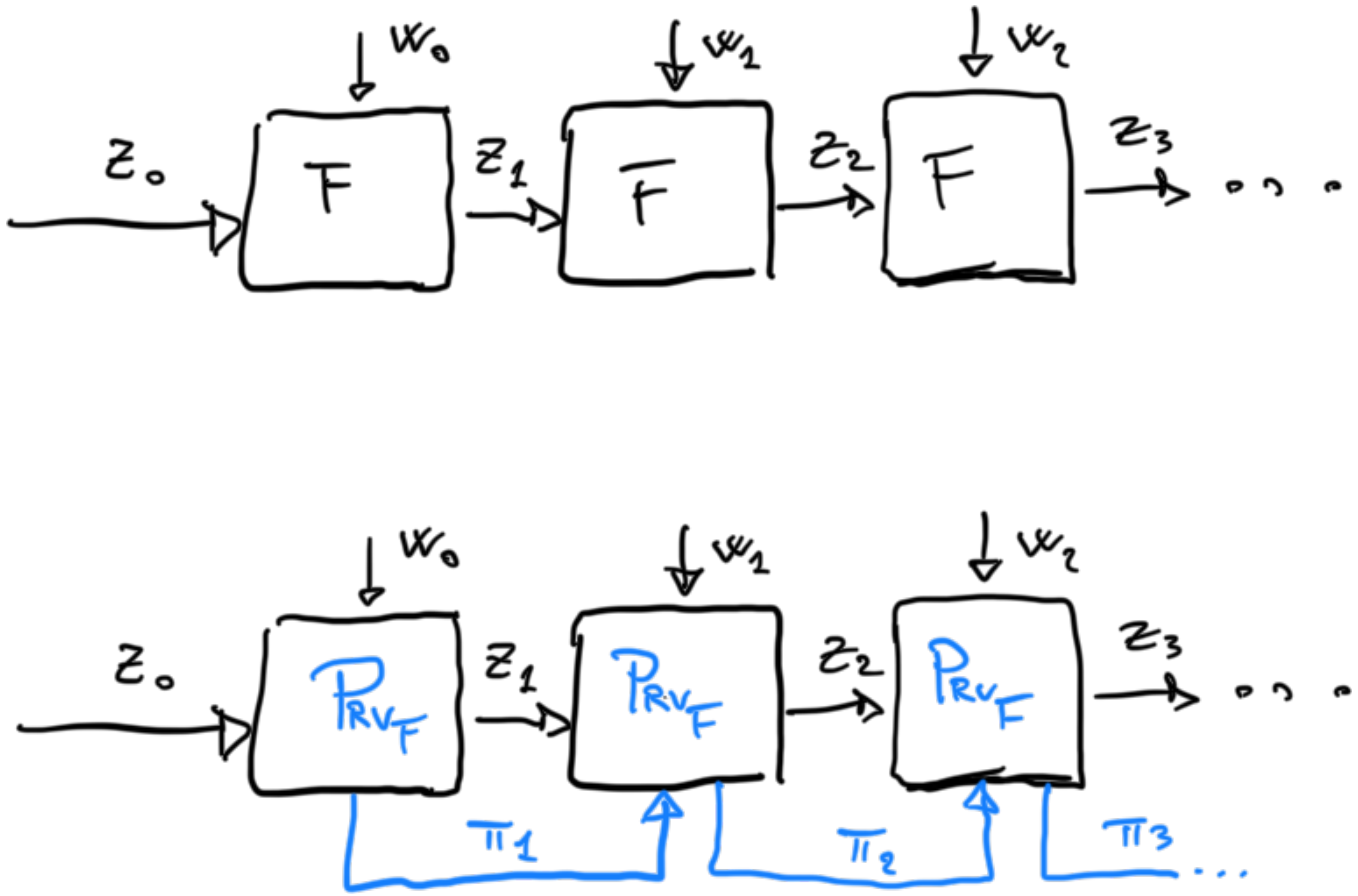
- …

Incrementally Verifiable Computations (IVC)



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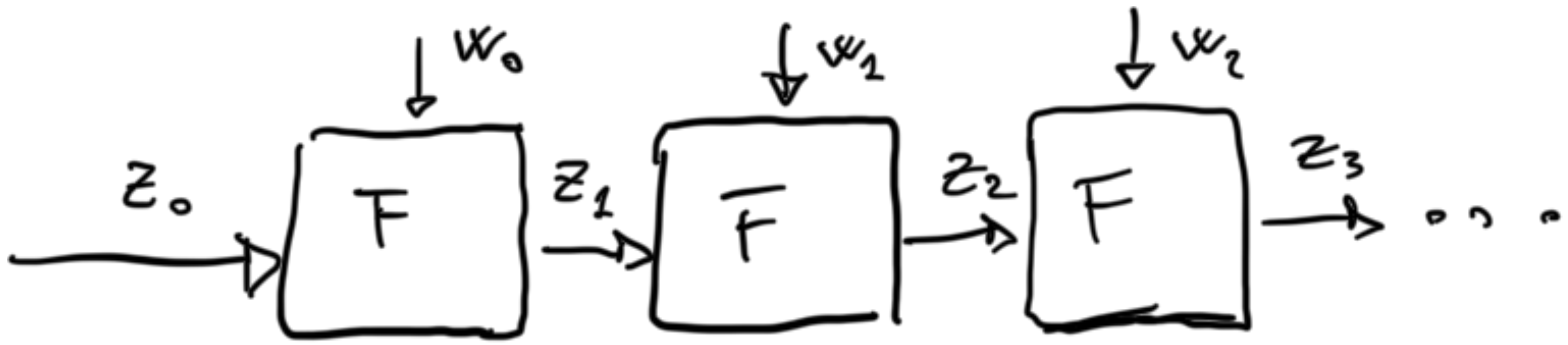

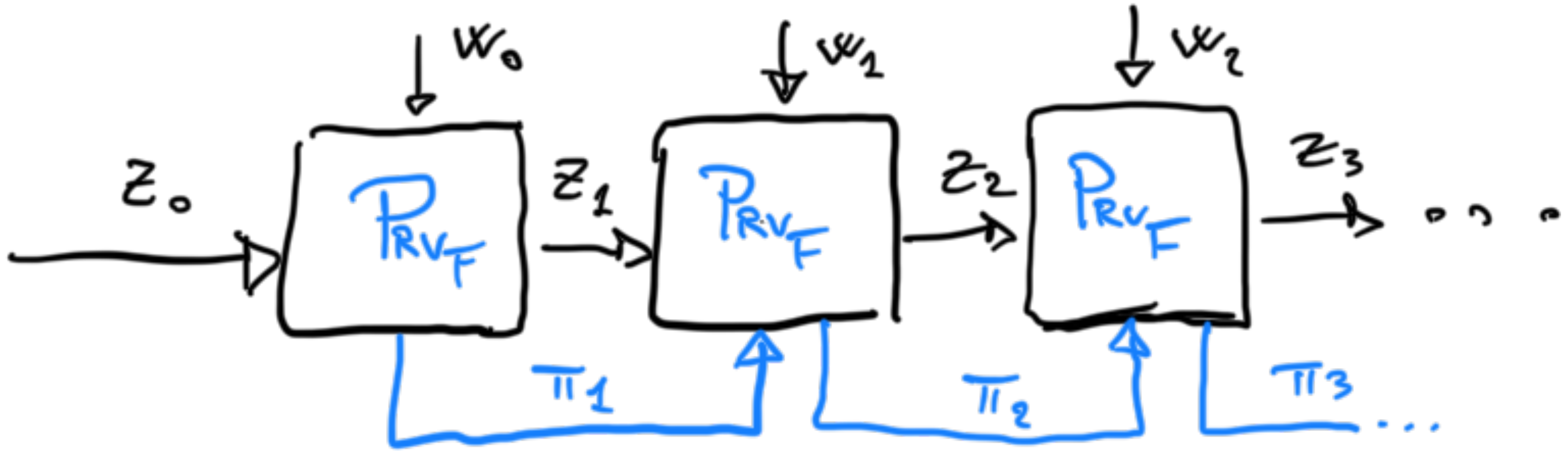

Proof size should be sublinear in the # of steps (the *depth* of the computation)

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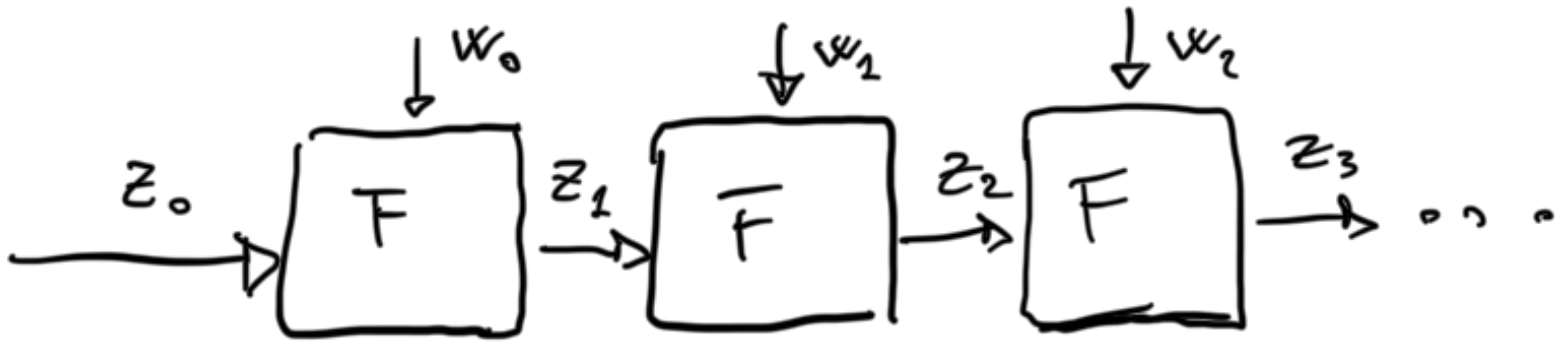

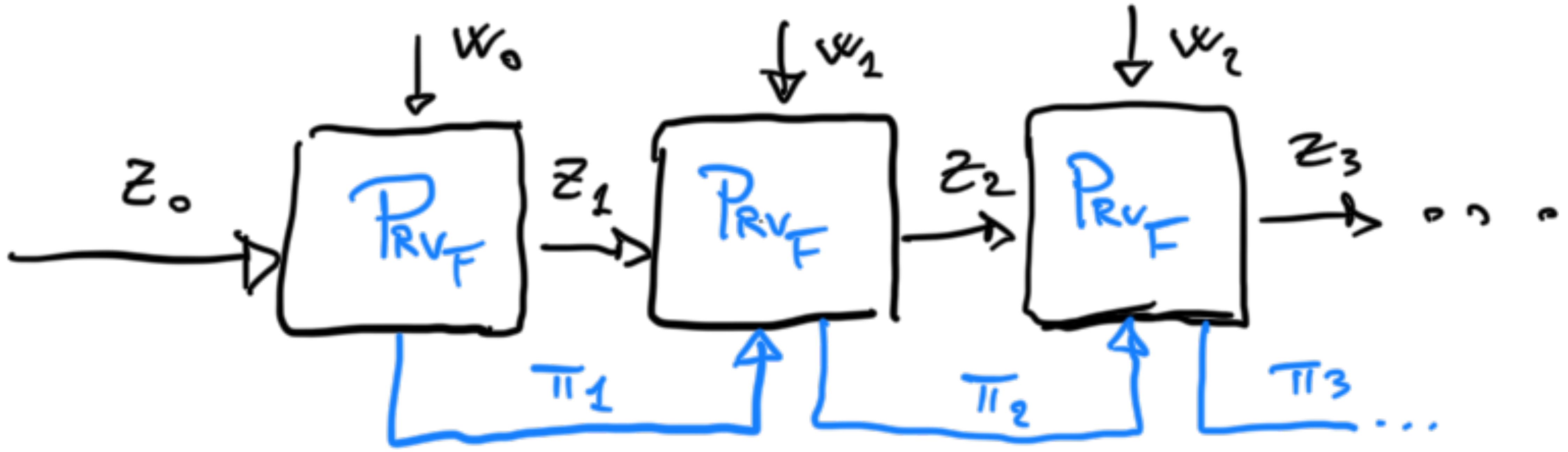

Advantages

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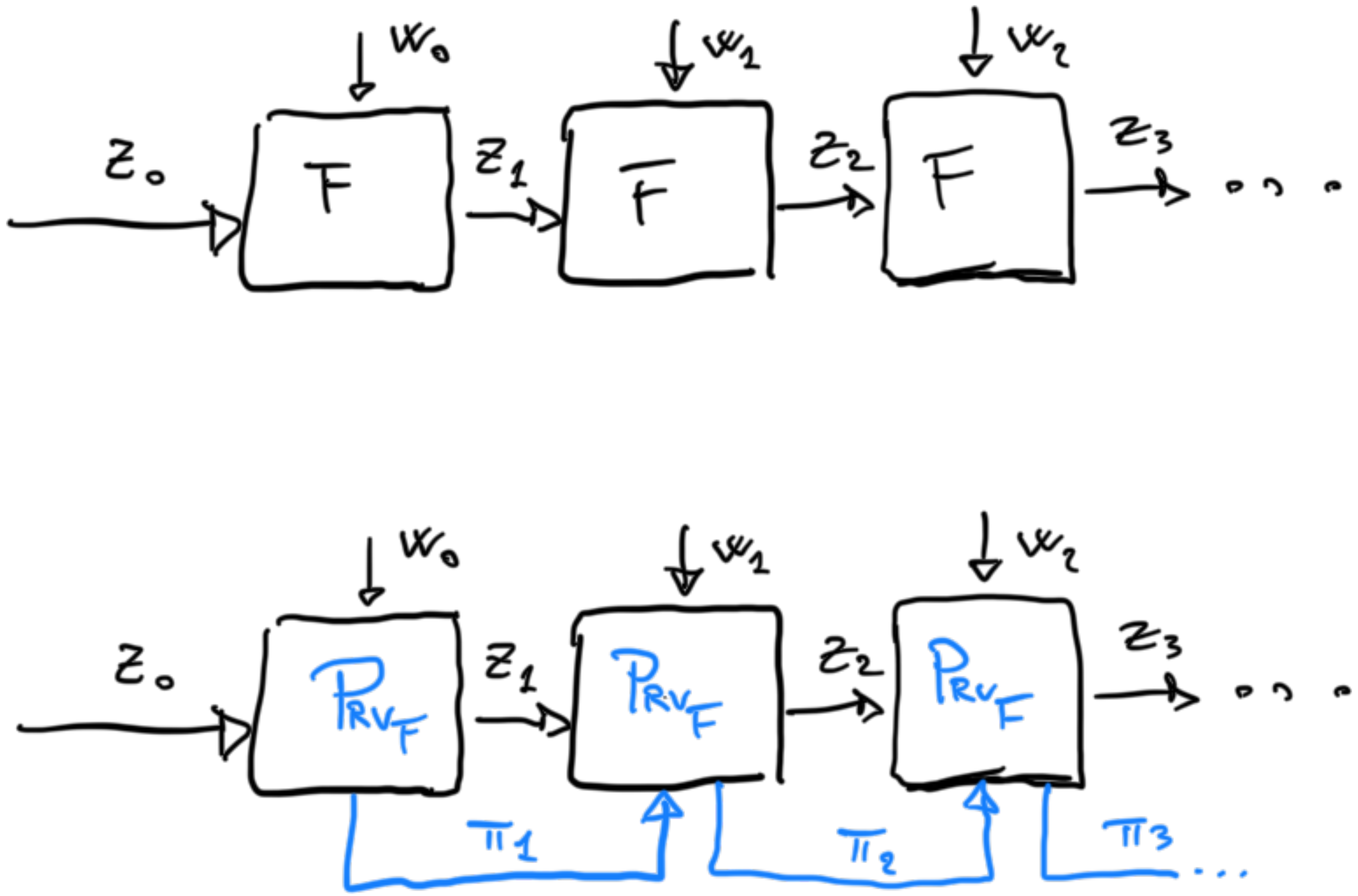

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- Low memory footprint

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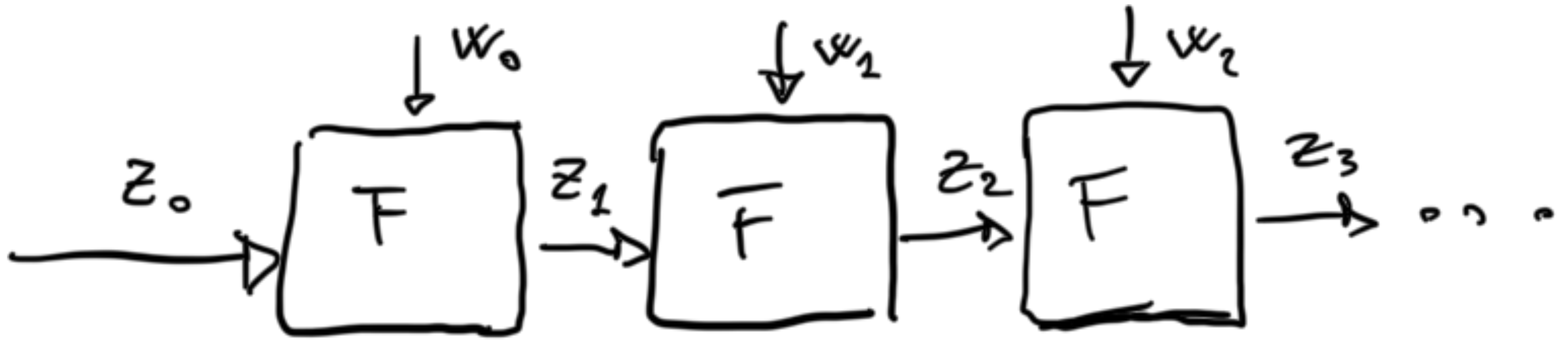

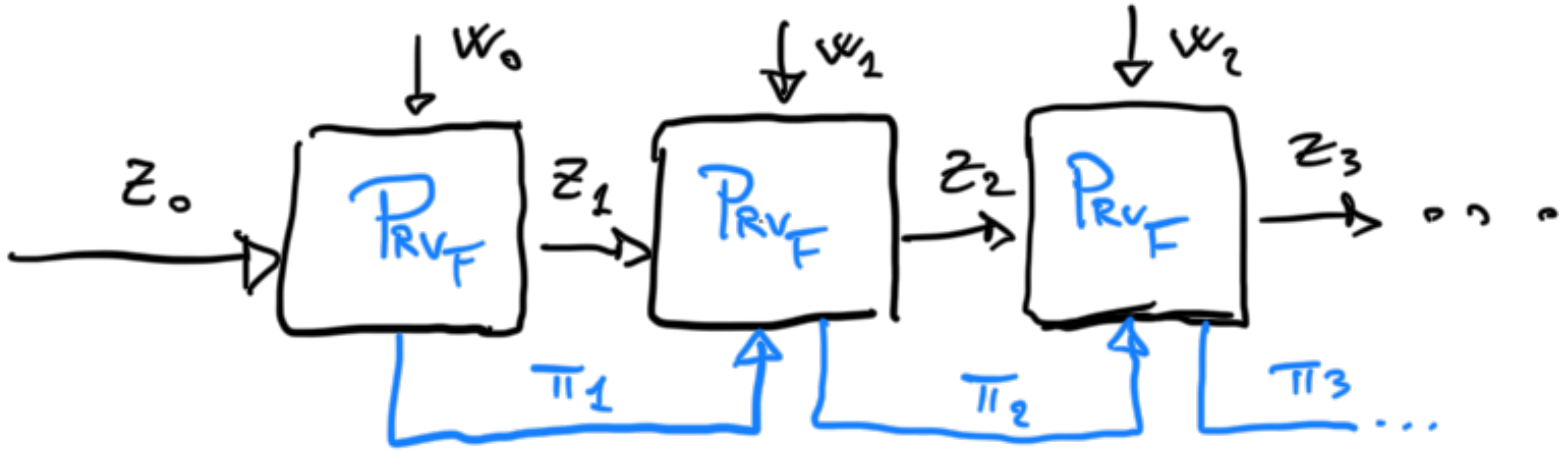

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- Pipelining opportunities

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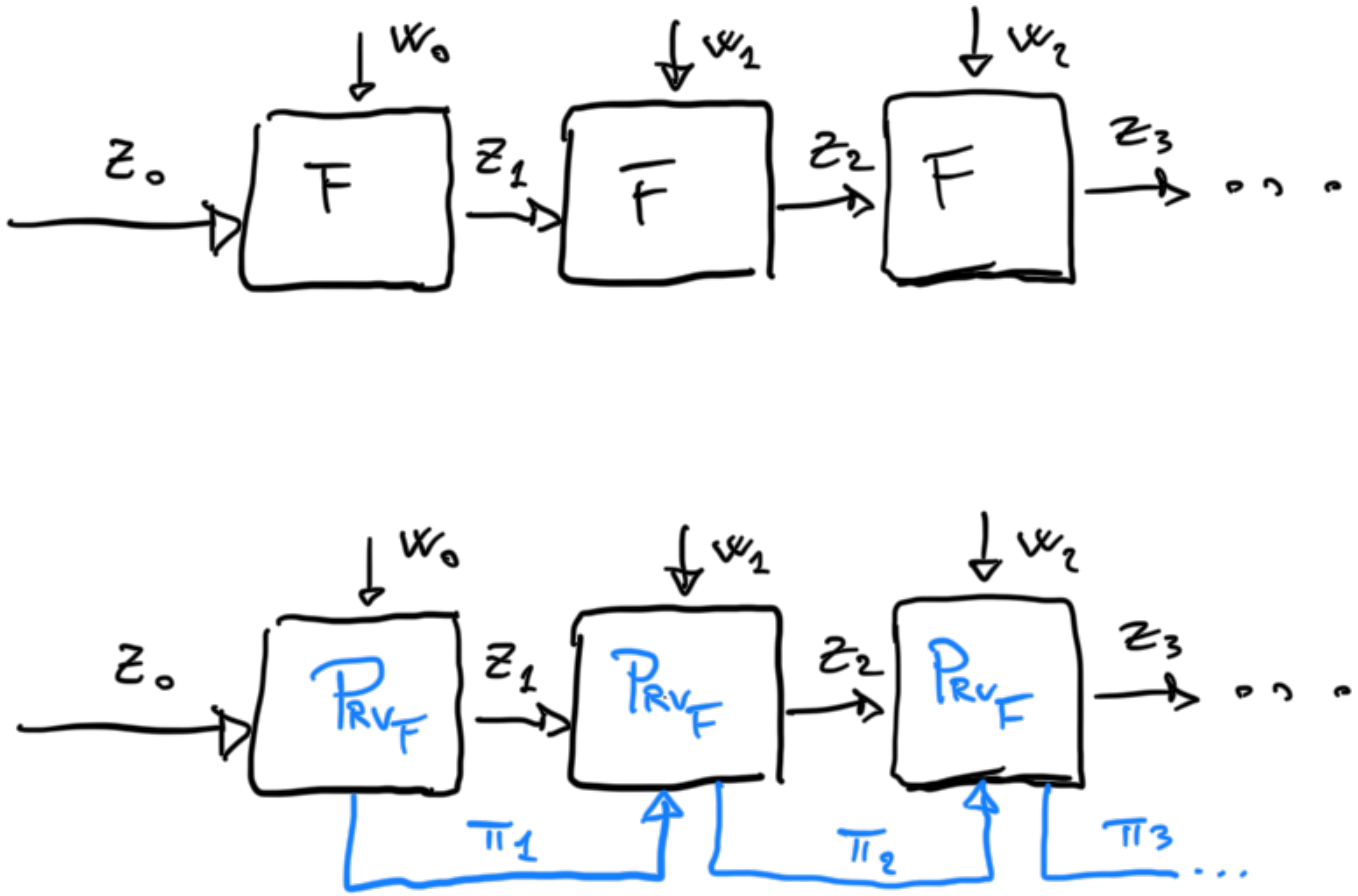

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- Natural model for incremental computations

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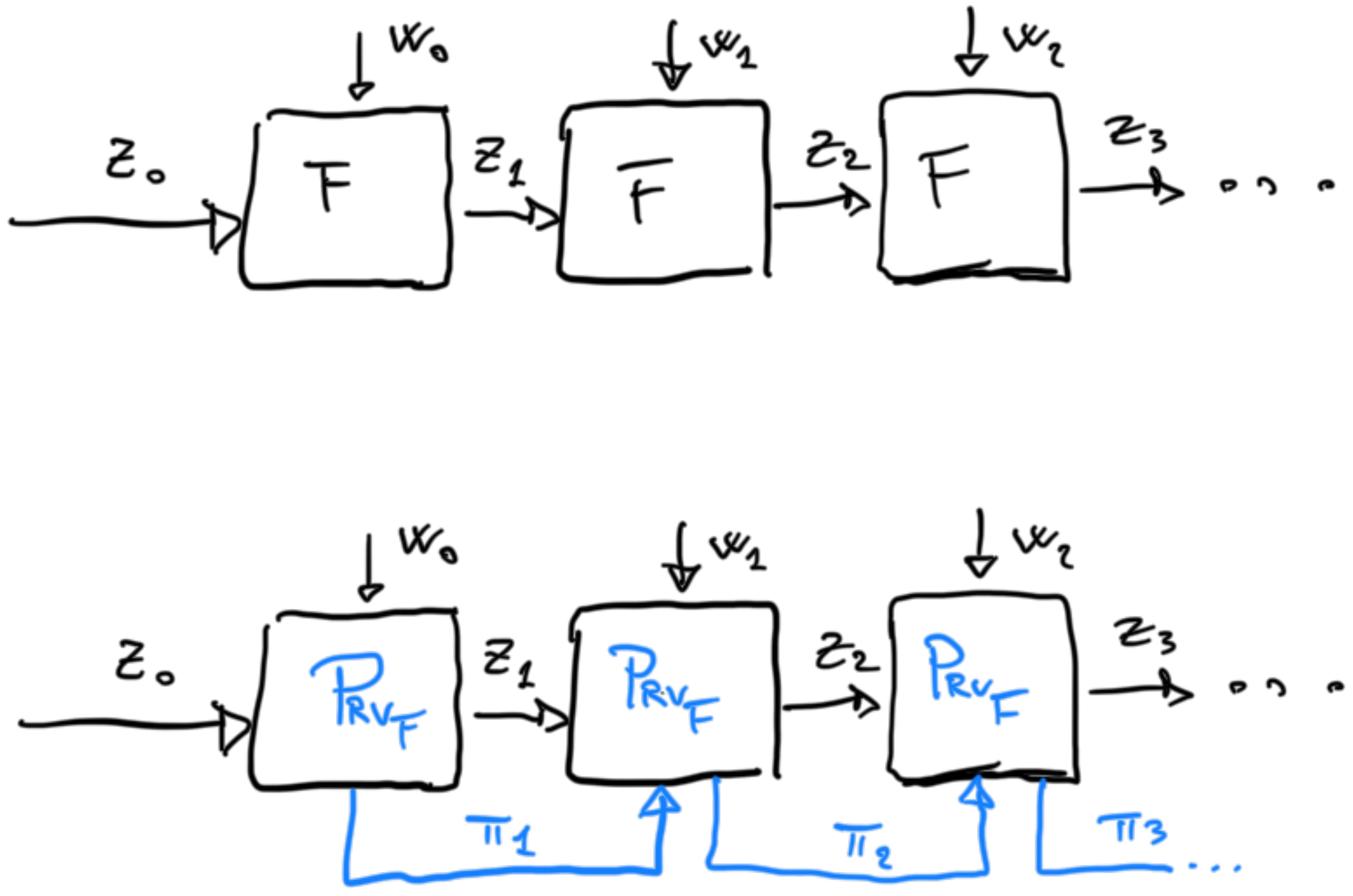

Advantages

- Low memory footprint
- Pipelining opportunities
- Natural model for incremental computations
- Proofs can be distributed (e.g., in settings with zero-knowledge)

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Constructions of IVC

(Practical or nearly-practical)

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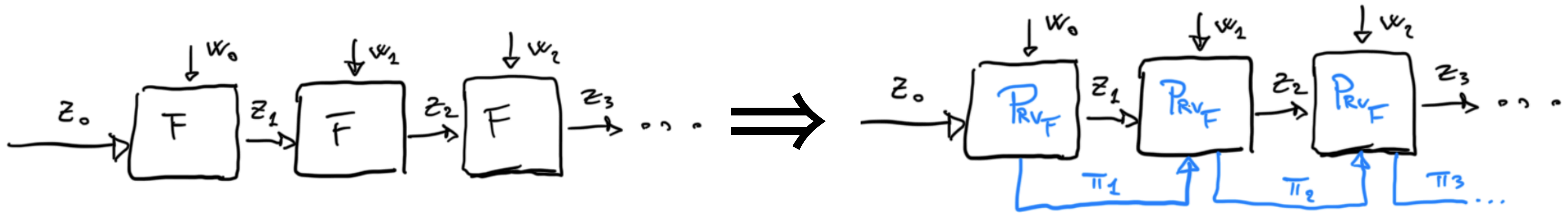

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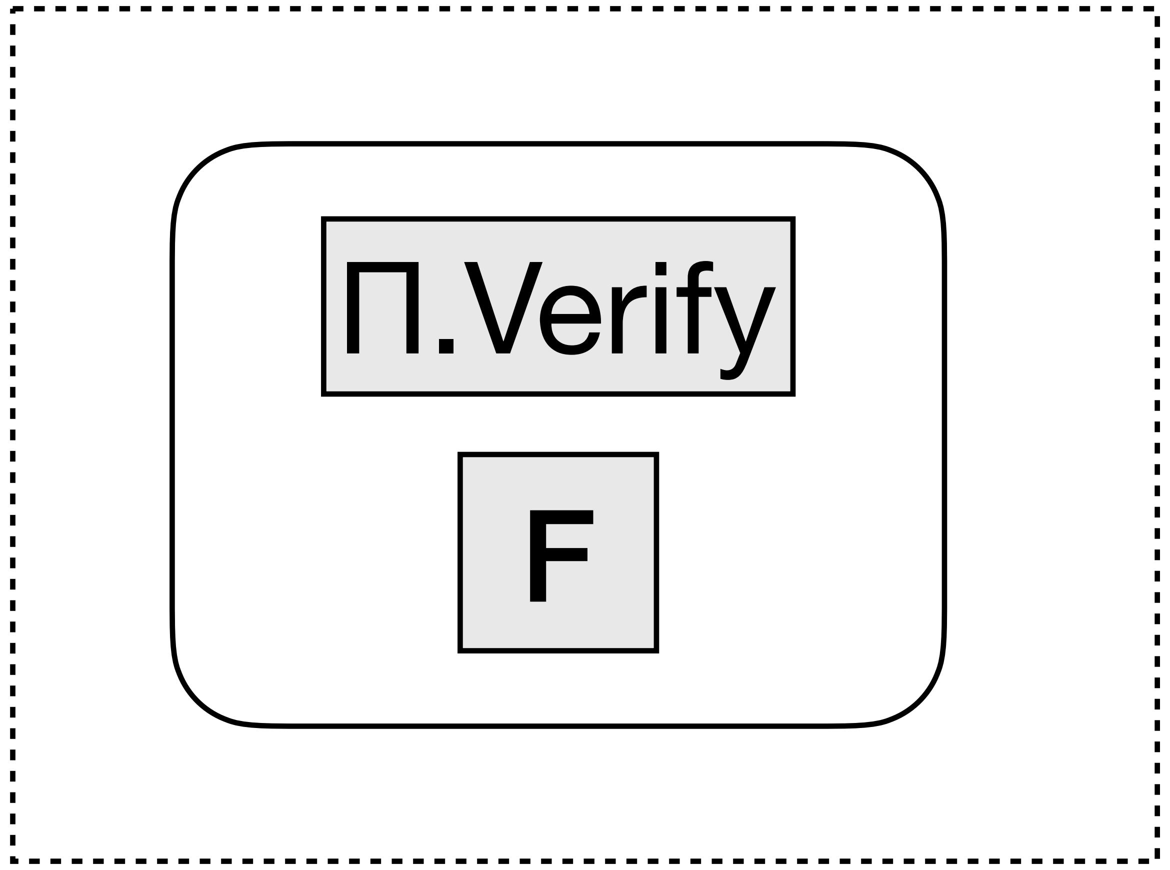
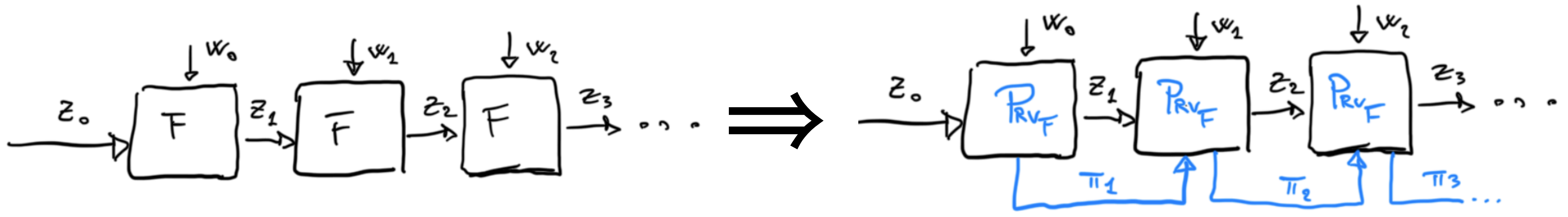


SNARK Prover’s statement (Π is a SNARK)

Canonical construction
(SNARK recursion)



Constructions of IVC

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Nova: Recursive Zero-Knowledge Arguments from Folding Schemes

Abhiram Kothapalli[†] Srinath Setty[*] Ioanna Tziala[‡]
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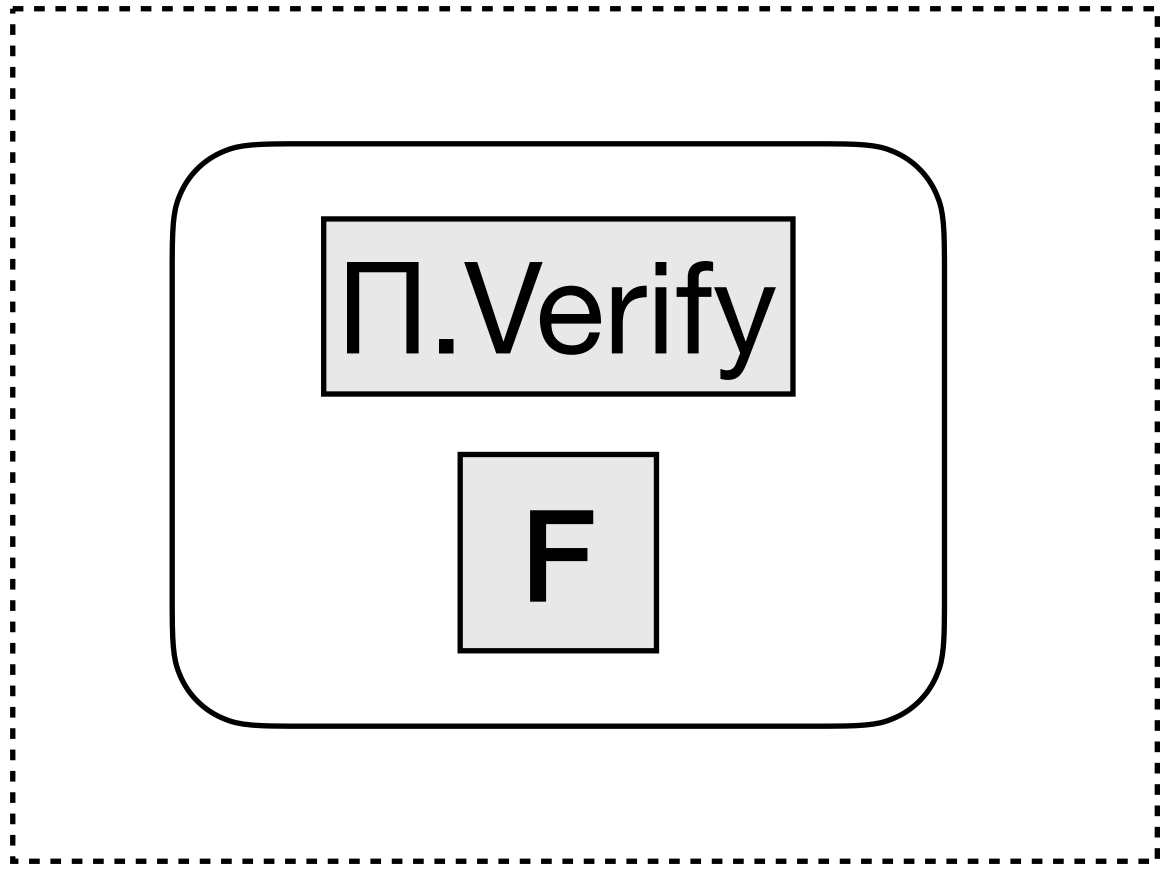

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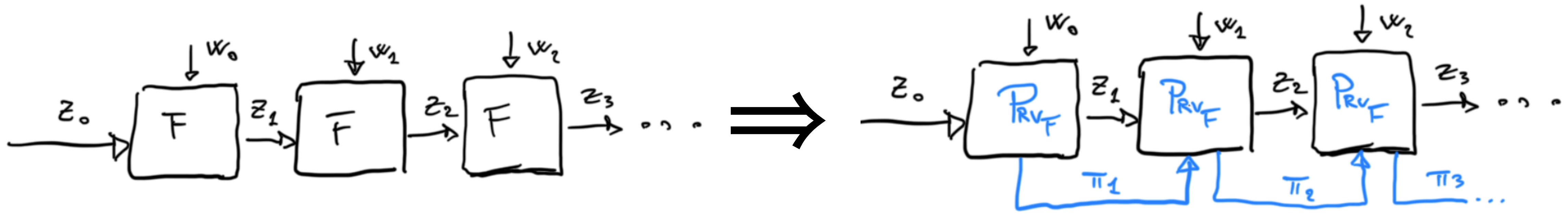

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Proof-Carrying Data without Succinct Arguments

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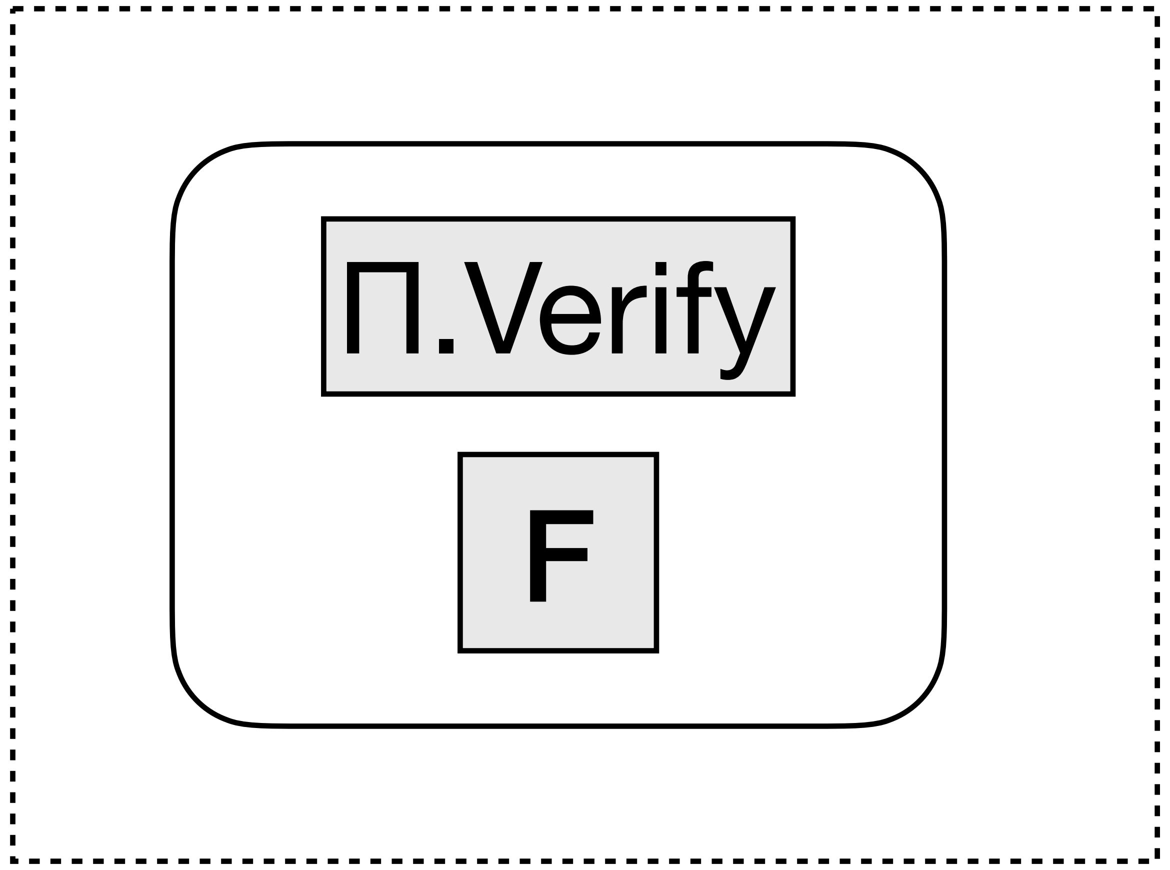
William Lin, will.lin@berkeley.edu, UC Berkeley
Pratyush Mishra, pratyush@berkeley.edu, UC Berkeley
Nicholas Spooner, nspooner@bu.edu, Boston University



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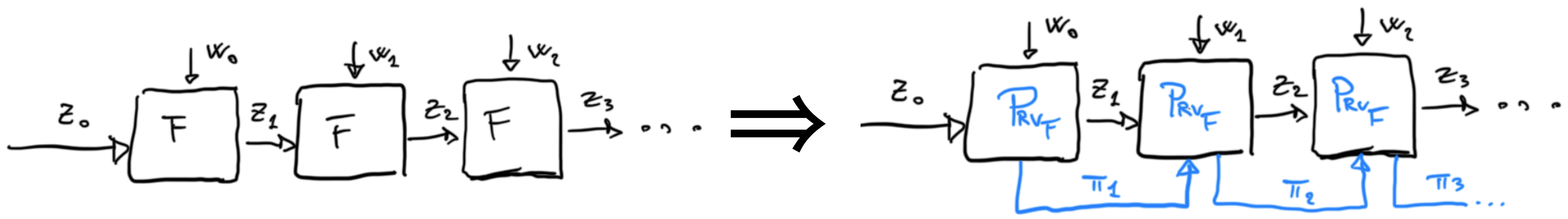

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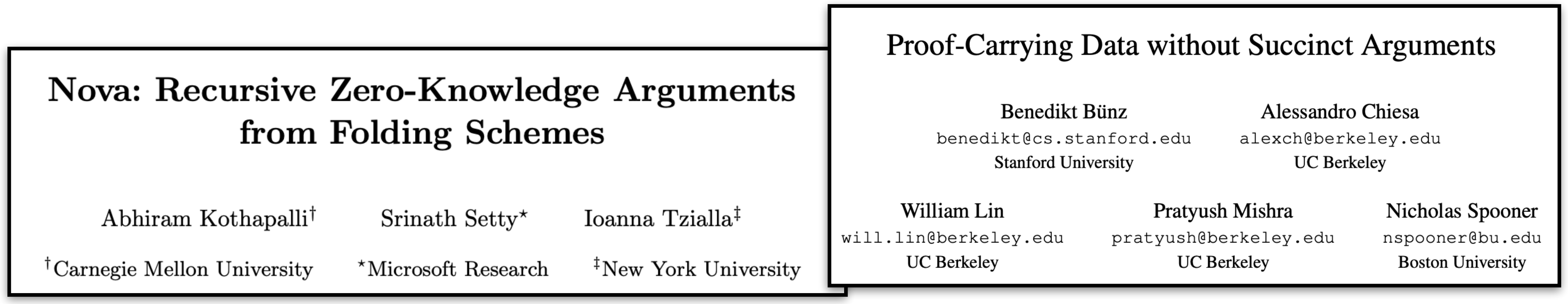

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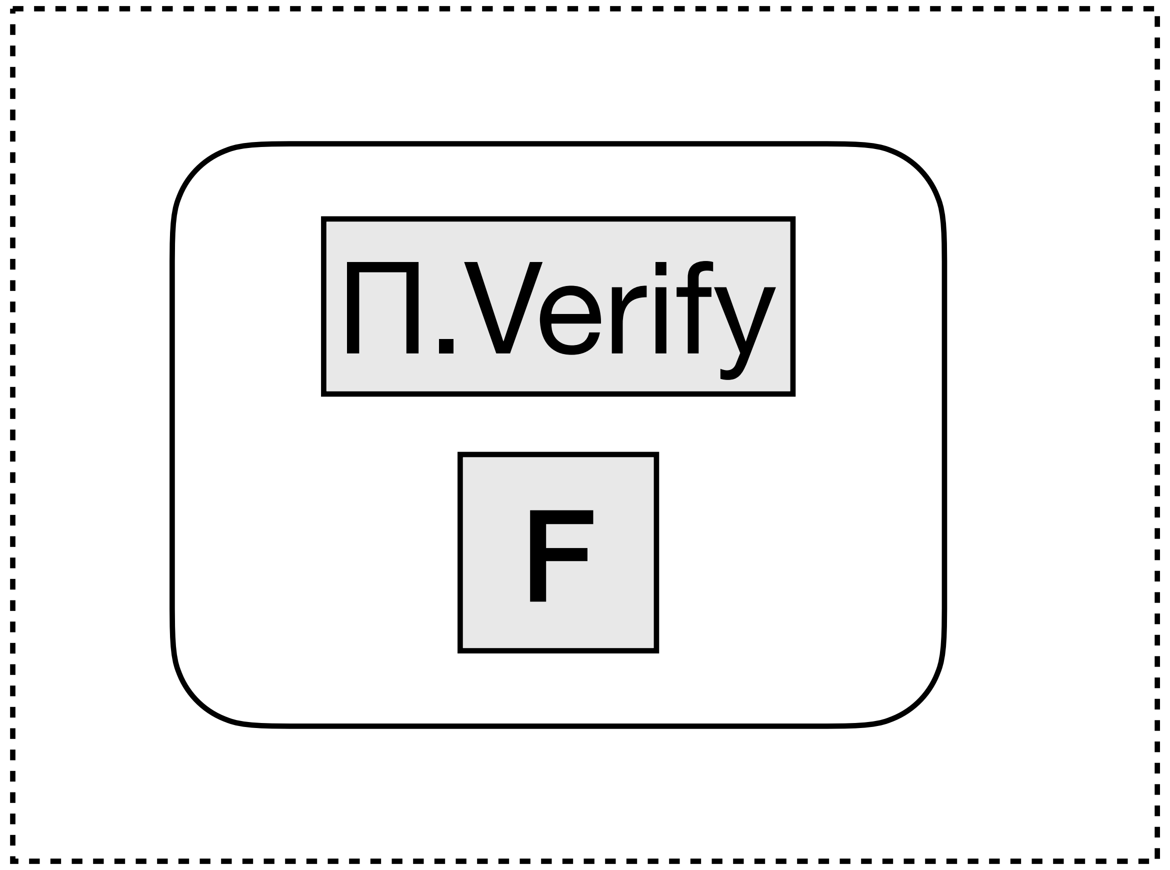

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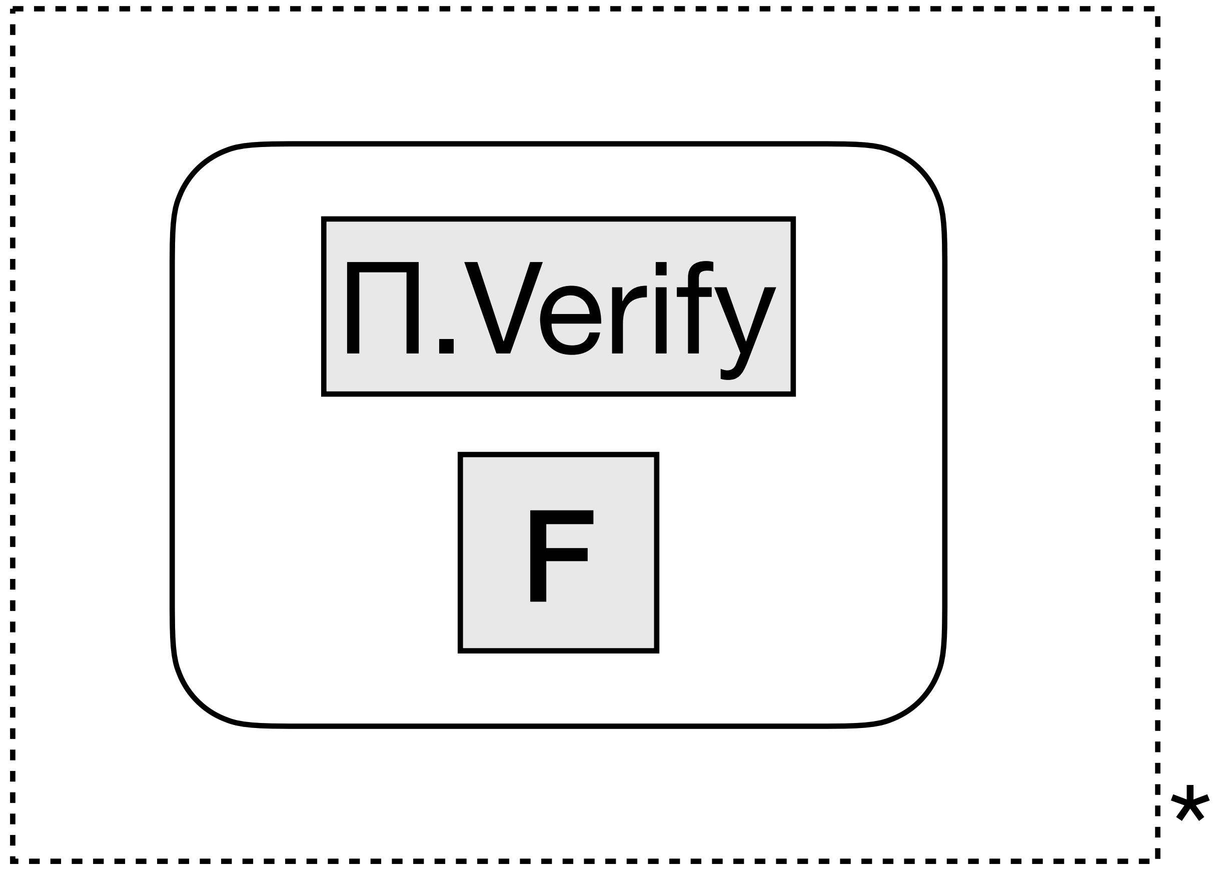
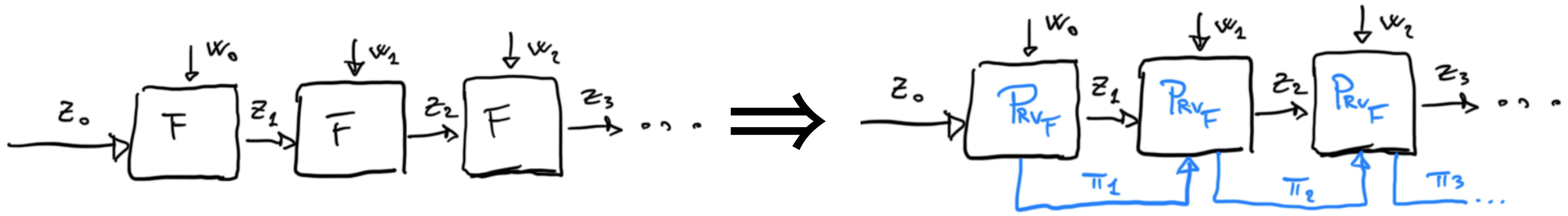


Folding/acc. Prover's statement (Π is a folding/acc. scheme)

Lightweight version (folding/accumulation recursion)



* very approximate rendition (there are more details)

Challenges in Proving the Security of IVC

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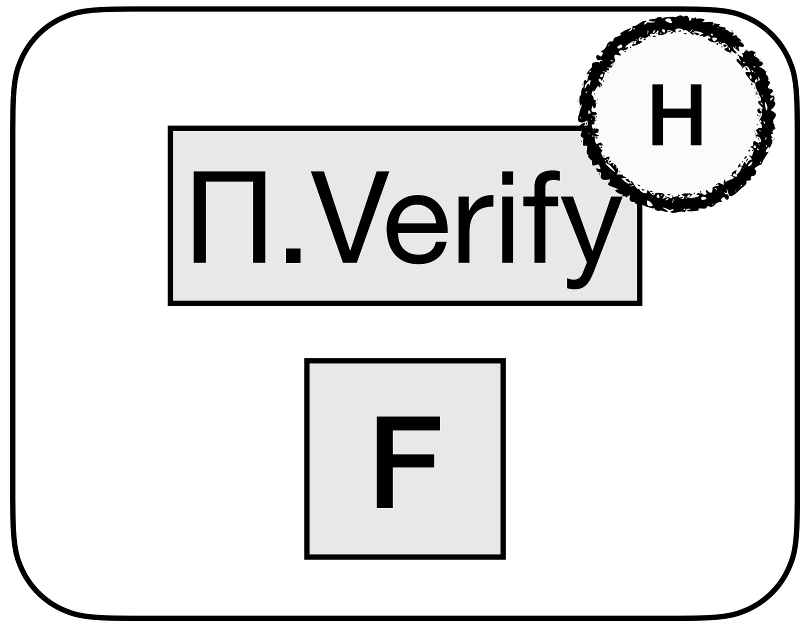

Random Oracle

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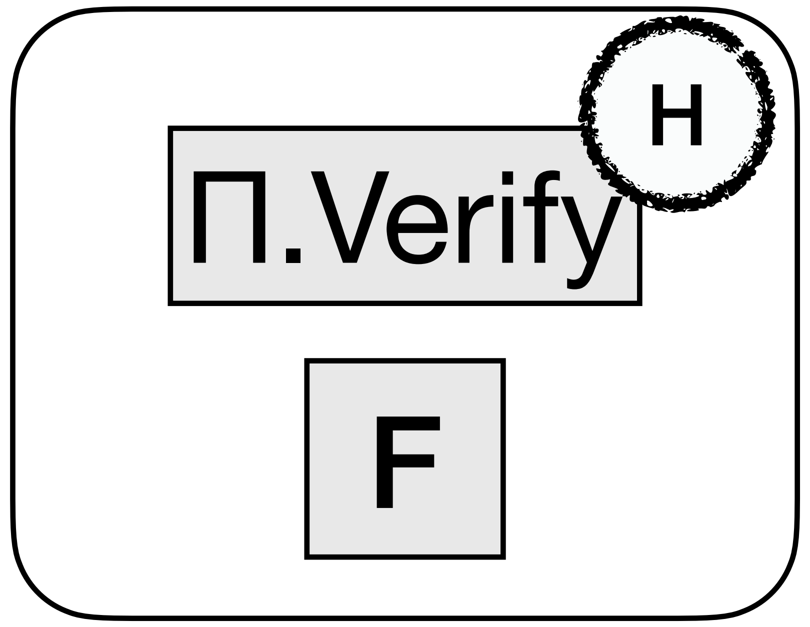

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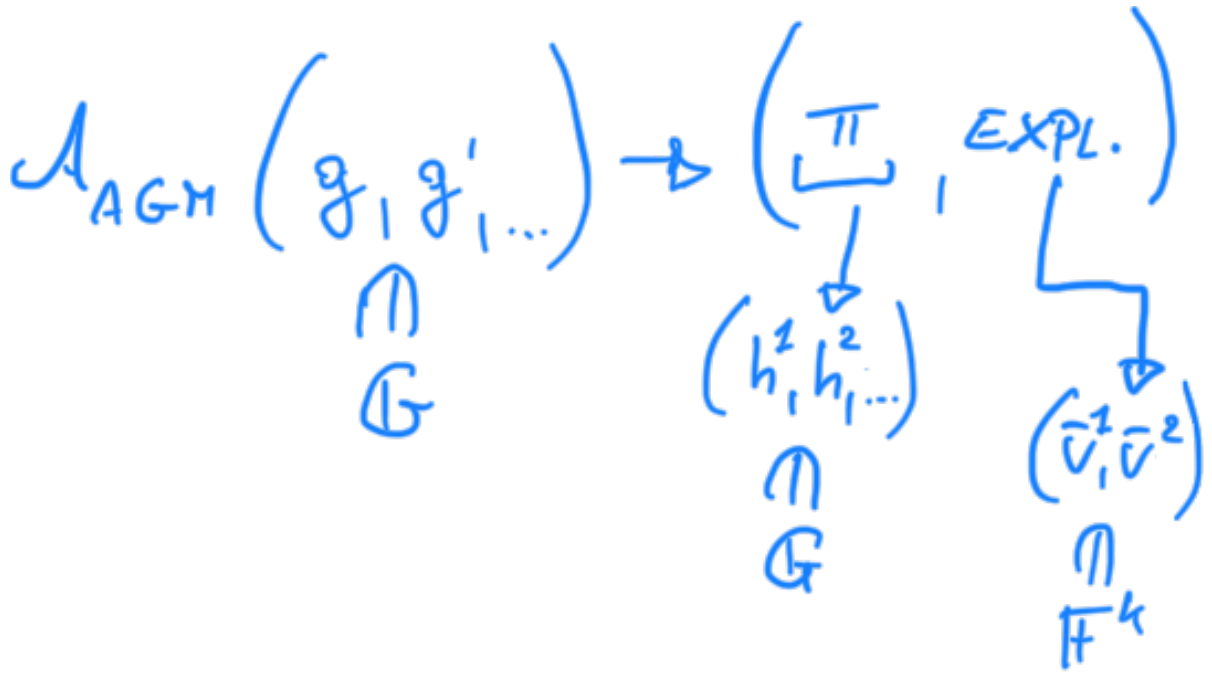

Algebraic Group Model (AGM)

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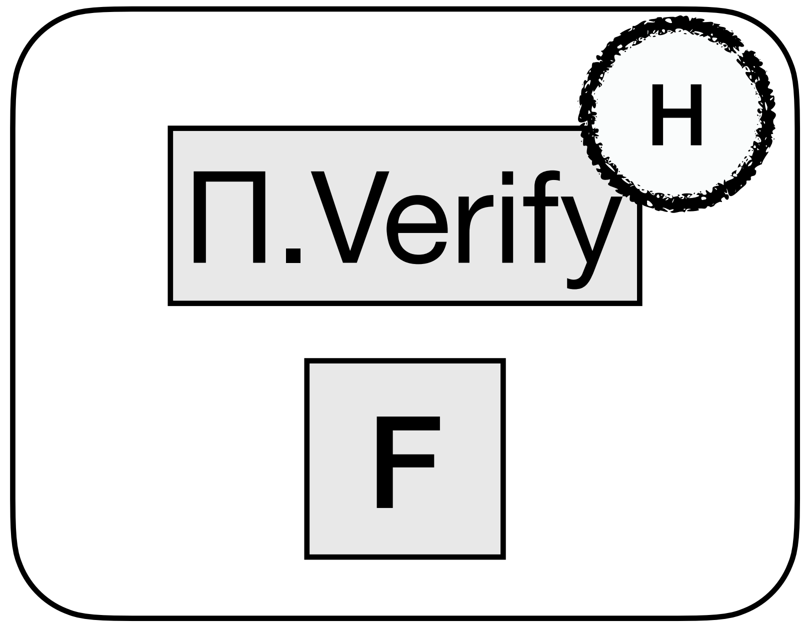

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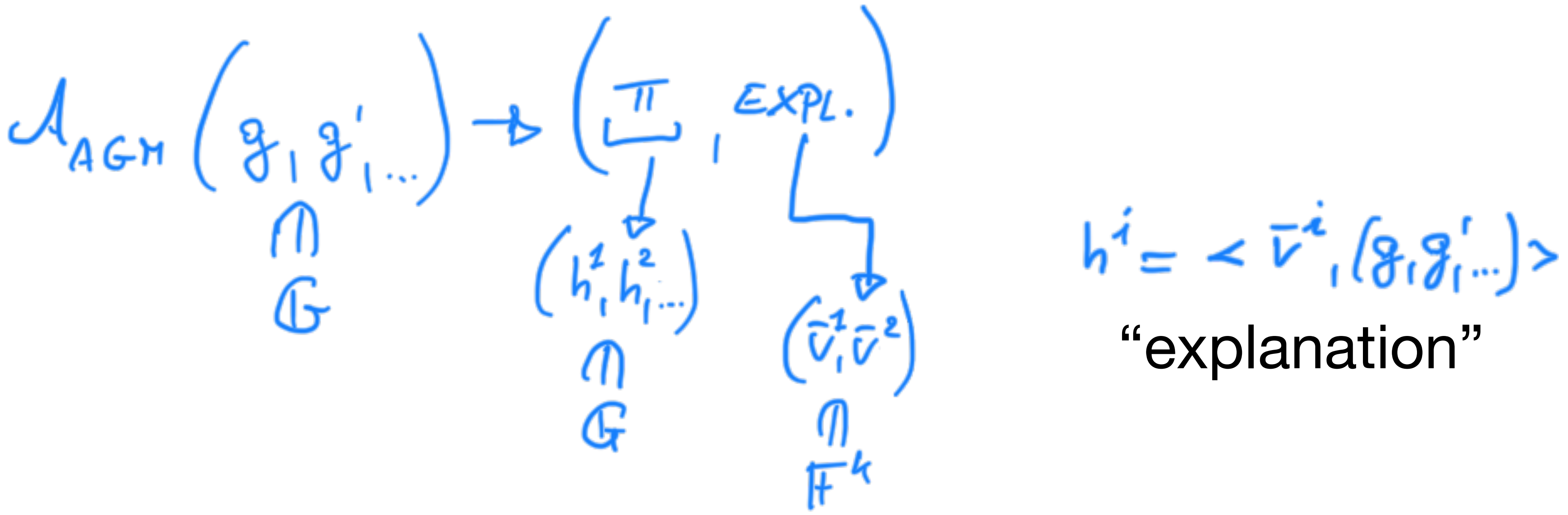

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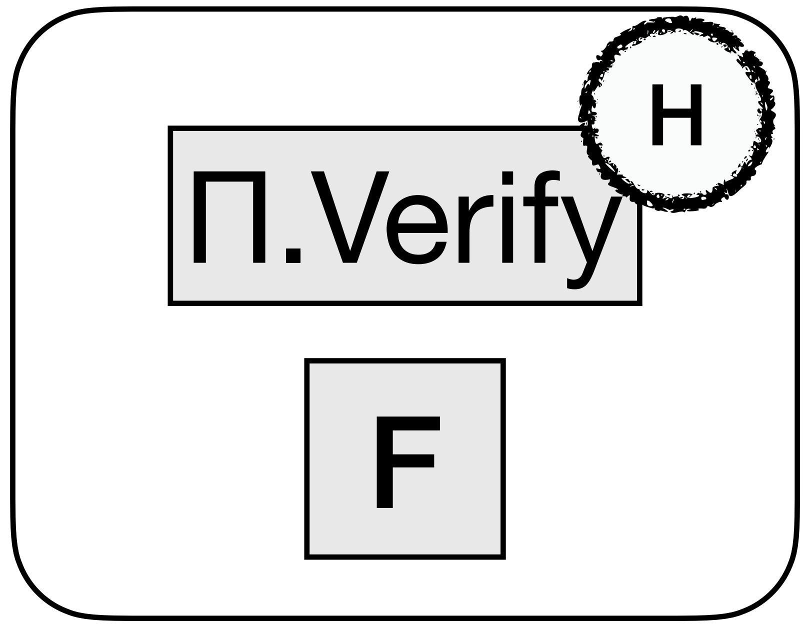

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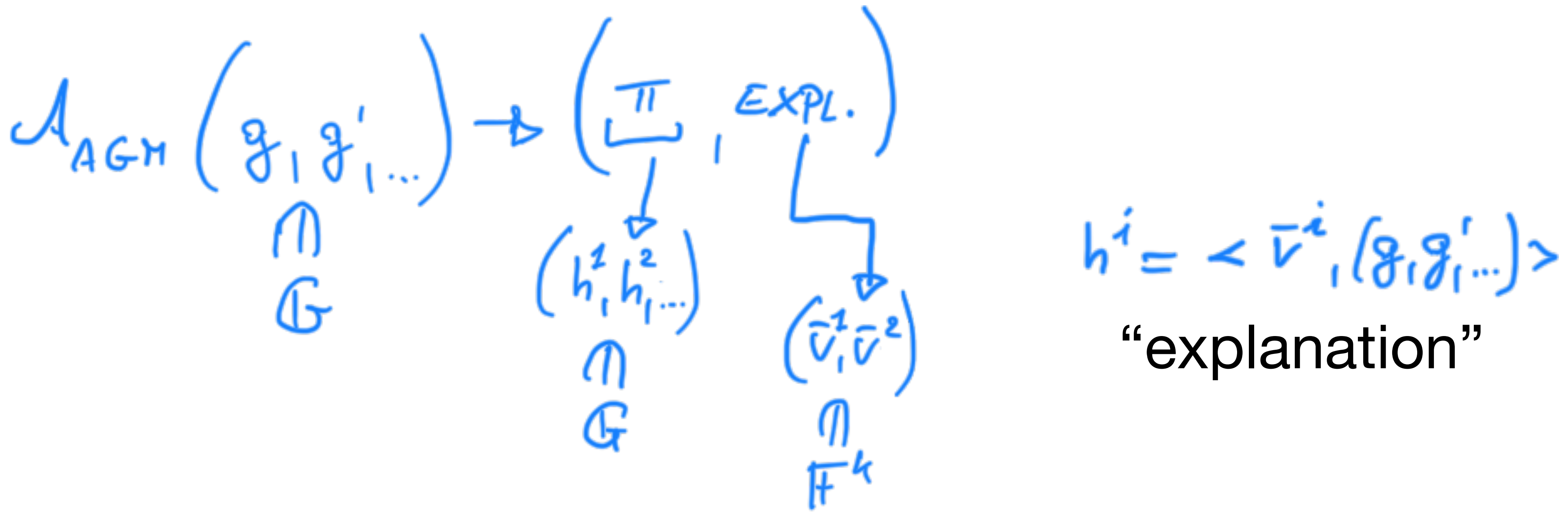

Algebraic Group Model (AGM)

- **Second challenge (<u>our focus</u>):** depth of the computation

How Do We Usually Prove Security in IVC?

A glimpse of what can go wrong and what depth has to do with it

$\mathcal{A}_{IVC} \to (z_0, z_d, d, \pi_d)$

$$z_0 \xrightarrow[w_0]{F} z_1 \xrightarrow[w_1]{F} \cdots \xrightarrow[w_{d-2}]{F} z_{d-1} \xrightarrow[w_{d-1}]{F} z_d$$

How Do We Usually Prove Security in IVC?

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IVC extractability

$\forall$ PPT $\mathcal{A}_{IVC}$ $\exists$ $\mathcal{E}_{IVC}$:

$$\left[\begin{array}{l} \mathcal{A}_{IVC} \to (z_0, z_d, d, \pi_d) \\ \mathcal{E}_{IVC} \to (w_0, \dots, w_{d-1}) \\ (z_0, z_d, d, \pi_d) \checkmark_{\text{verify}} \Rightarrow z_0 \overset{F^{(\times d)}}{\underset{w_0, \dots, w_{d-1}}{\rightsquigarrow}} z_d \end{array}\right.$$

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IVC extractability

$\forall$ PPT $\mathcal{A}_{\mathsf{IVC}}$ $\exists$ $\mathcal{E}_{\mathsf{IVC}}$ (poly time):

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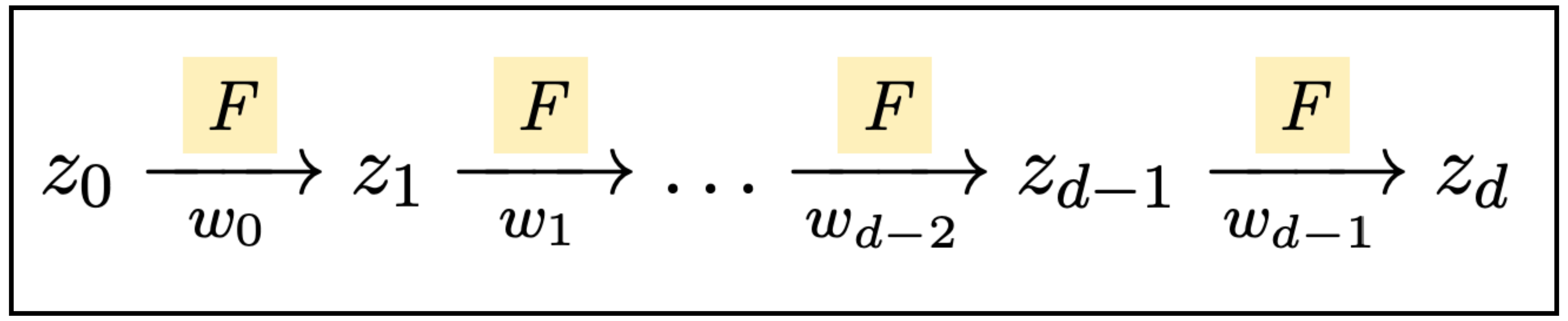
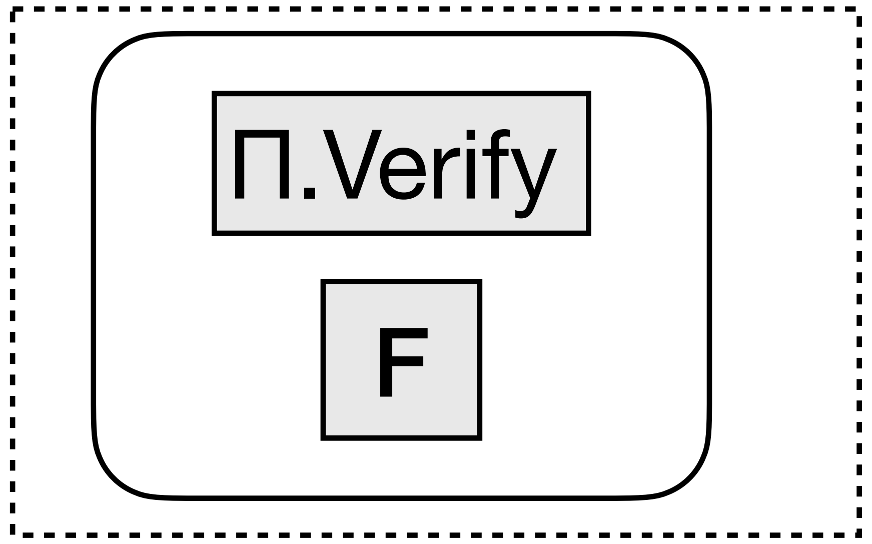
IVC extractability

$\forall$ PPT $\mathcal{A}_{\mathrm{ivc}}$ $\exists$ $\mathcal{E}_{\mathrm{ivc}}$ (poly time):

- $\mathcal{A}_{\mathrm{ivc}} \rightarrow (z_0, z_d, d, \pi_d)$
- $\mathcal{E}_{\mathrm{ivc}} \rightarrow (w_0, \ldots, w_{d-1})$
- (z_0, z_d, d, π_d) ✓ Verify $\Rightarrow z_0 \xrightarrow[w_0, \ldots, w_{d-1}]{F\,(\times d)} z_d$

$\mathcal{A}_{\mathrm{ivc}} \rightarrow (z_0, z_d, d, \pi_d)$





SNARK Prover's statement (Π is a SNARK)

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IVC extractability

(poly time)

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$$\left[\begin{array}{l} \mathcal{A}_{ivc} \to (z_0, z_d, d, \pi_d) \\ \mathcal{E}_{ivc} \to (w_0, \dots, w_{d-1}) \\ (z_0, z_d, d, \pi_d)\ \checkmark_{\text{verify}} \Rightarrow z_0 \xrightarrow[w_0, \dots, w_{d-1}]{F\ (\times d)} z_d \end{array}\right.$$

$$\mathcal{A}_{ivc} \to (z_0, z_d, d, \pi_d)$$

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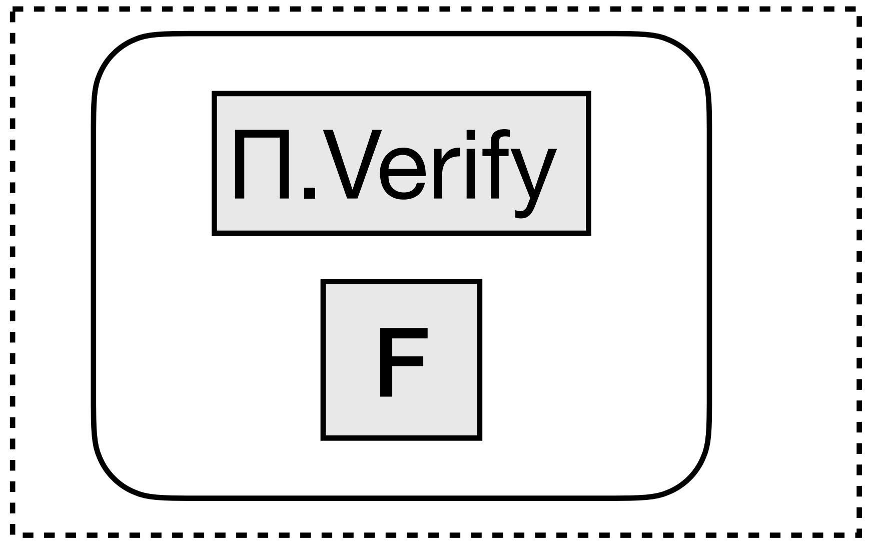
SNARK extractability

(poly time)

$\forall$ PPT $\mathcal{A}_{\Pi}$ $\exists\, \mathcal{E}_{\mathcal{A}}$:

$$\left[\begin{array}{l} \mathcal{A}_{\Pi} \to (x, \pi) \\ \mathcal{E}_{\mathcal{A}} \to w \\ (x, \pi)\ \checkmark_{\text{verify}} \Rightarrow (x, w) \in R_F \end{array}\right.$$

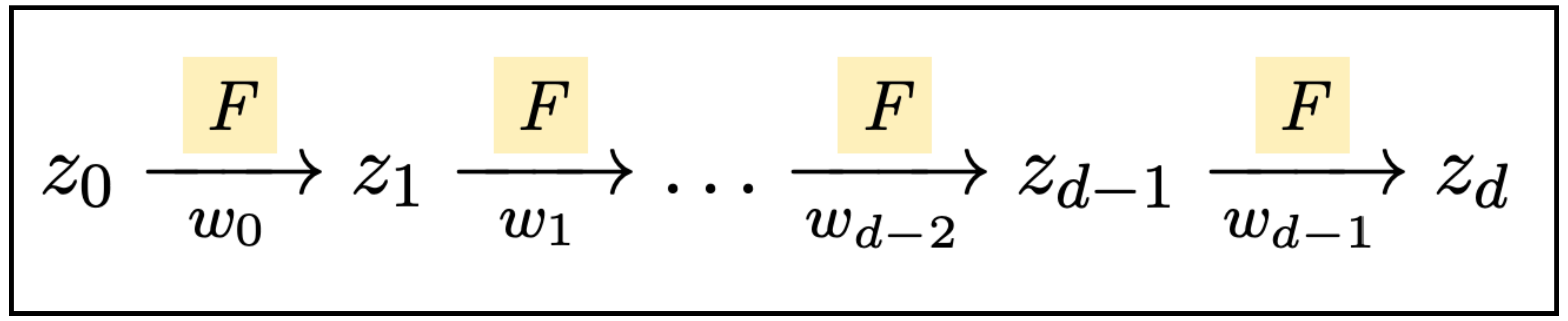


SNARK Prover's statement (Π is a SNARK)

How Do We Usually Prove Security in IVC?

A glimpse of what can go wrong and what depth has to do with it

$\mathcal{A}_{ivc} \to (z_0, z_d, d, \pi_d)$



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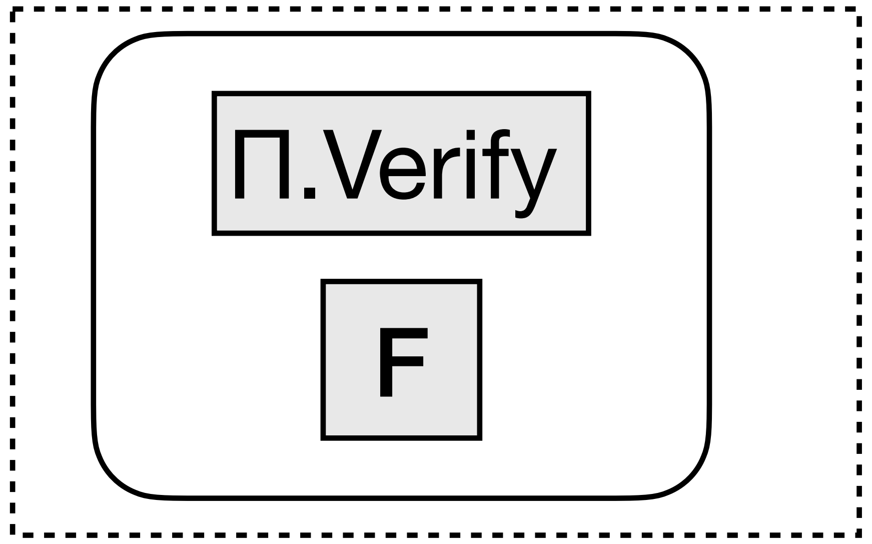

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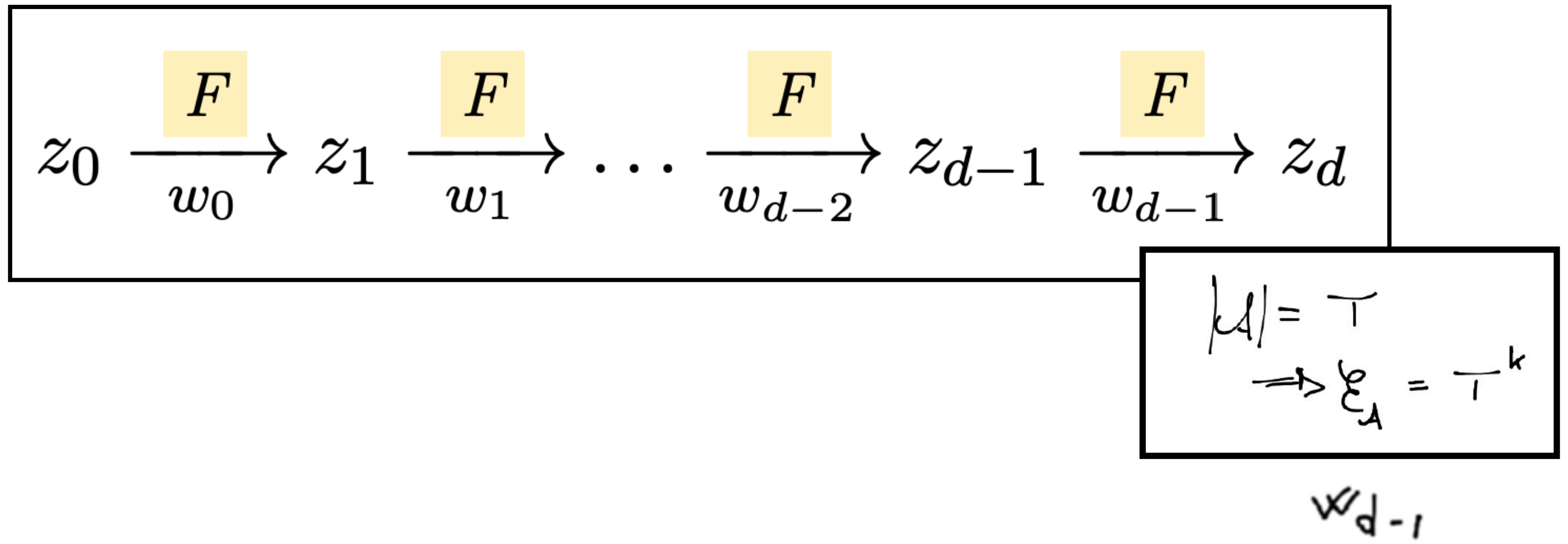

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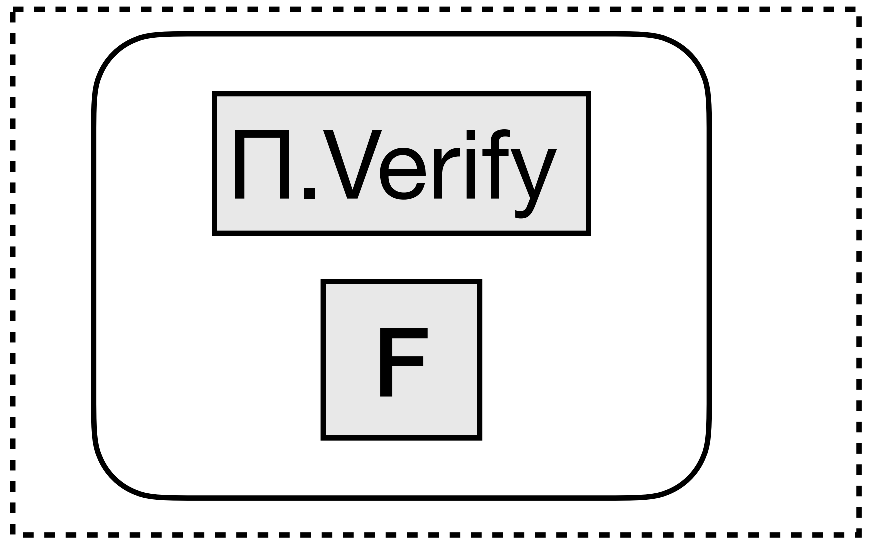

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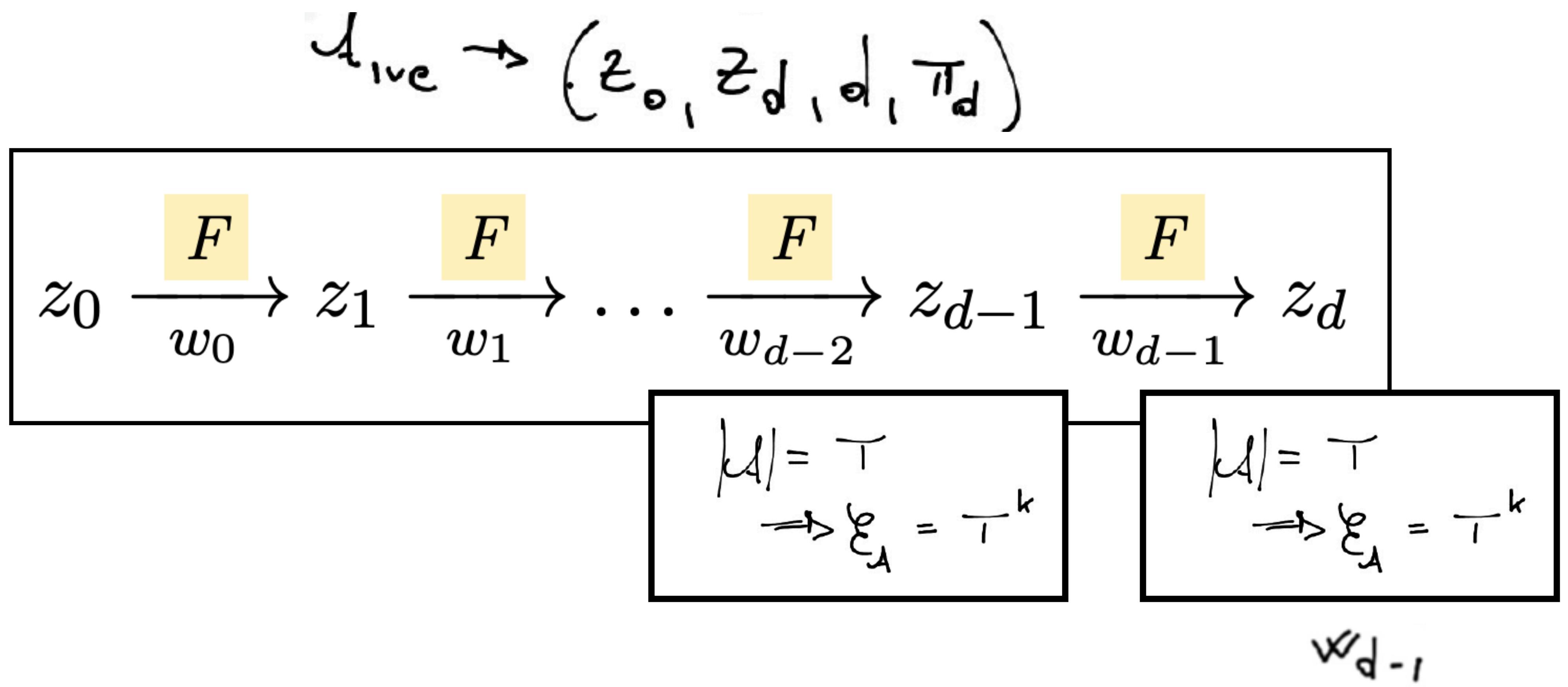

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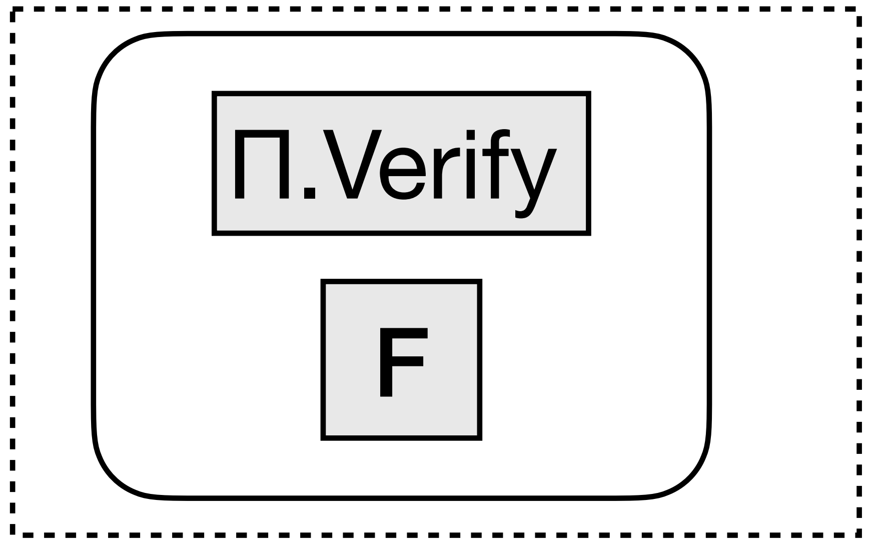

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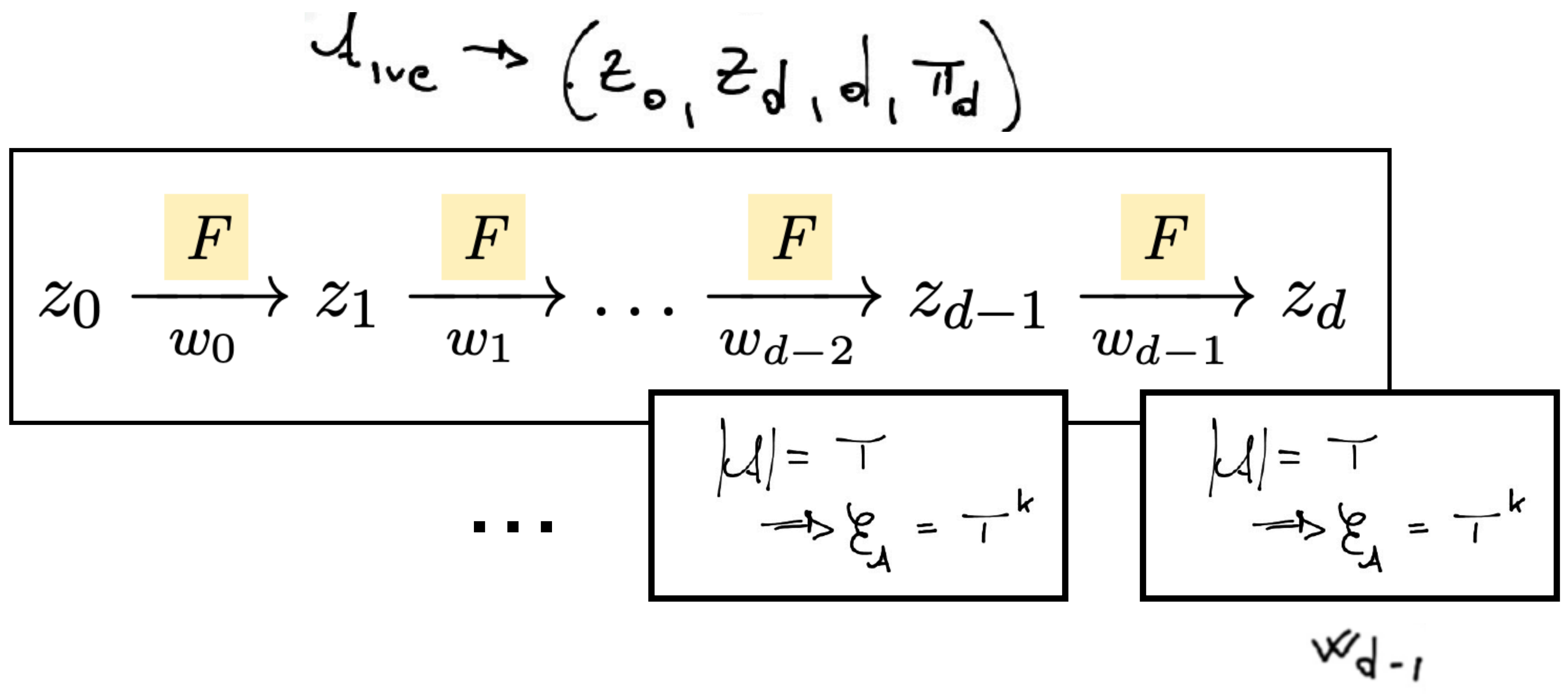

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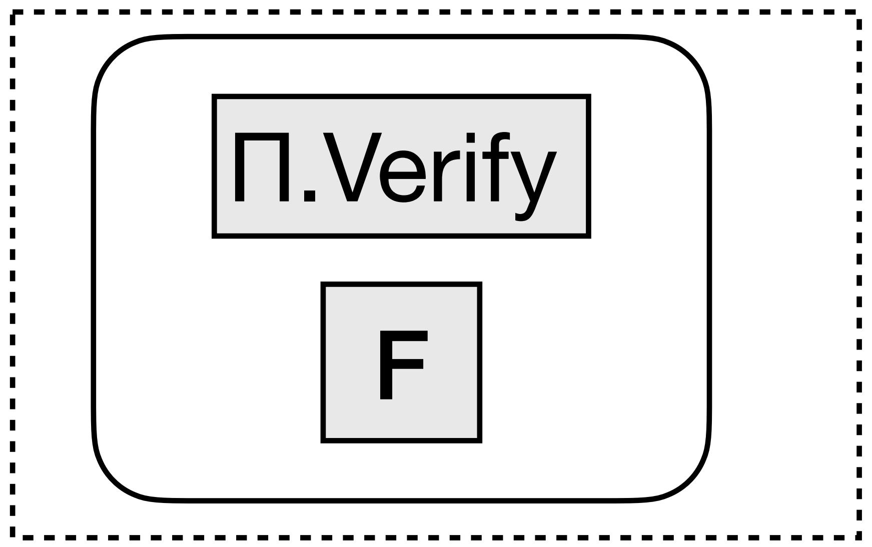

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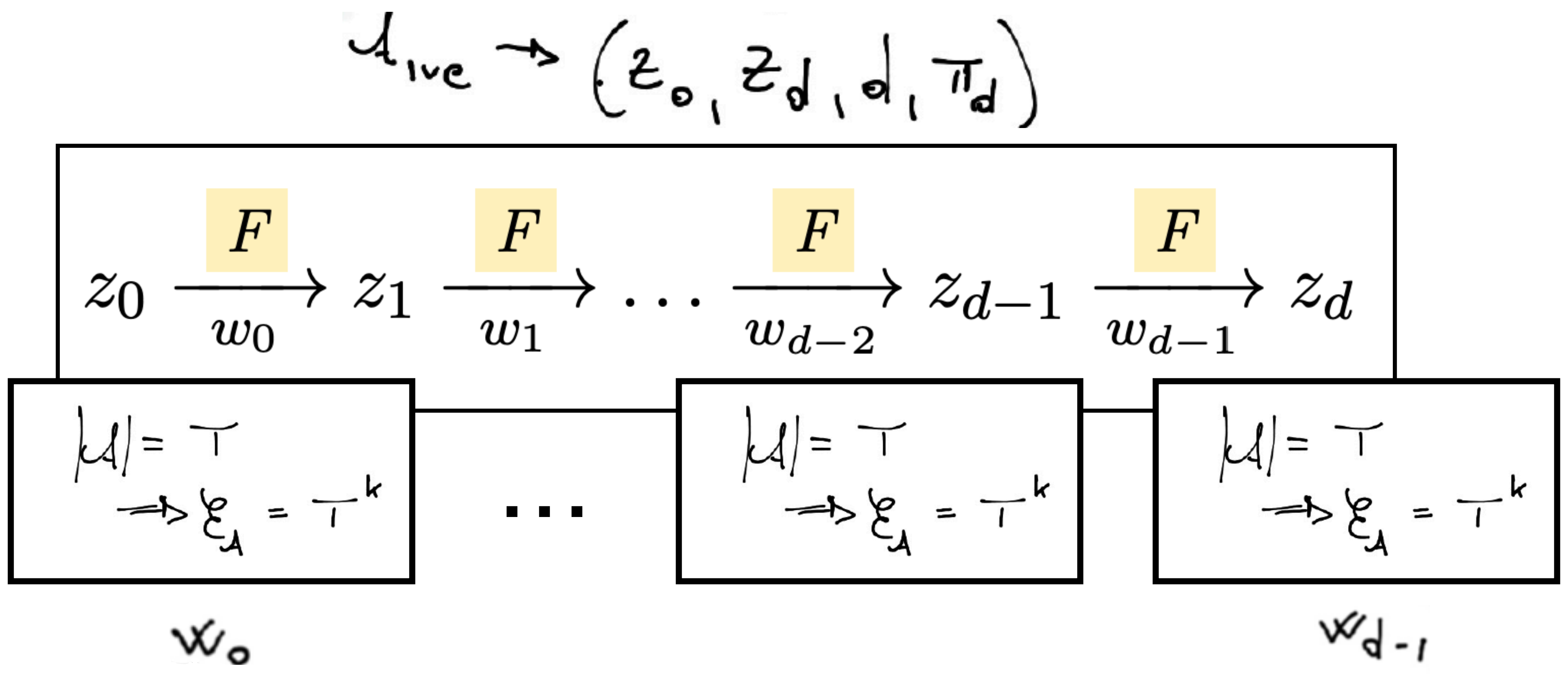

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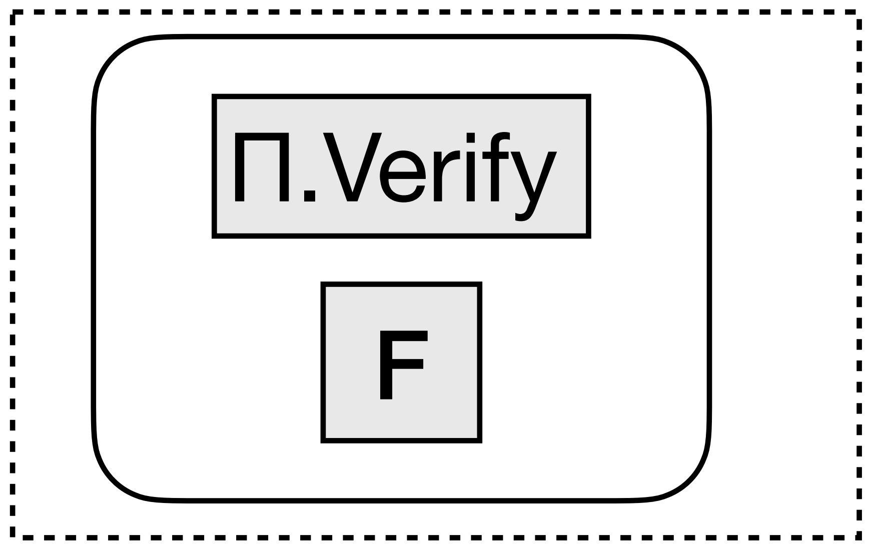

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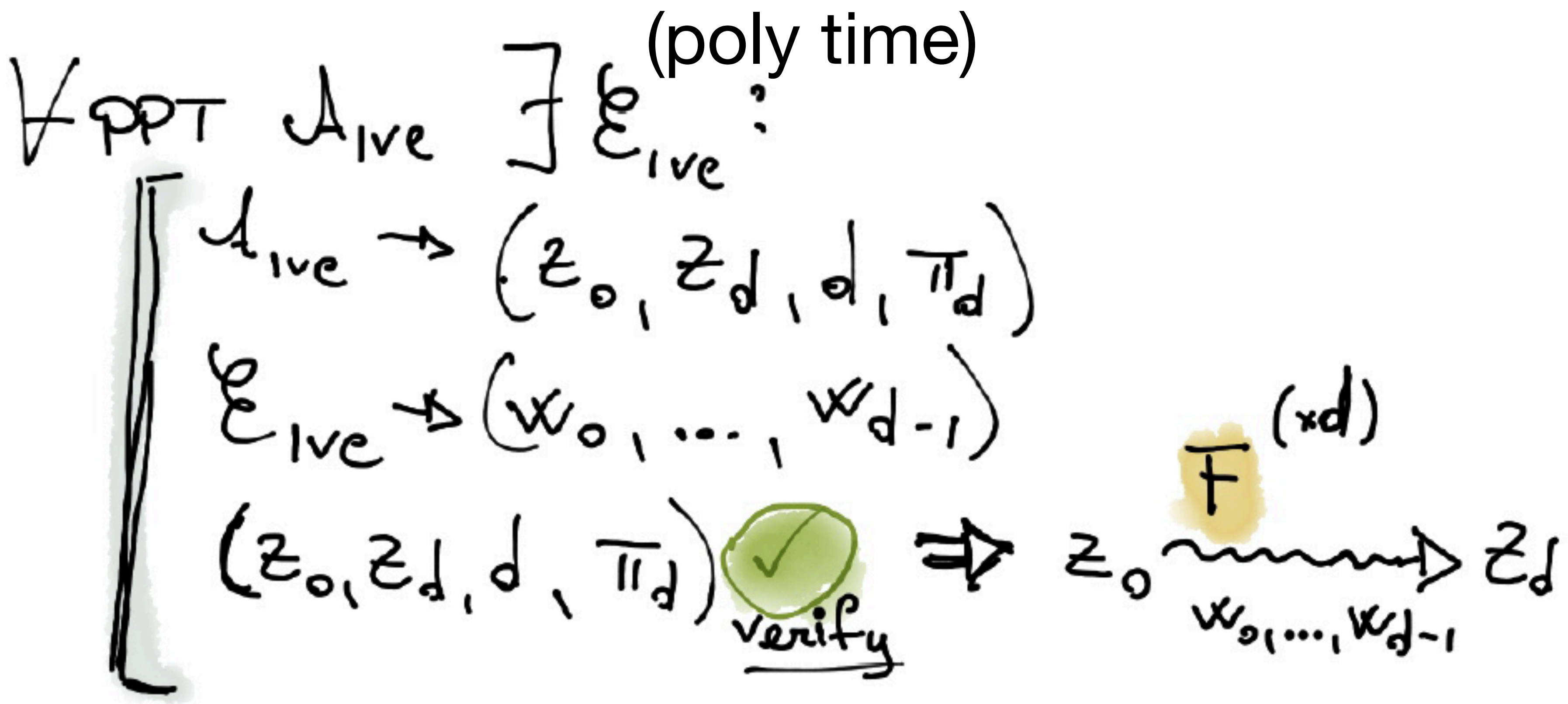

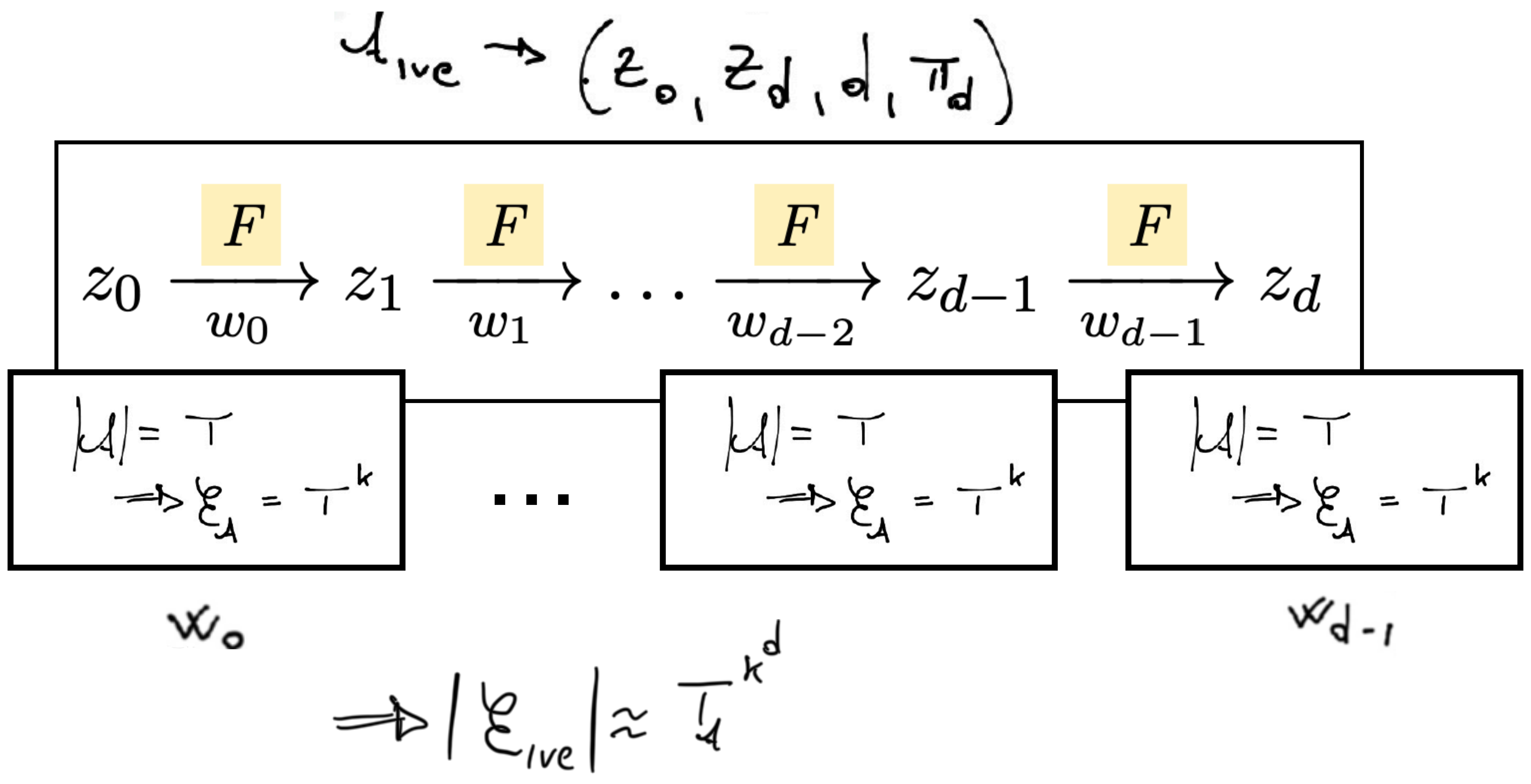

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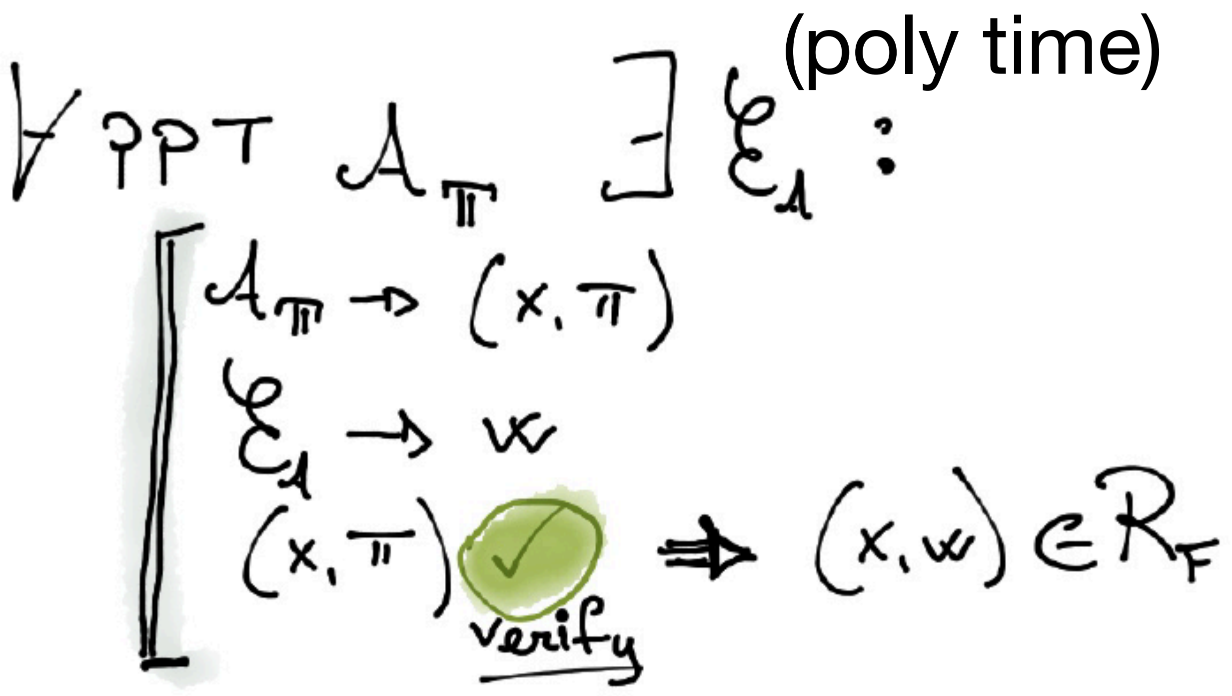

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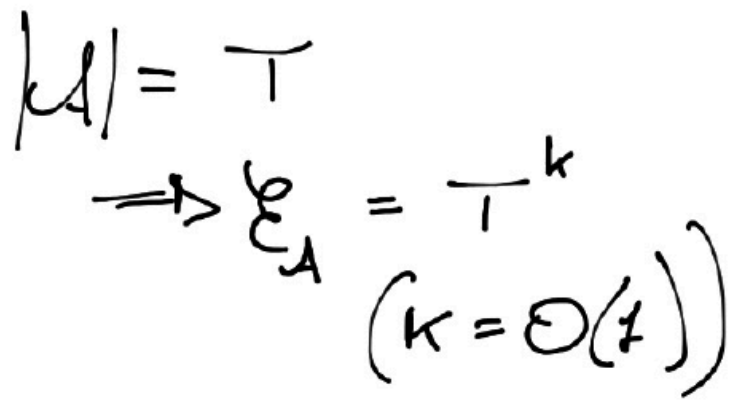

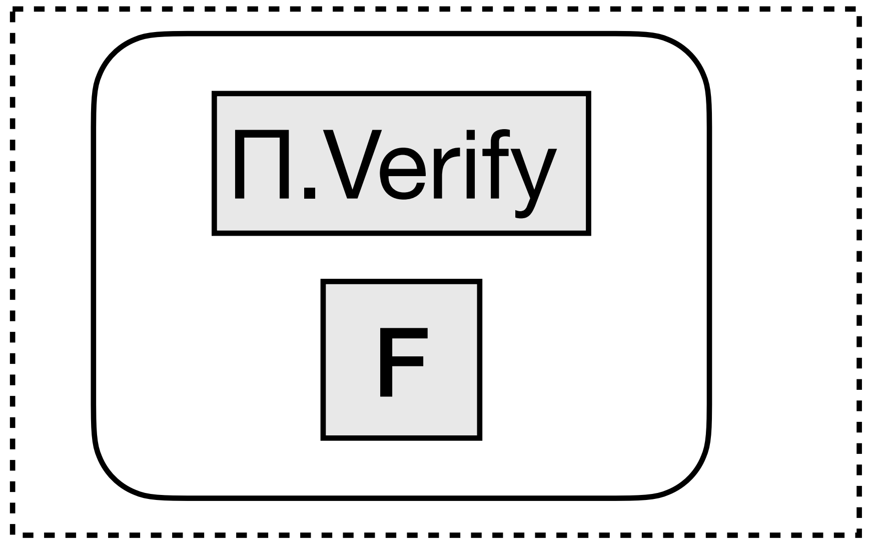

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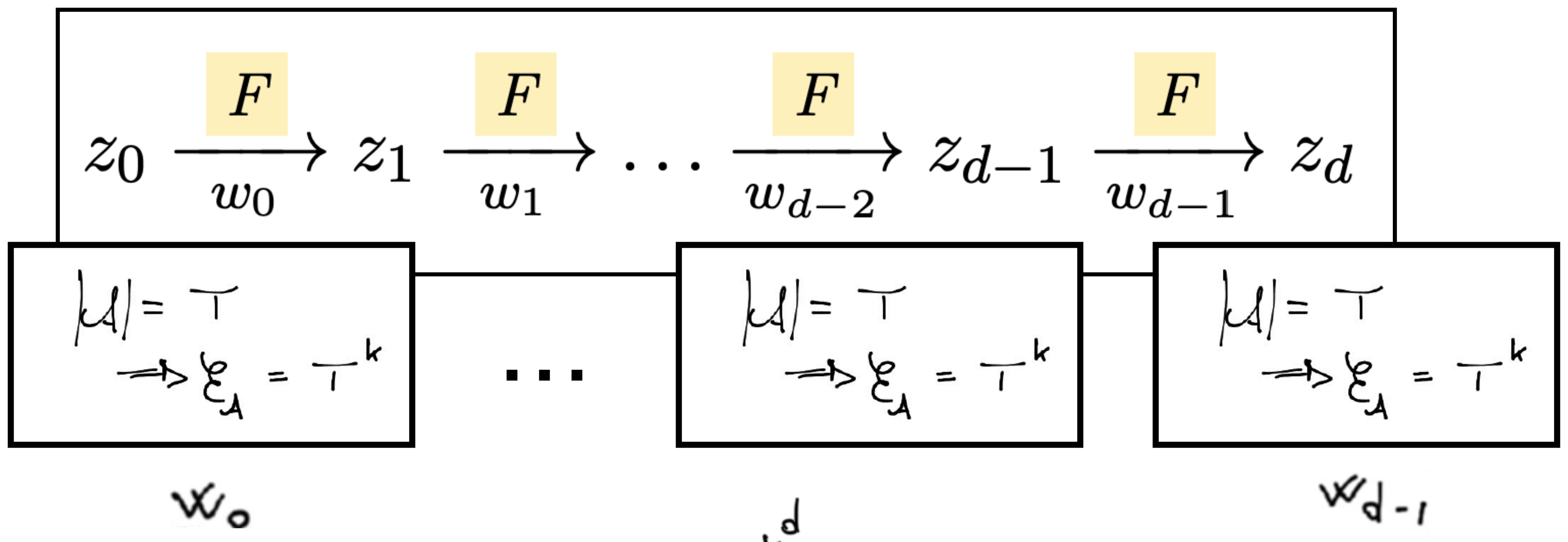
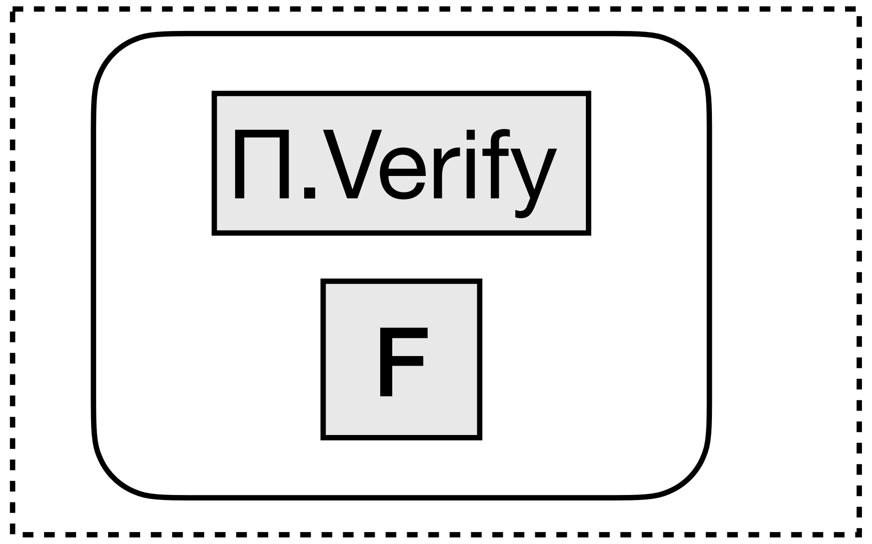


$\Rightarrow |\mathcal{E}_{ivc}| \approx T_\mathcal{A}^{k^d}$

$\Rightarrow \left(d \in \omega(1) \Rightarrow |\mathcal{E}_{ivc}| \notin poly\right)$



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The “Tree Approach”

A canonical way to go around the problem we just saw (via extractability)

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Recursive Composition and Bootstrapping
for SNARKs and Proof-Carrying Data

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Mangrove: A Scalable Framework for Folding-based SNARKs

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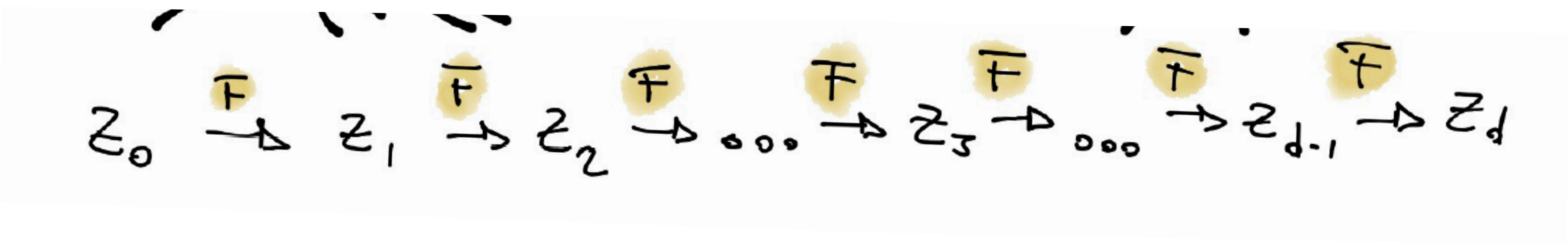

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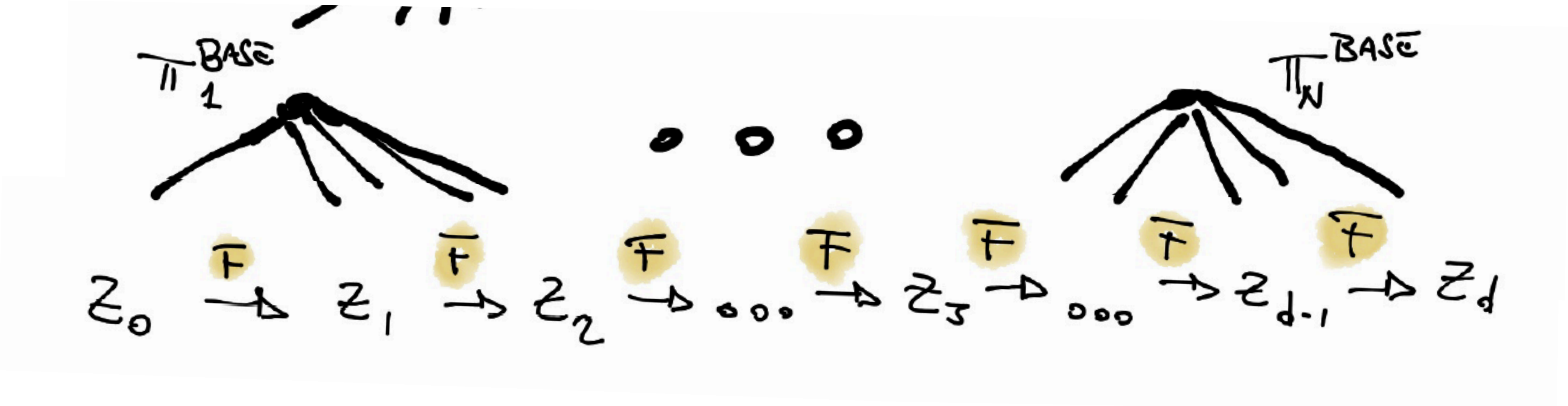

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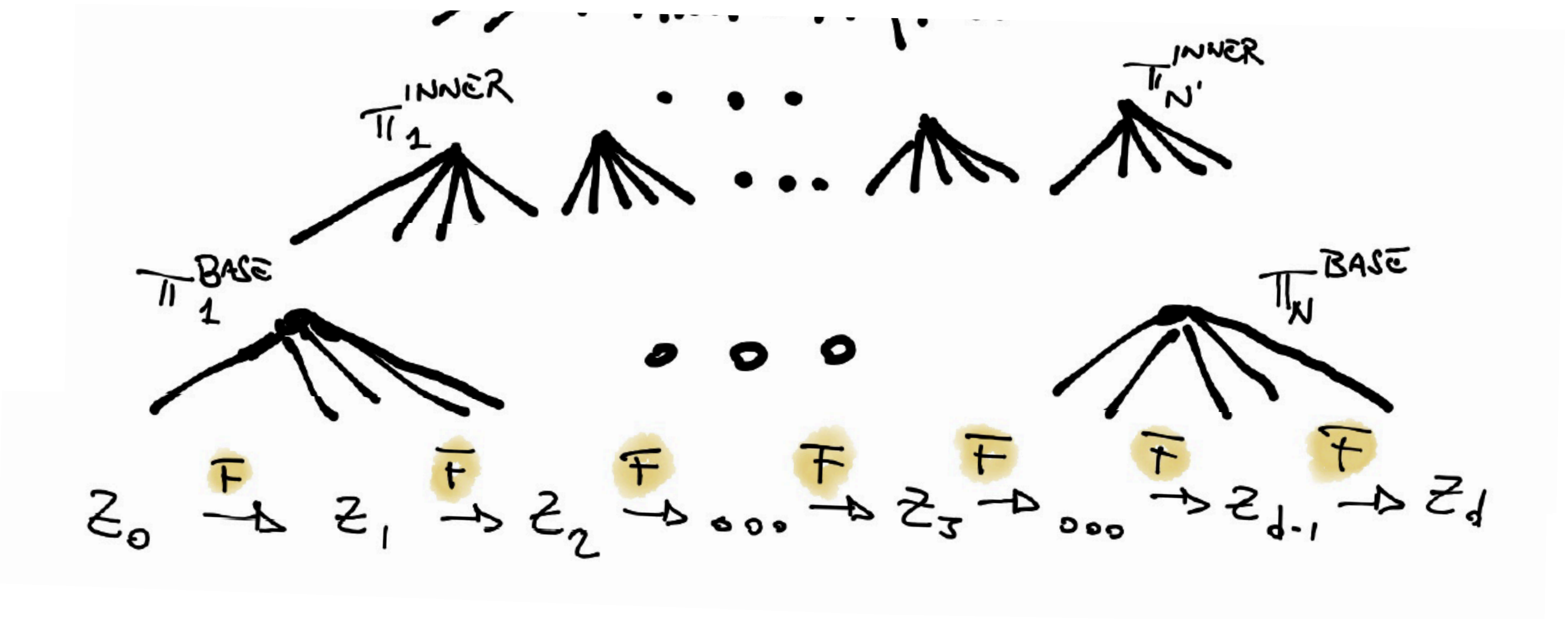

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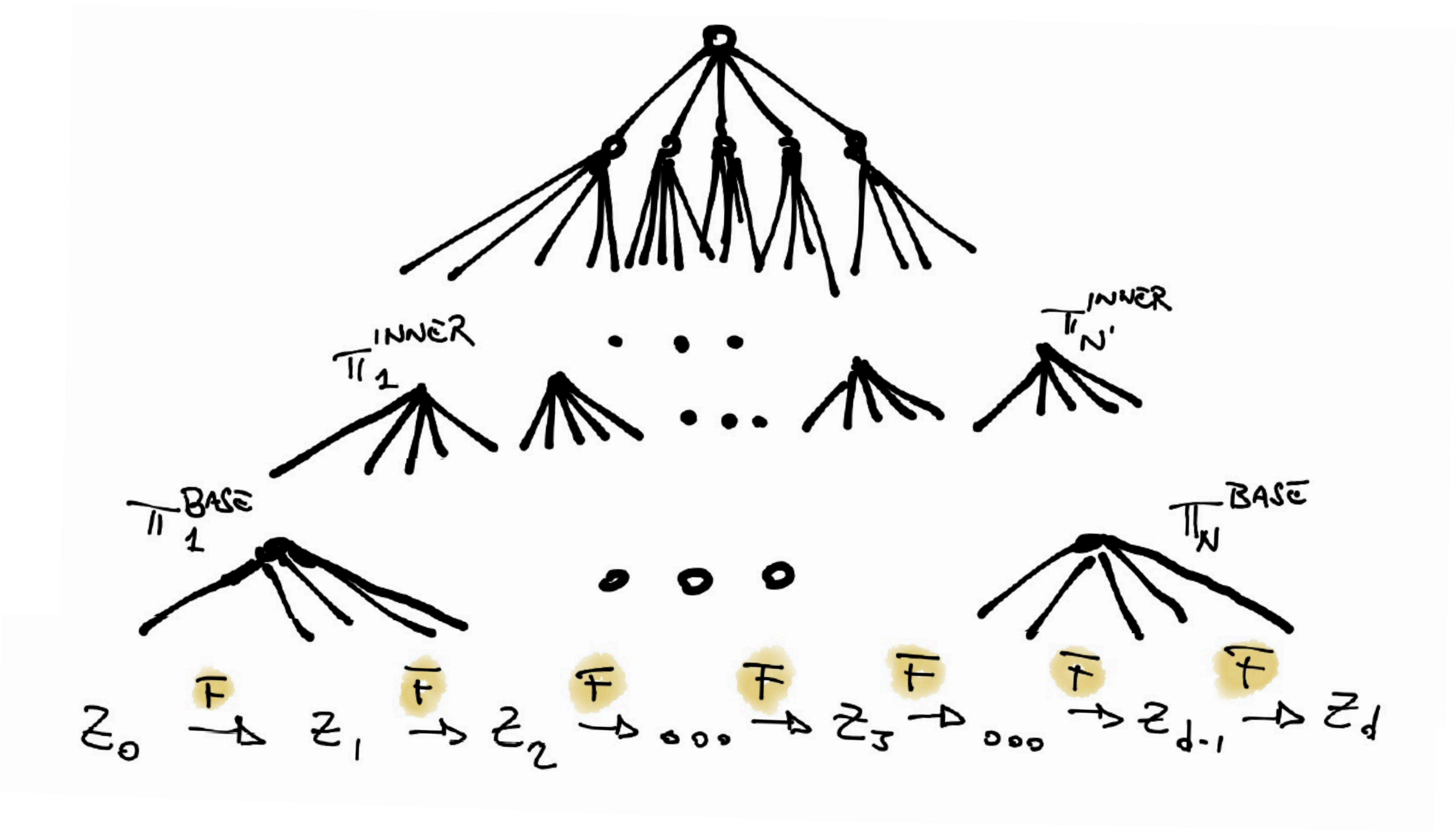

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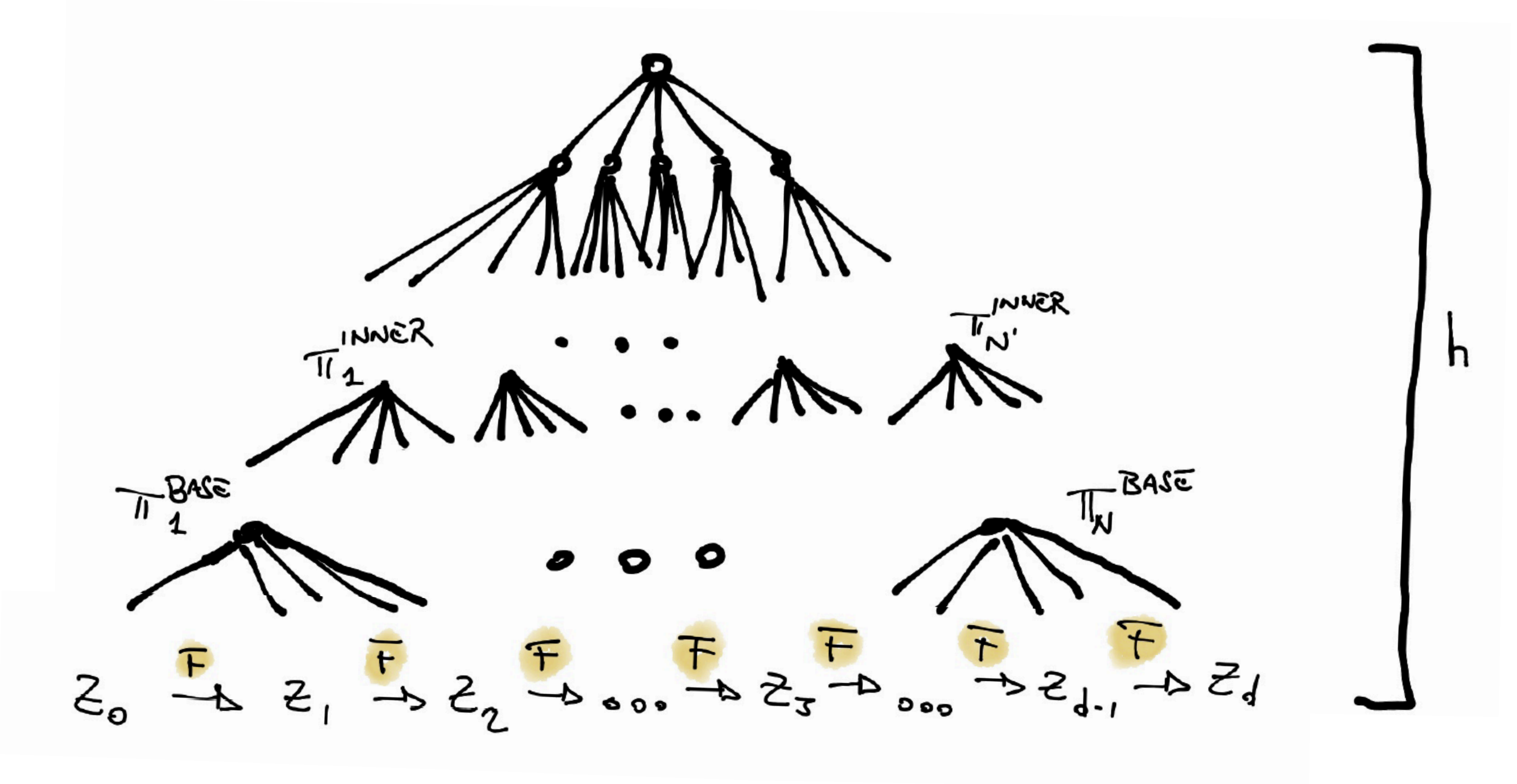

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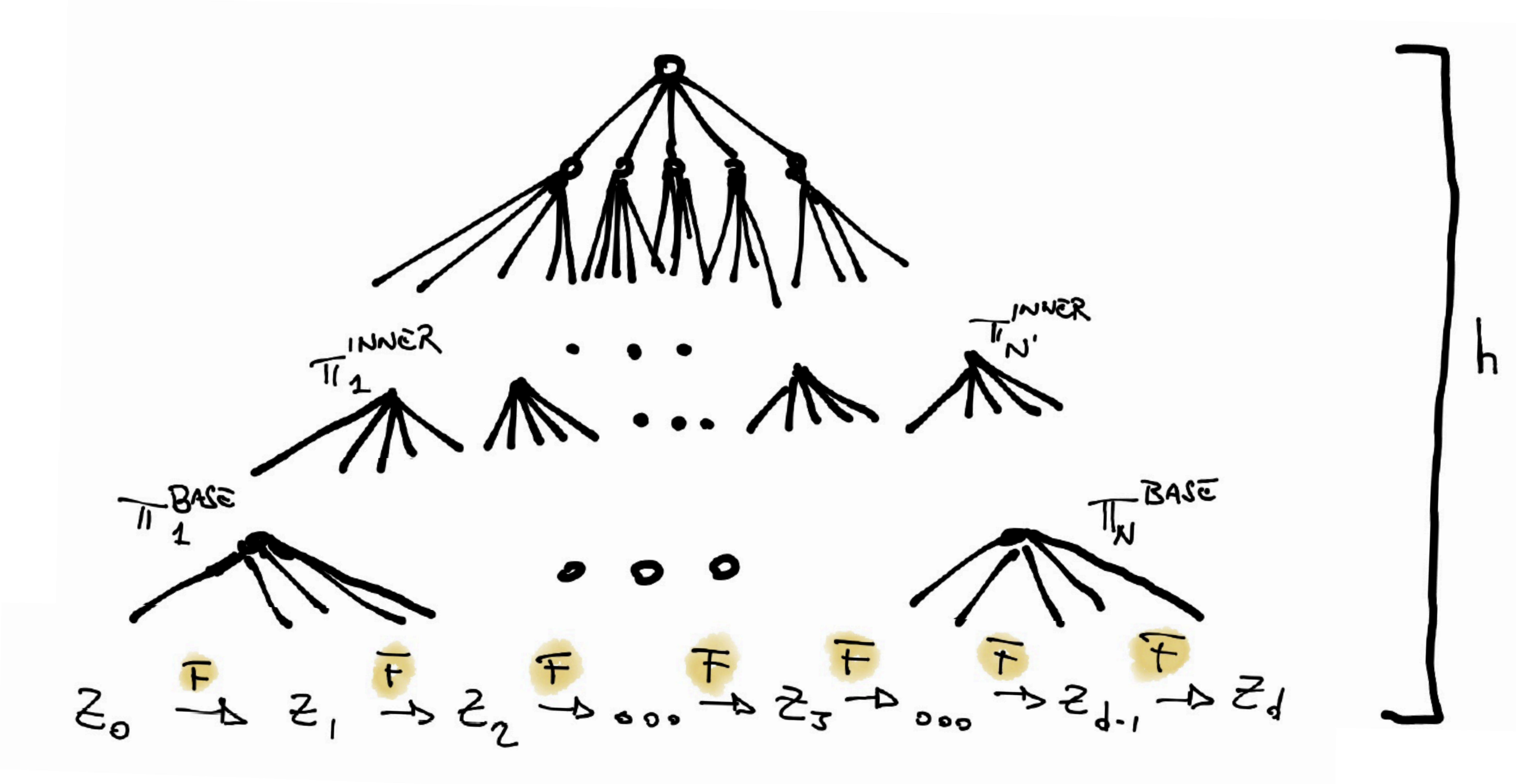

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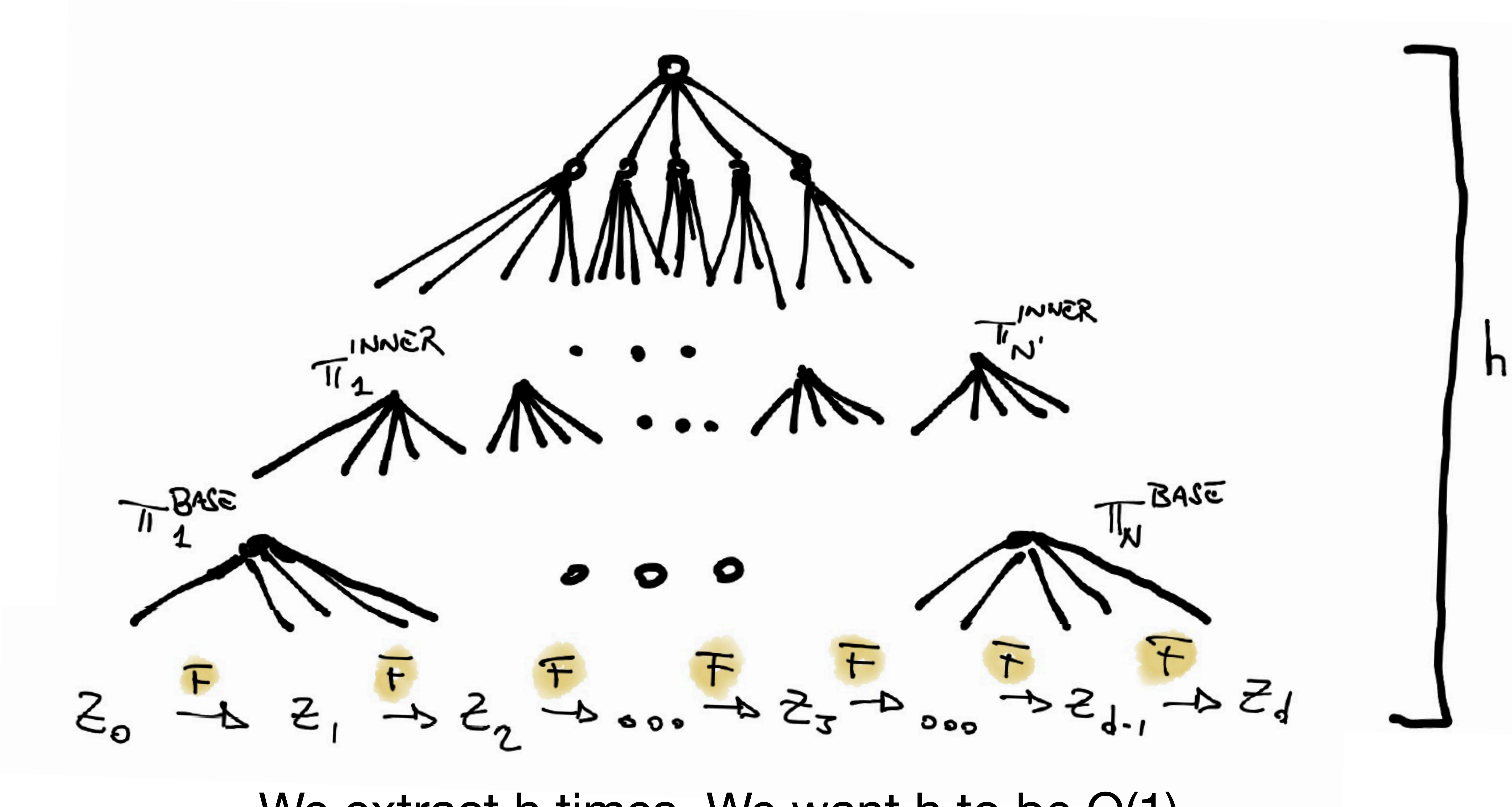

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We extract h times. We want h to be O(1)
For that, choose branching factor O(λ).

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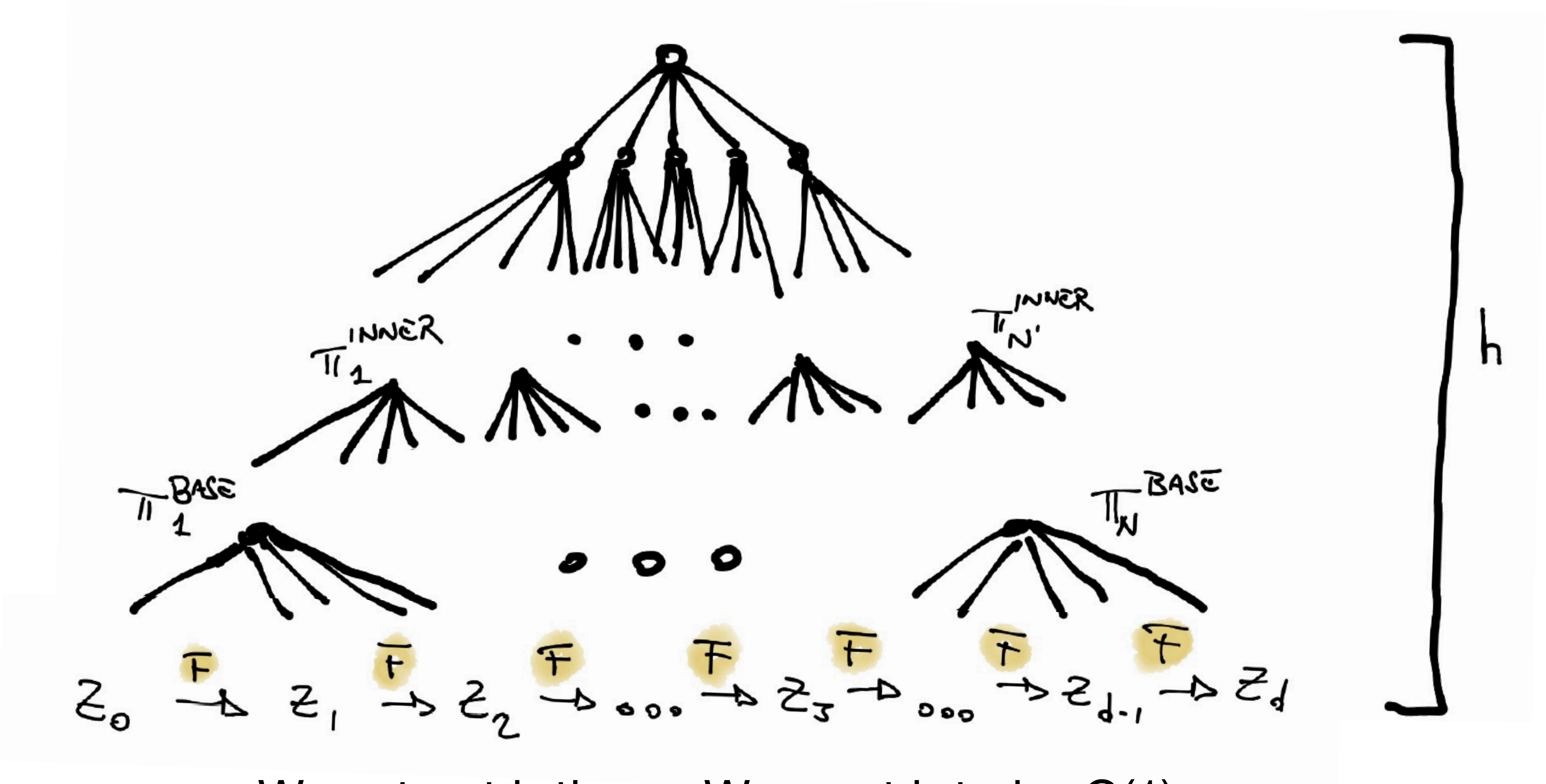
This construction works but it is not the plain recursive construction from before anymore.



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Why Does Security Beyond O(1) Depth Matters?

A digression on motivation

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    - round functions require $\approx \lambda$ iterations
- General improved understanding of *where* we can use *which* constructions

How the Community Has Addressed This—A Landscape

Using/proving secure schemes beyond O(1) depth

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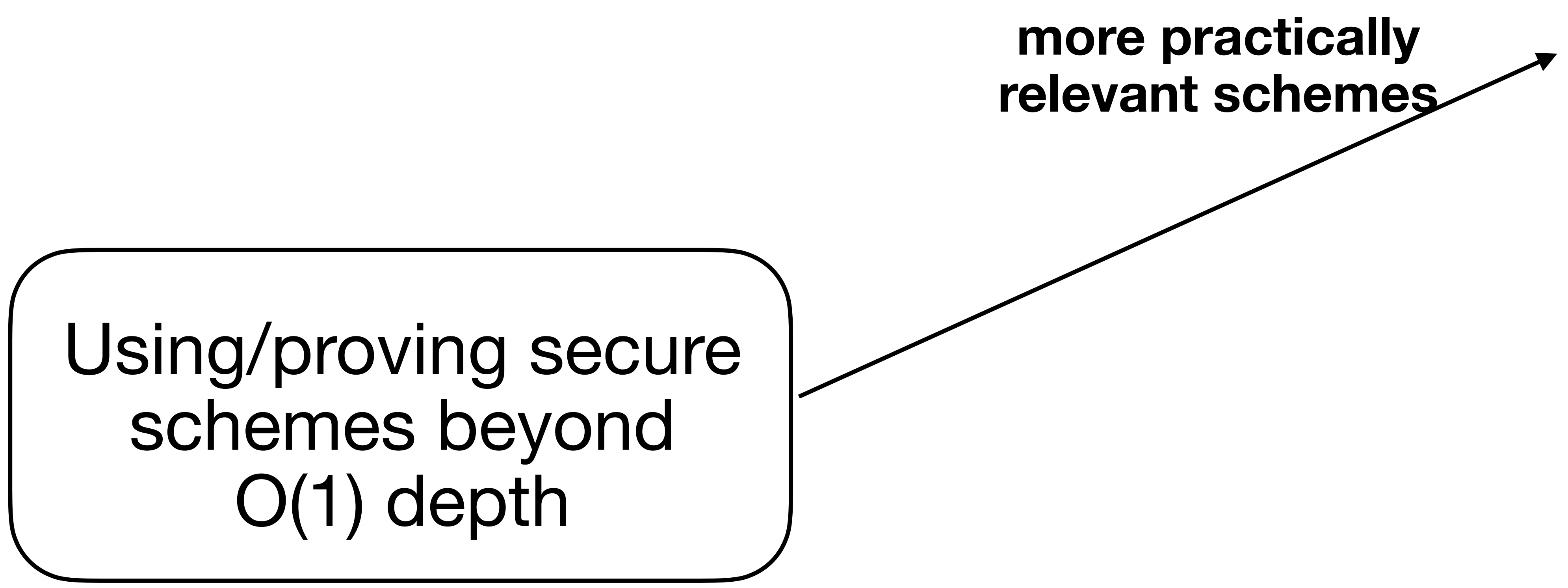

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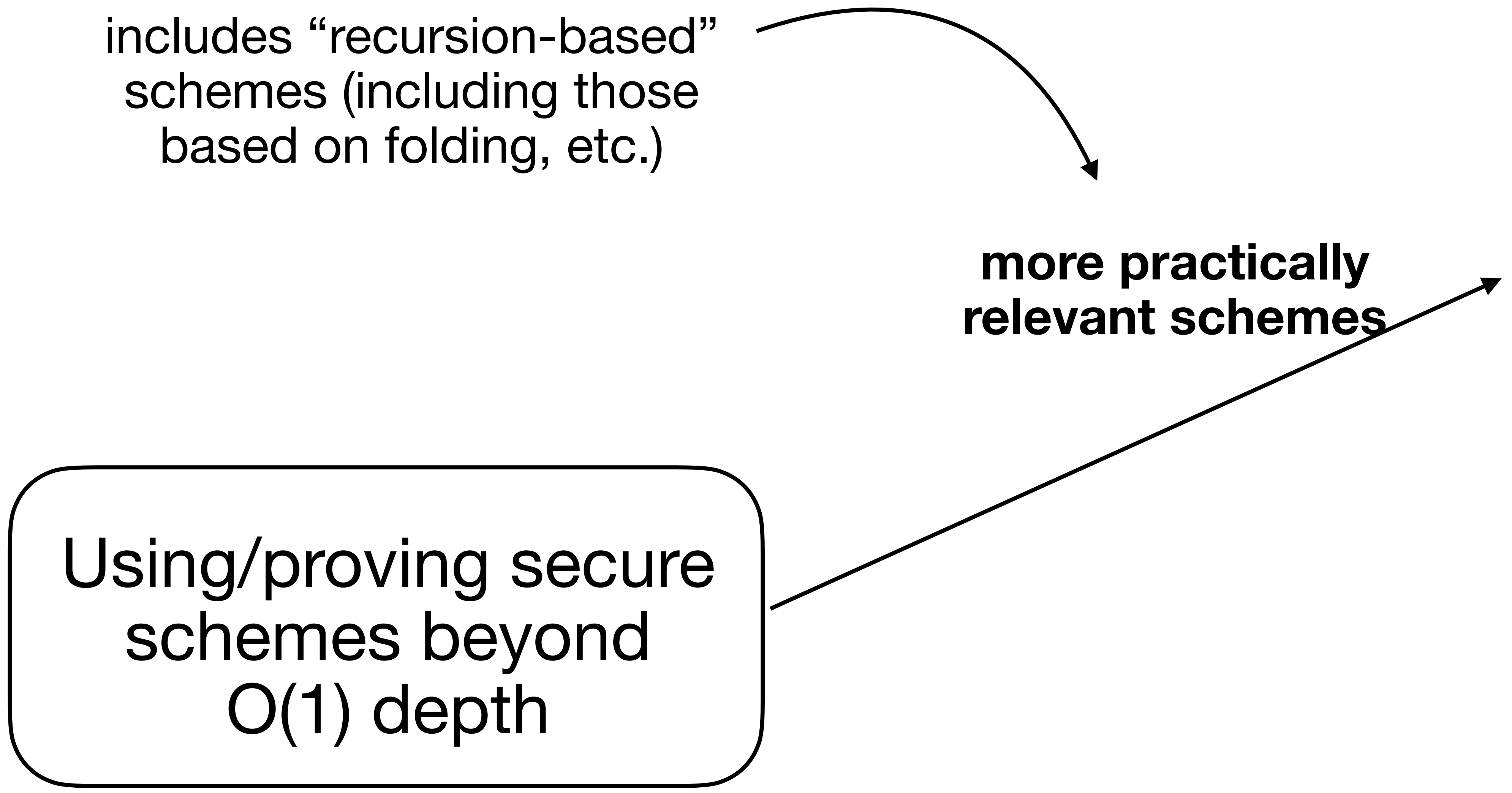

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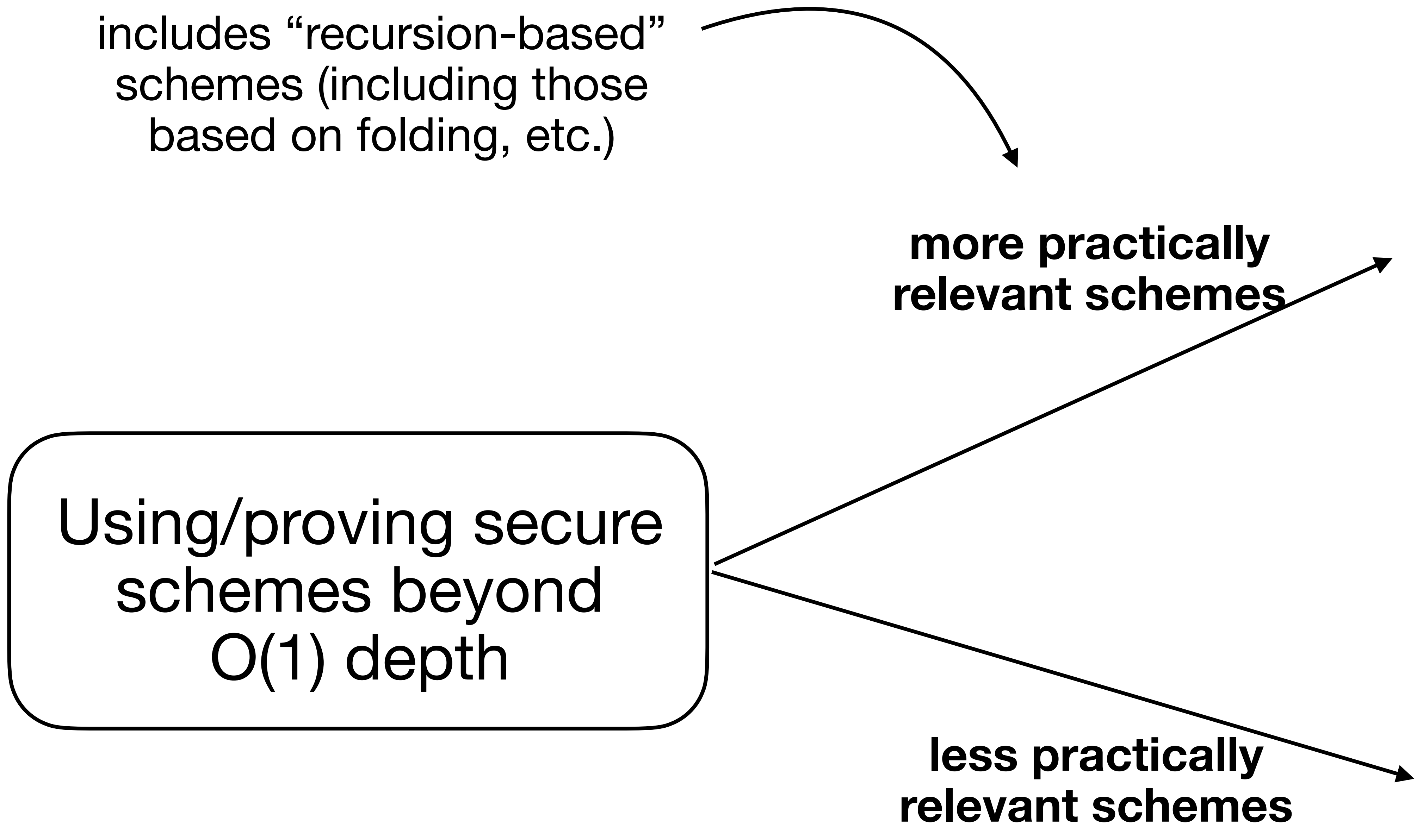

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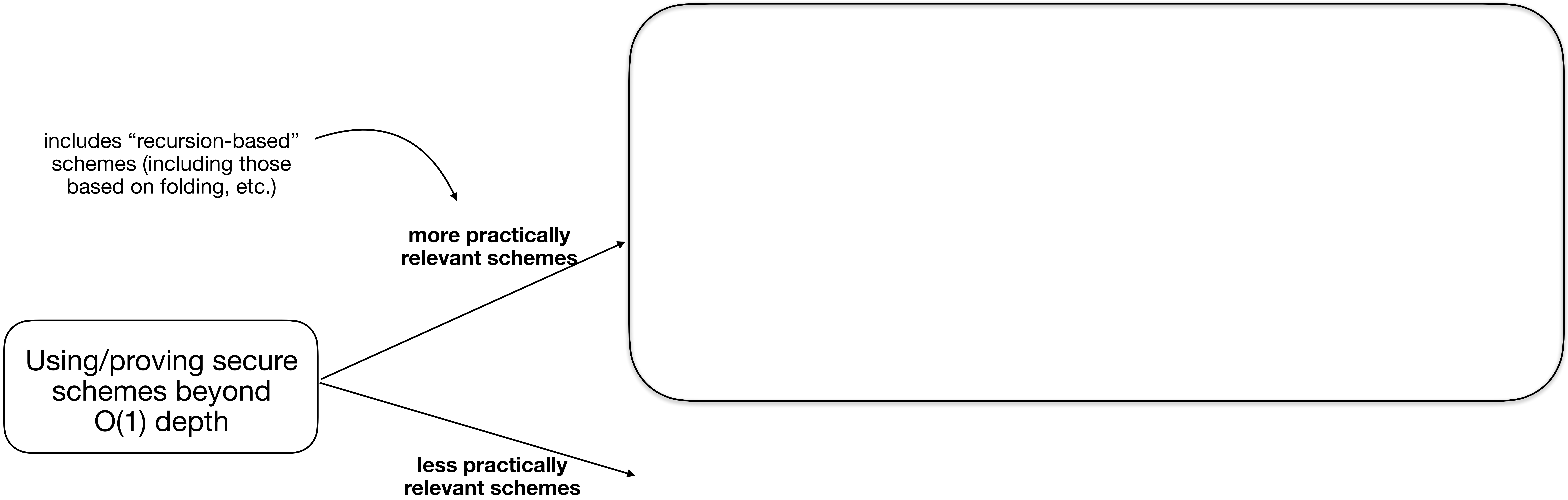

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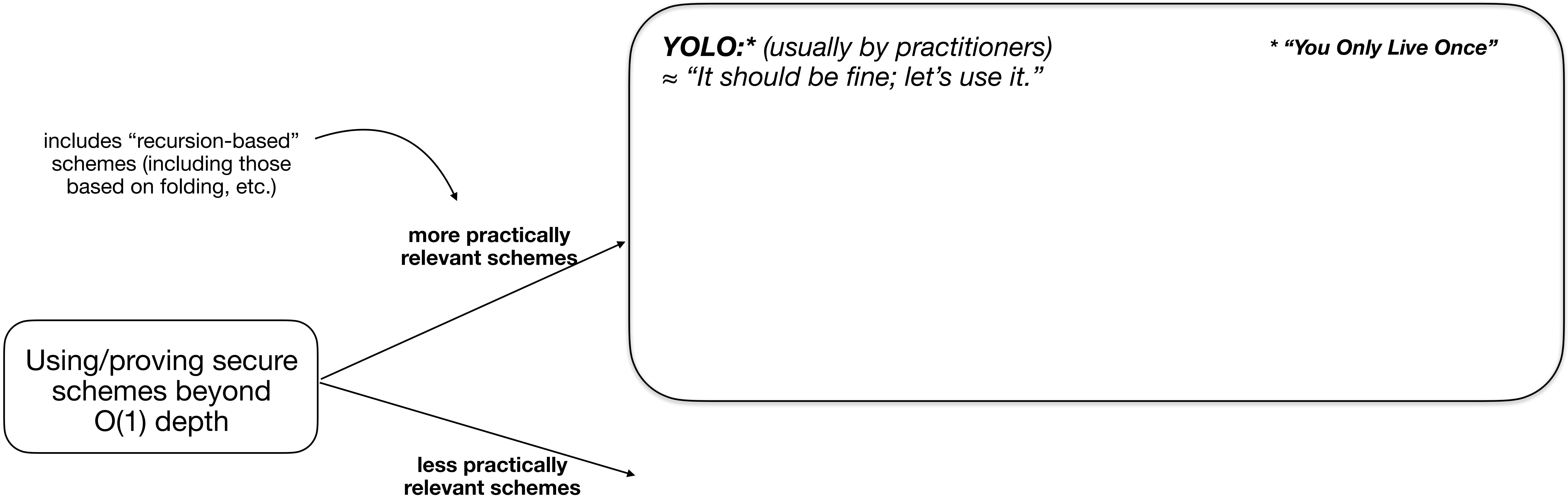

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Modifies schemes (or applicable only at times)

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More complex, more inefficient

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Still open:

When are existing constructions secure/insecure beyond O(1) depth?

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Soundness for non-deterministic computations

Incrementally Verifiable Computation for NP from Standard Assumptions

Pratish Datta*, NTT Research — Abhishek Jain†, NTT Research and JHU — Zhengzhong Jin‡, Northeastern — Alexis Korb§, UCLA — Surya Mathialagan¶, MIT — Amit Sahai‖, UCLA

Limitations

Often it might not be warranted.

Modifies schemes (or applicable only at times)

More complex, more inefficient

This Work's Question

Still open:

When are existing constructions secure/insecure beyond O(1) depth?

The problem at hand

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We approach this question through two main conceptual lenses.

Lens 1: “*Depth*” as a Core Object of Study

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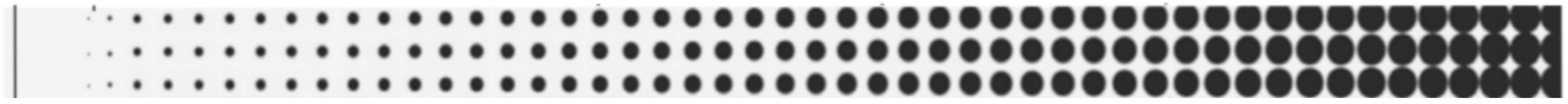
??



O(1) O($\log^2(\lambda)$) O($\sqrt{\lambda}$) O(λ)

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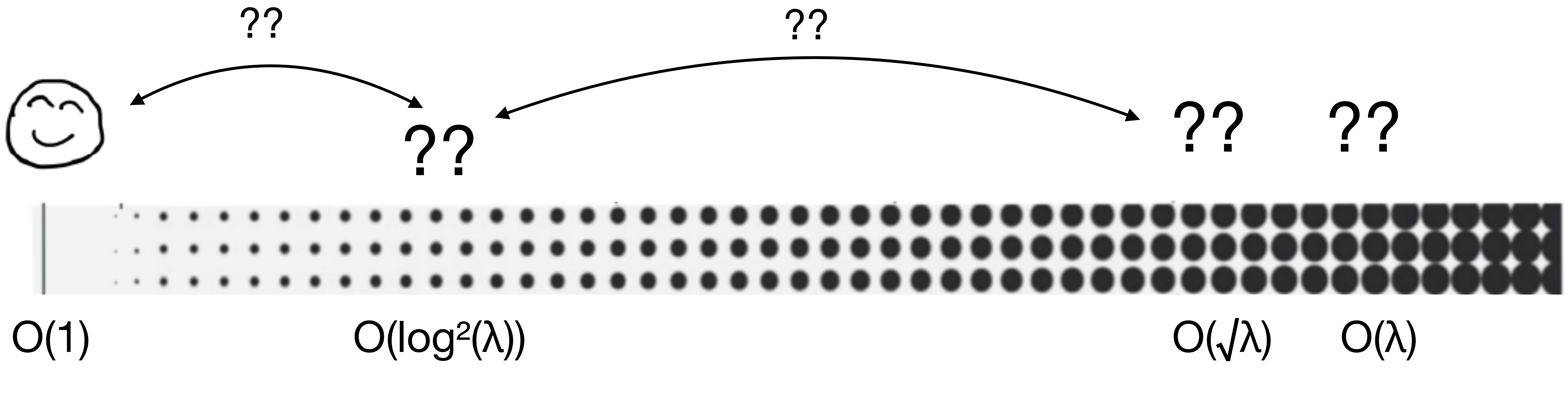

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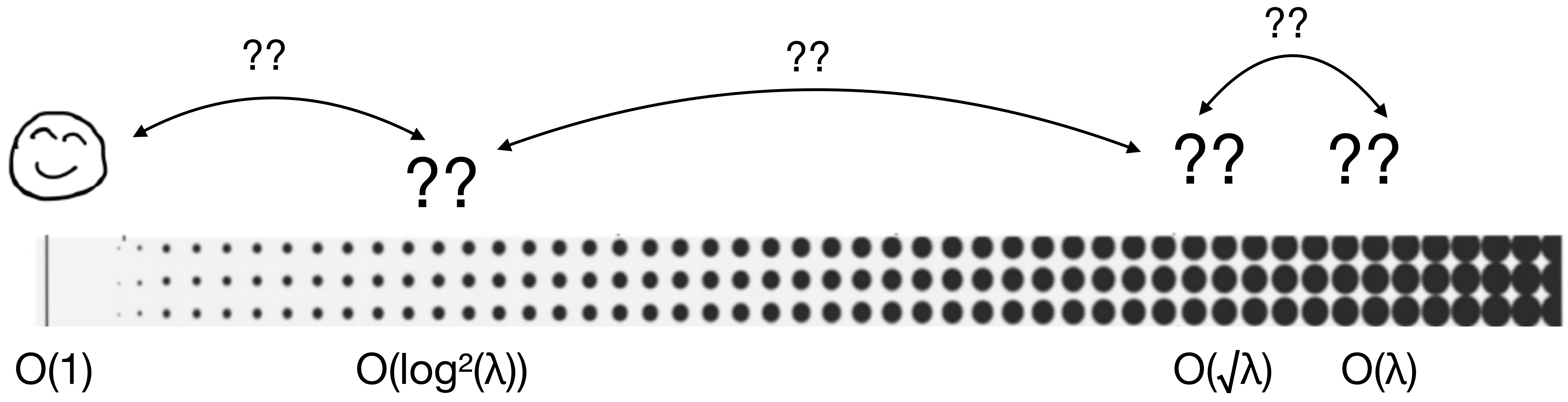

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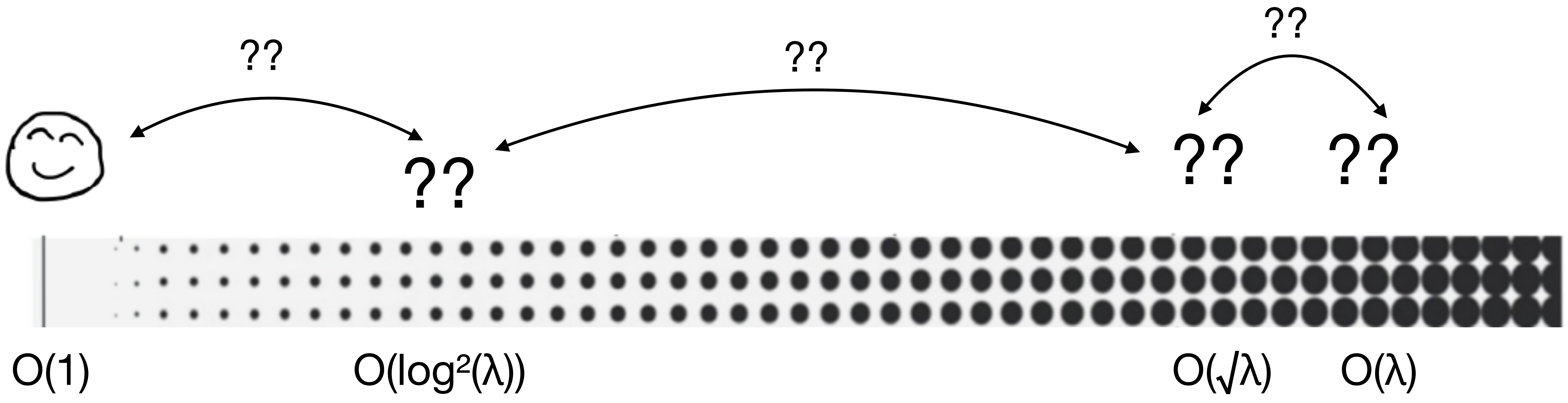

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A note on abuse of language:
I will say
"*big/bigger*" to mean "*fast/er growing*";
"*small/smaller*" to mean "*slow/er growing*"

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  - another notion of (non-extractable) soundness that we introduce, but that is more expressive than the above.
    - ≈ incremental analogue of functional commitments

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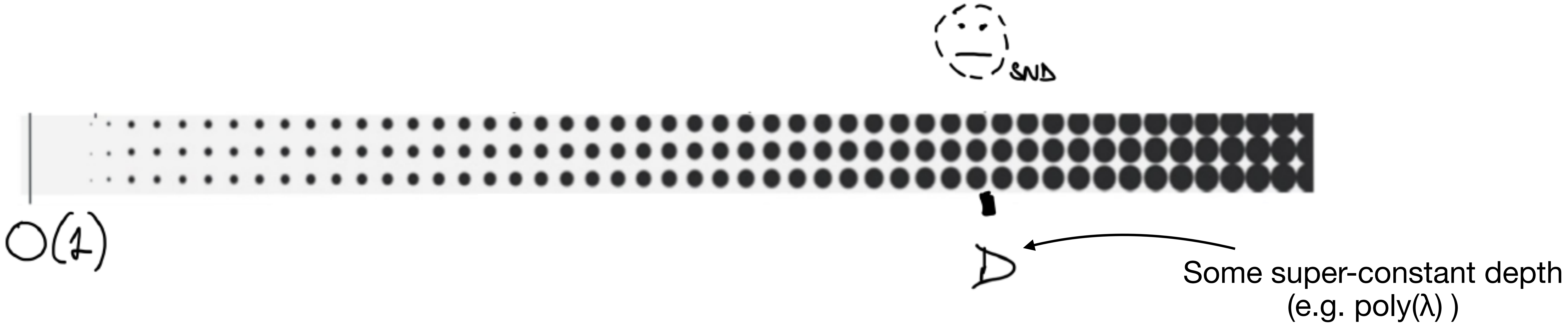

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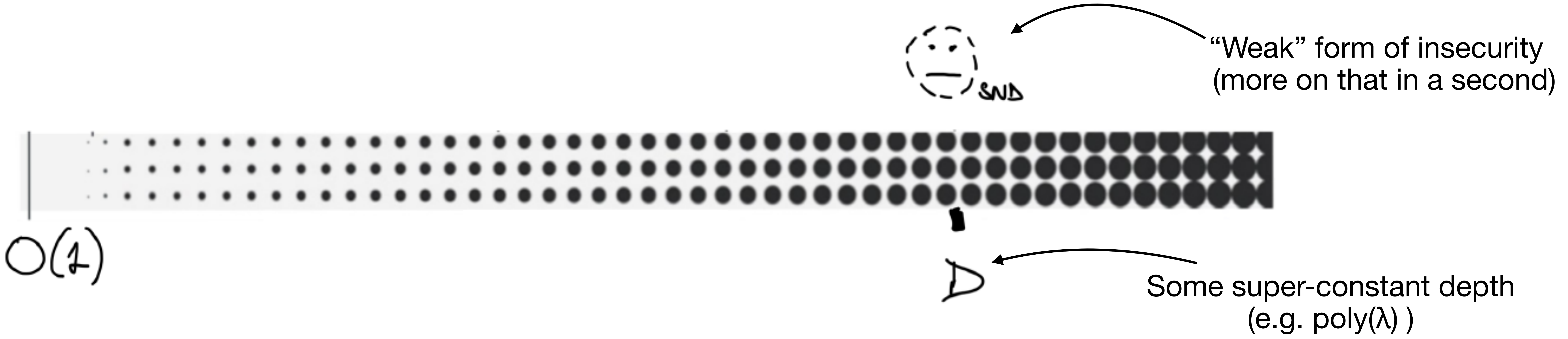

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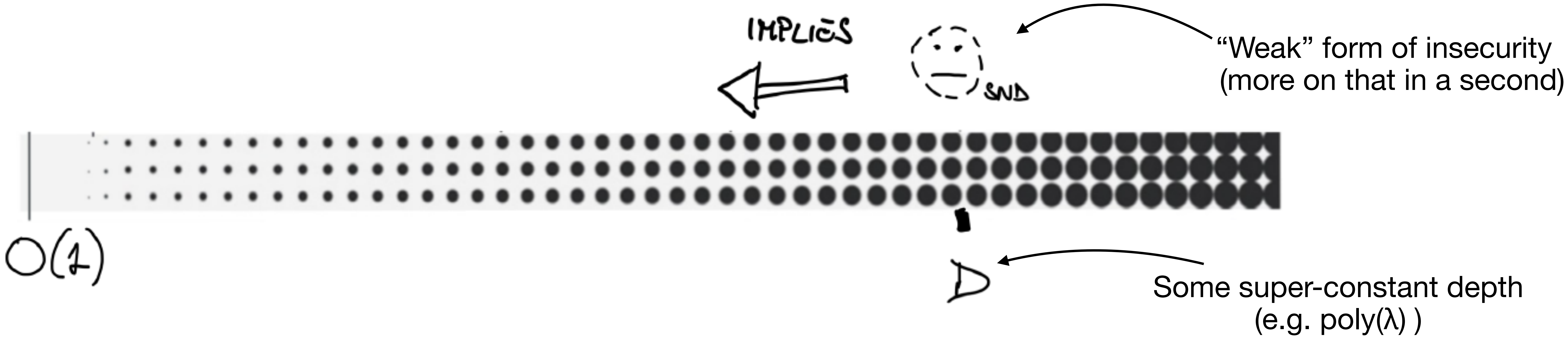

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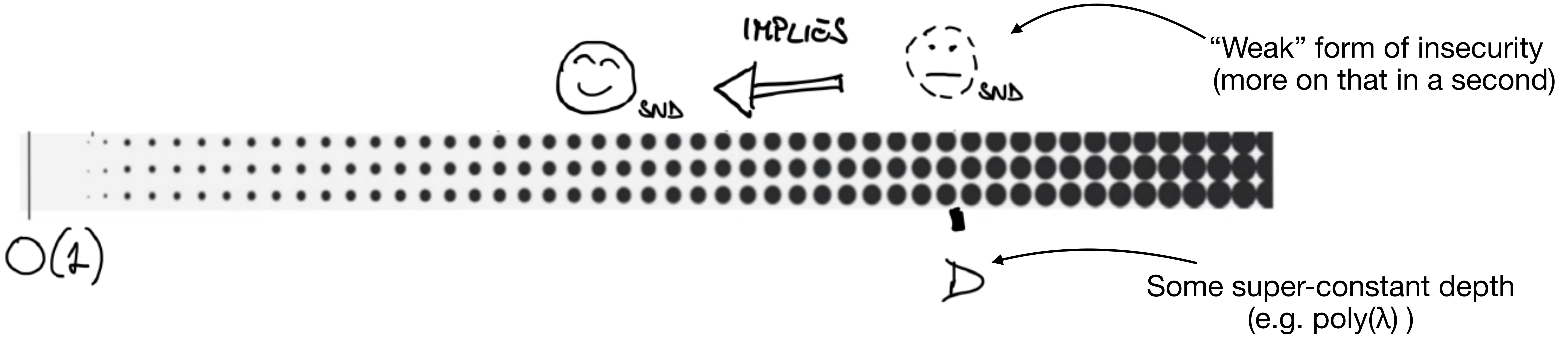

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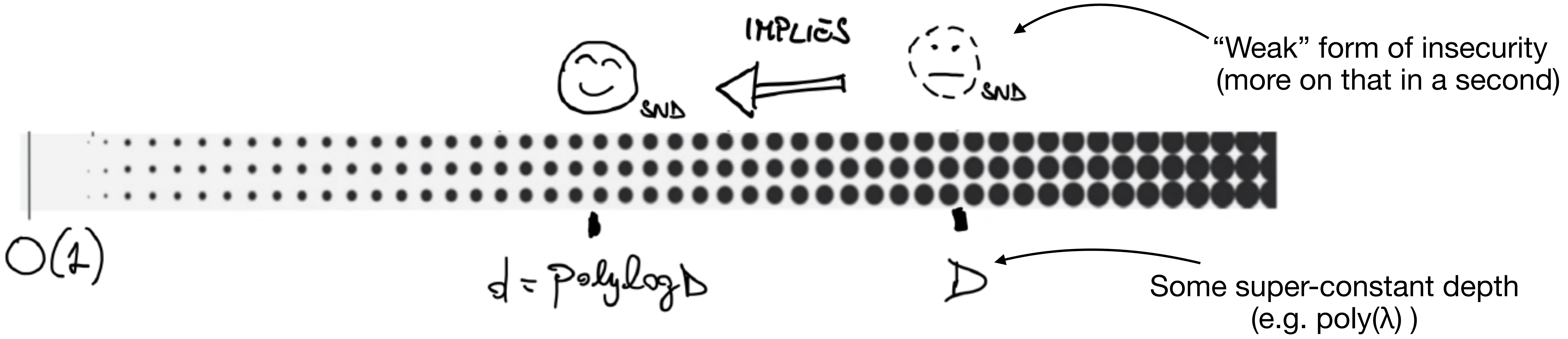

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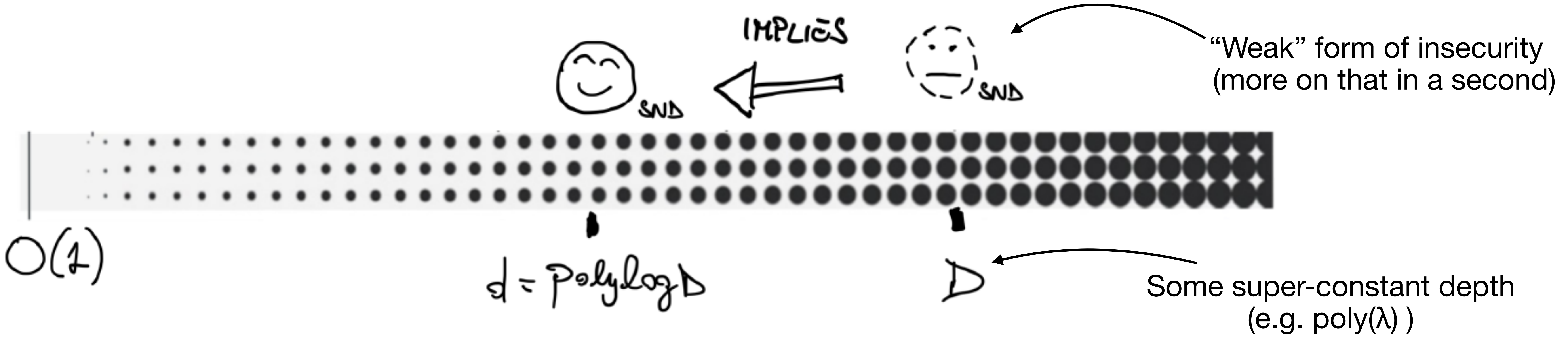
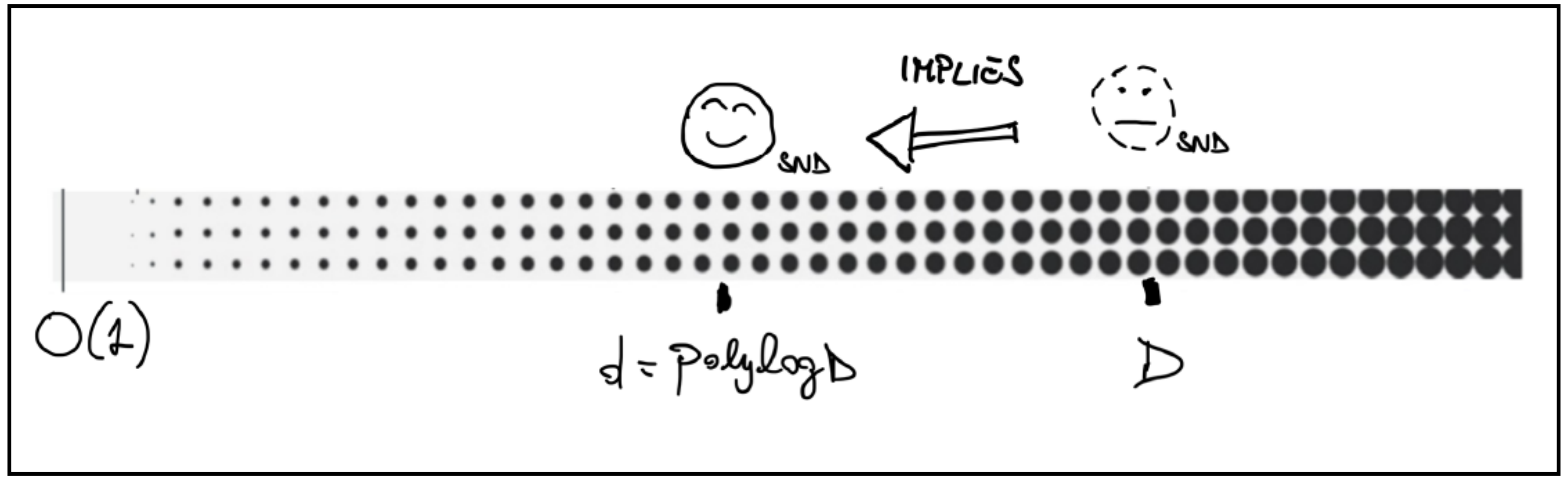


Implication:

to prove security at some ω(1) depth d,

show some ω(1) depth D where this weak property holds.

What Do We Mean by "Weak" Insecurity?



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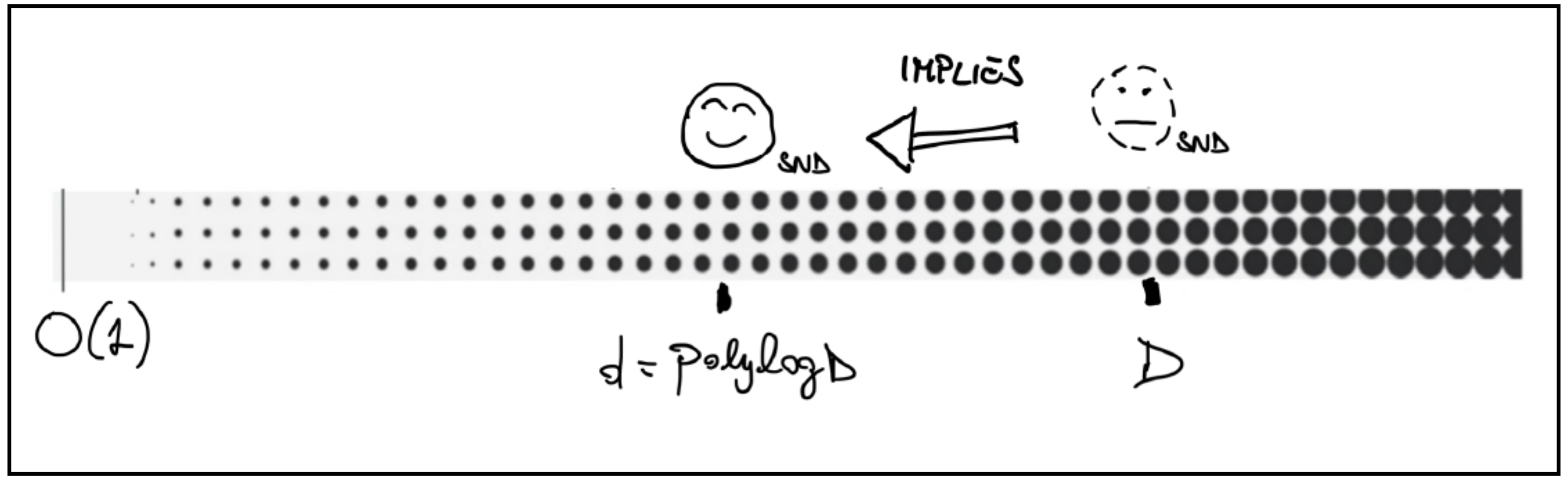

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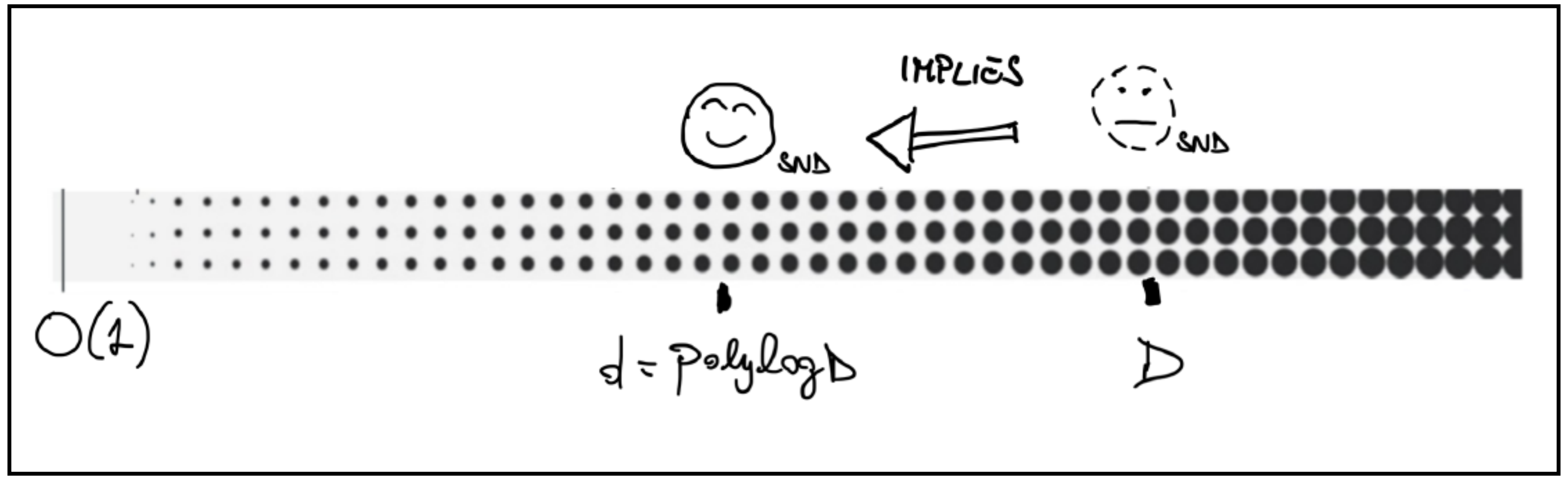

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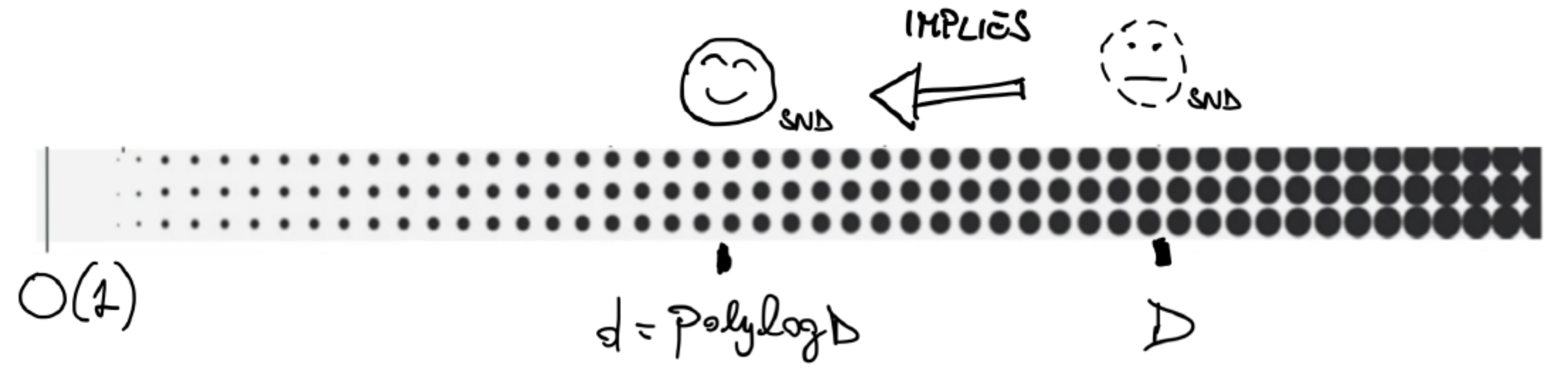

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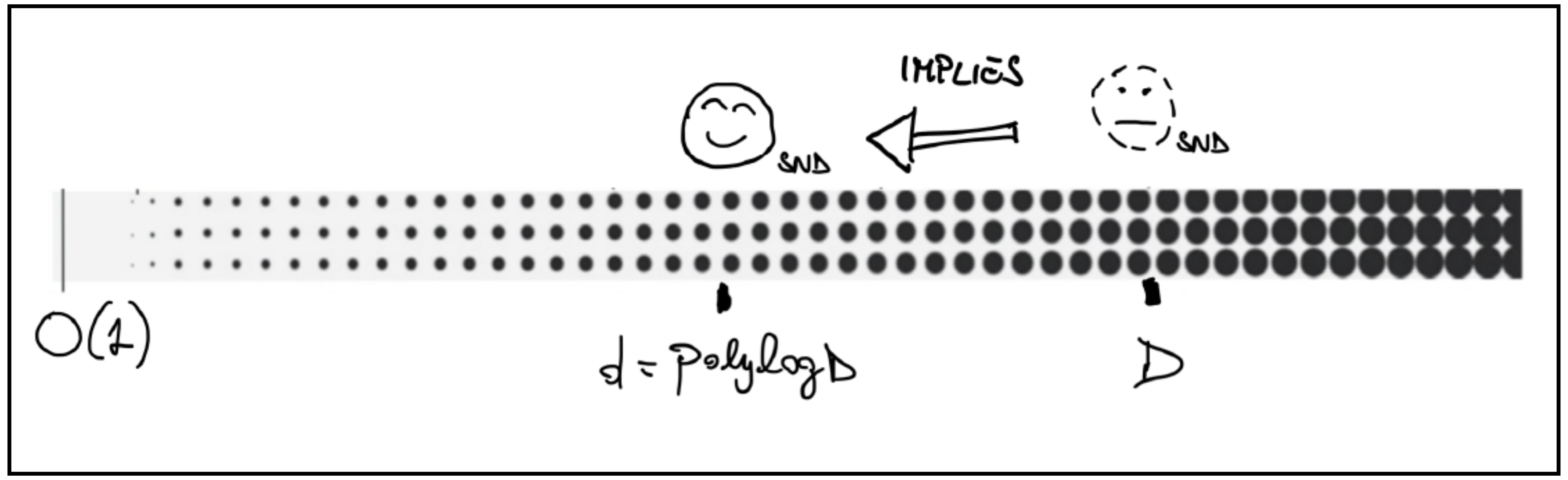

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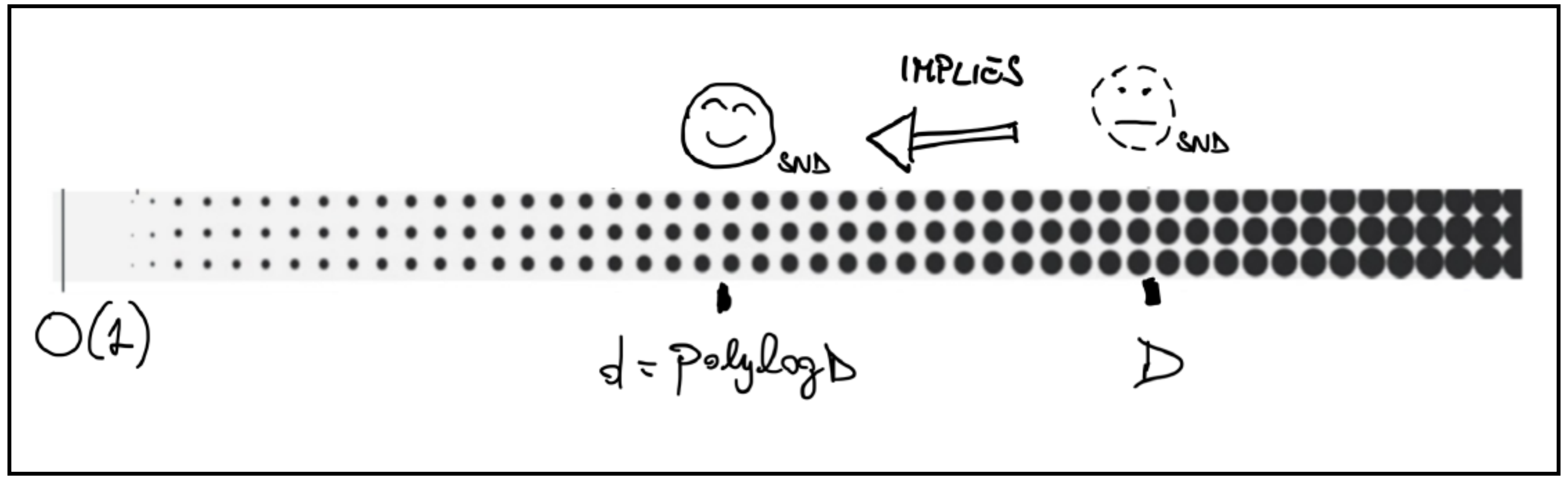

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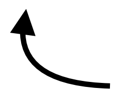

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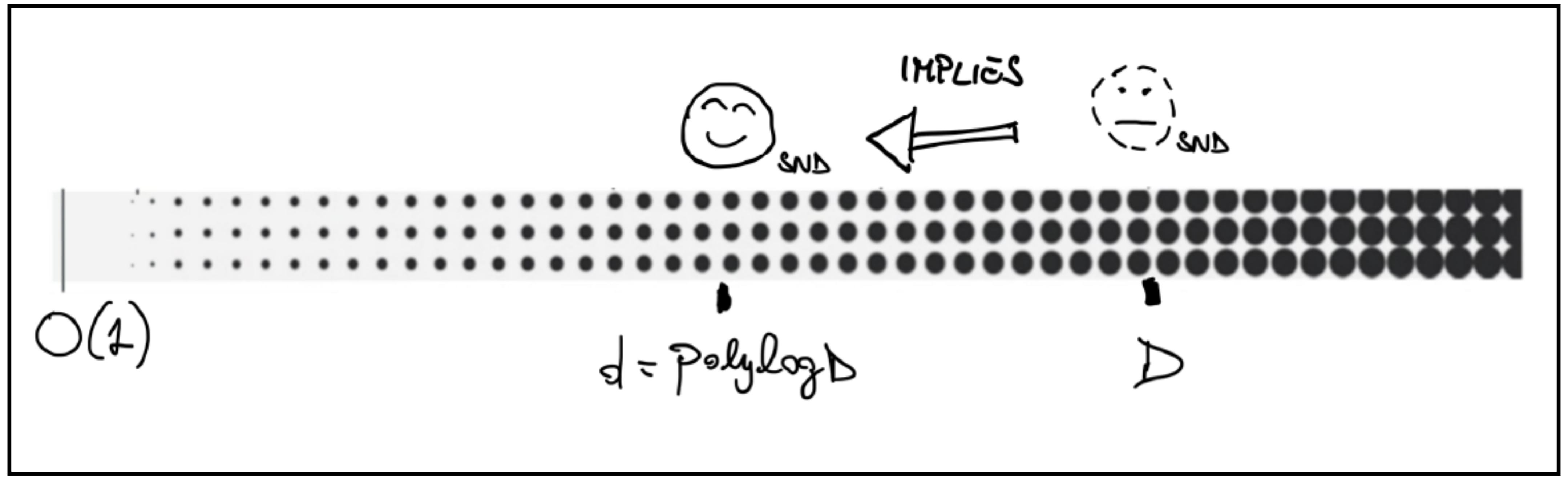

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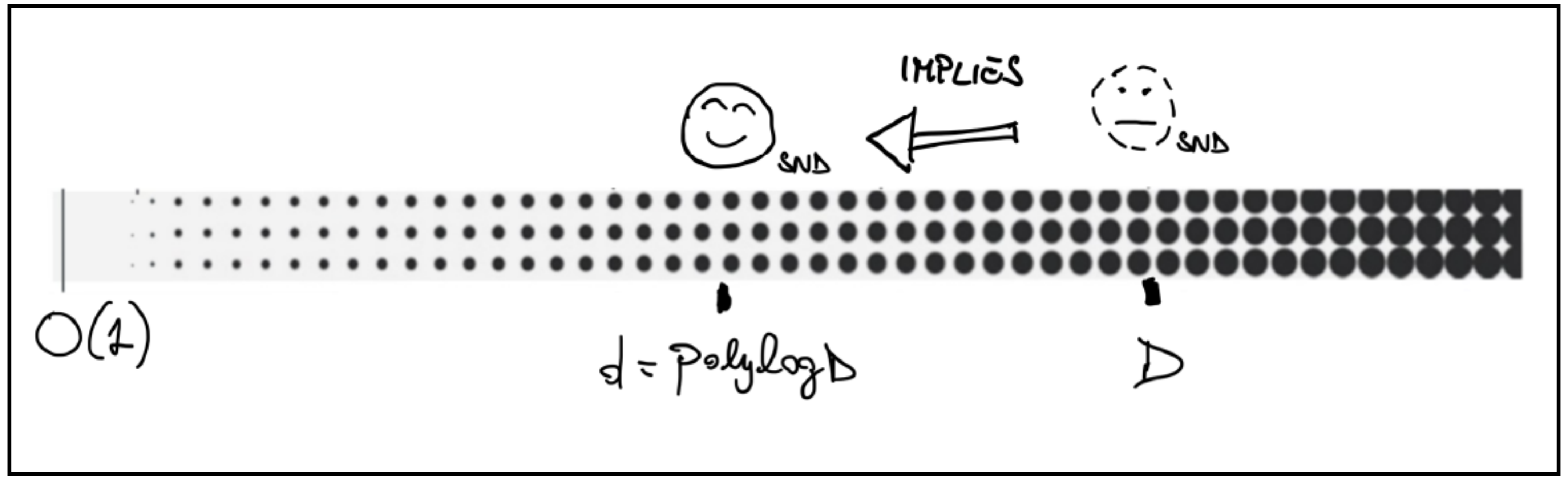

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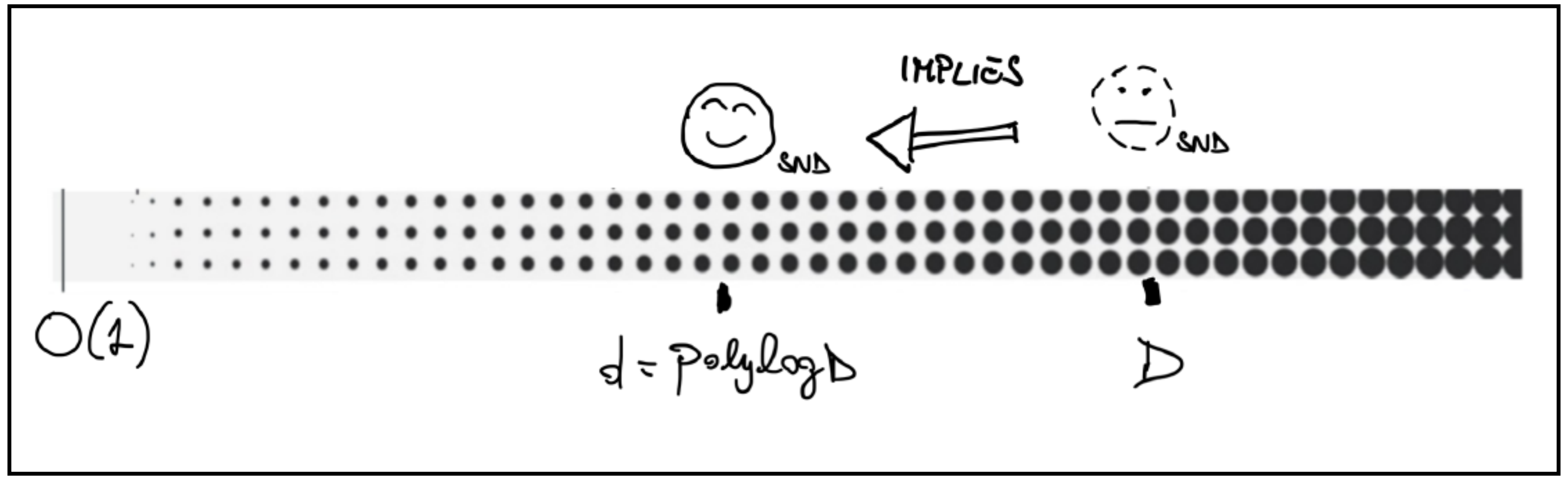

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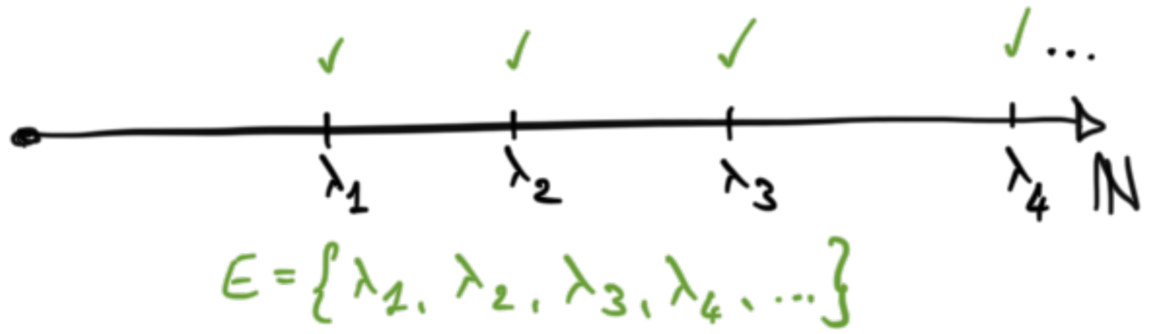

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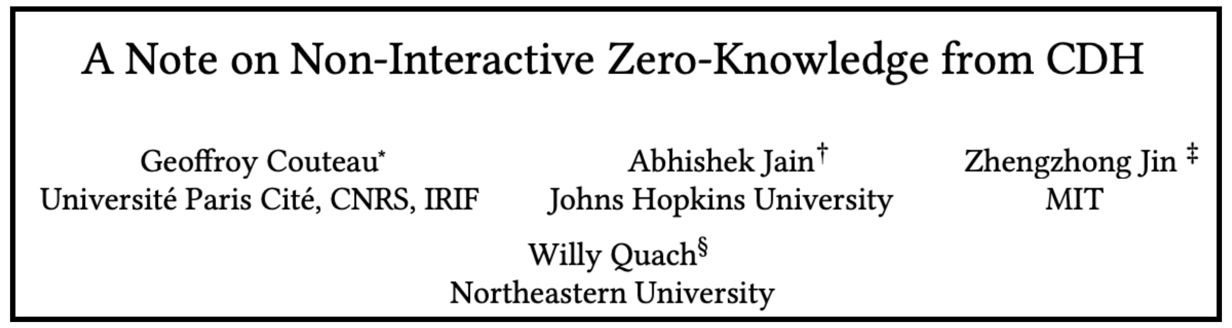

A Note on Non-Interactive Zero-Knowledge from CDH

Geoffroy Couteau[*] Université Paris Cité, CNRS, IRIF
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[CRYPTO '23]: builds i.o.-SND NIZKs from sub-exp CDH.

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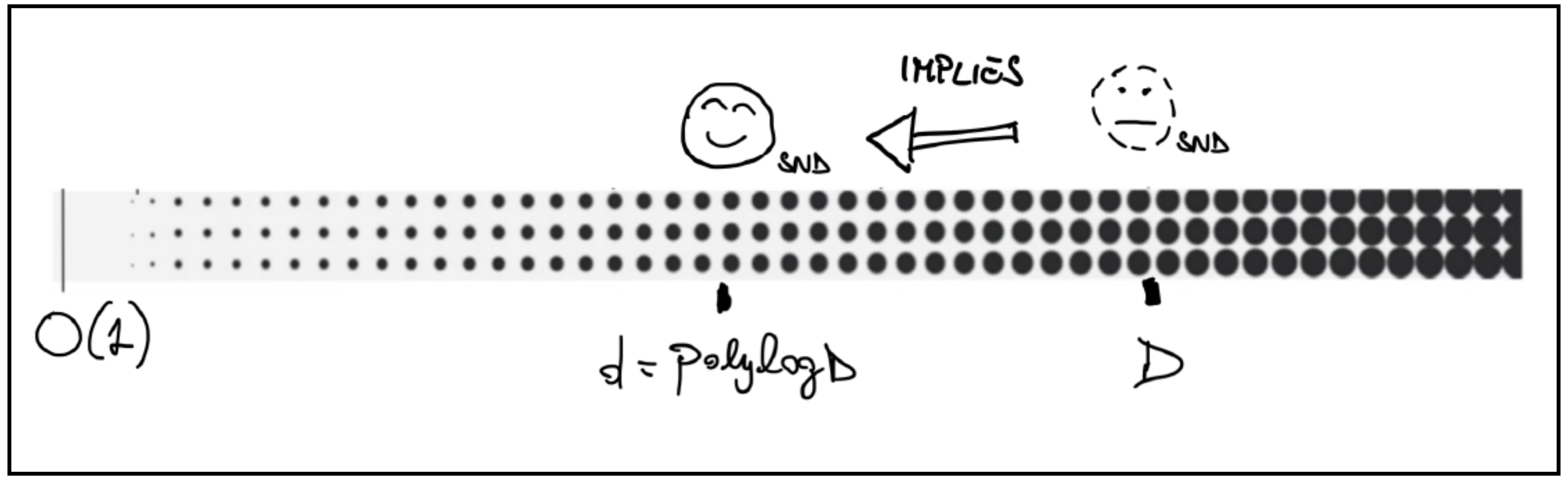

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On the Possibility of Basing Cryptography on EXP ≠ BPP

Yanyi Liu — Cornell University — yl2866@cornell.edu
Rafael Pass* — Cornell Tech — rafael@cs.cornell.edu

One-Way Functions and pKt Complexity

Shuichi Hirahara* Zhenjian Lu† Igor C. Oliveira‡

[CRYPTO '21,TCC '24]:
connect ∃ of i.o.-OWF to certain worst-case assumptions.

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Motivating question for next result:

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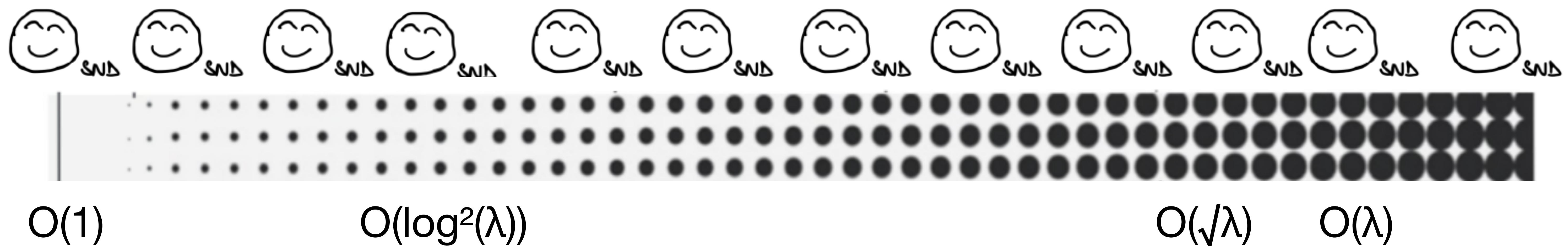

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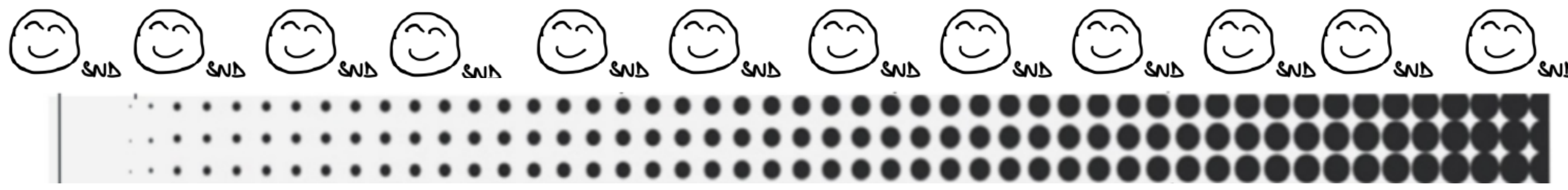

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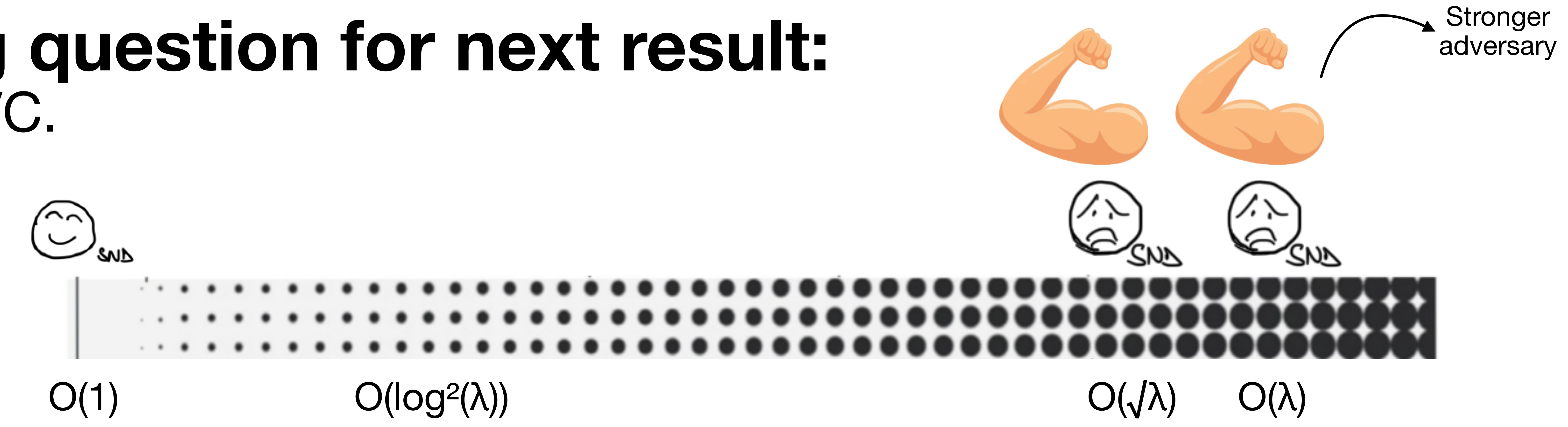

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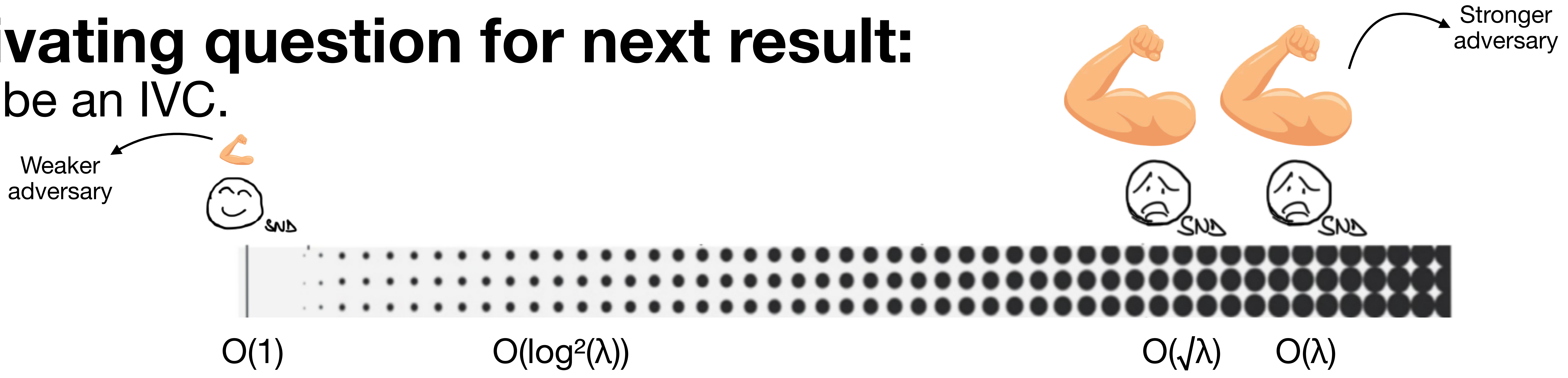

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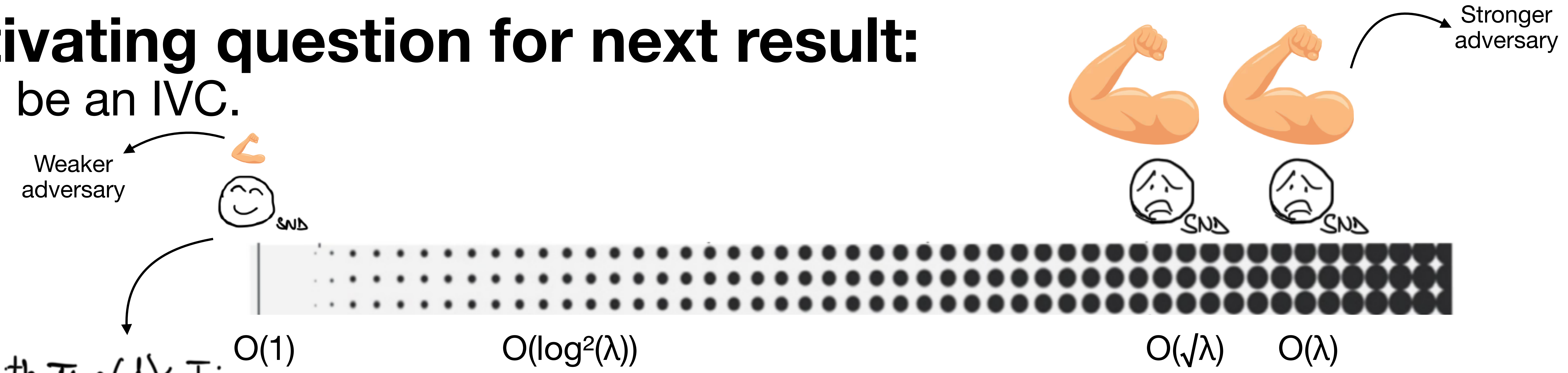

$\forall T = poly(\lambda)$, $\forall \mathcal{A}$ with $Time(\mathcal{A}) \le T$:

$ADV_{\mathcal{A}}(\lambda)@[DEPTH = O(1)]$ is NEGL.

Case 2: insecure somewhere.

Our Results

(continued)

Motivating question for next result:

Let Π be an IVC.

Case 2: insecure somewhere.

Our Results

(continued)

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Our Results

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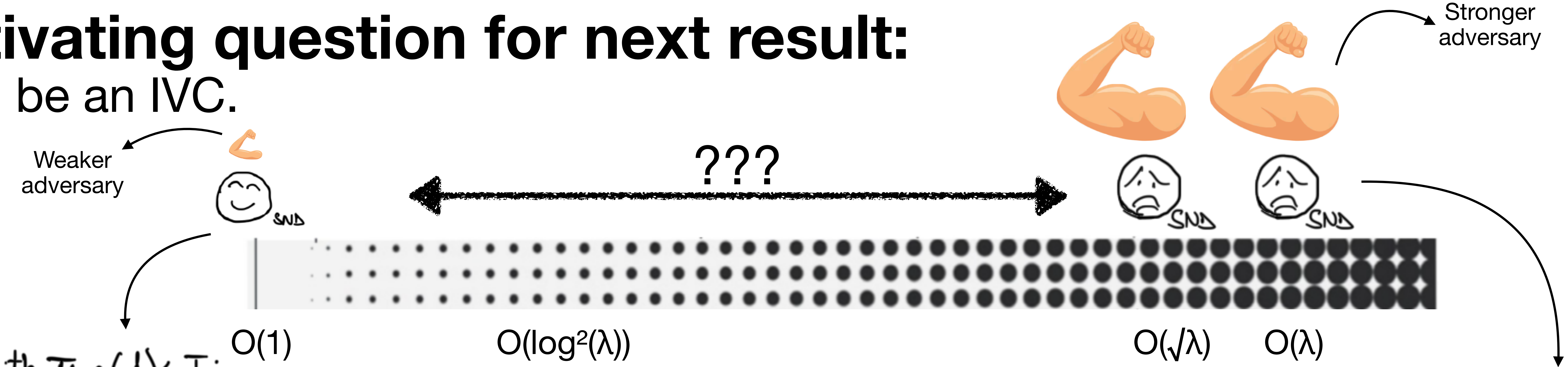

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$\approx \text{ADV}_{\mathcal{A}}(\lambda) \geq \frac{1}{P(\lambda)}$

FOR poly $P(\cdot)$, INFINITELY MANY λ-s

Our Results

(continued)

Motivating question for next result:

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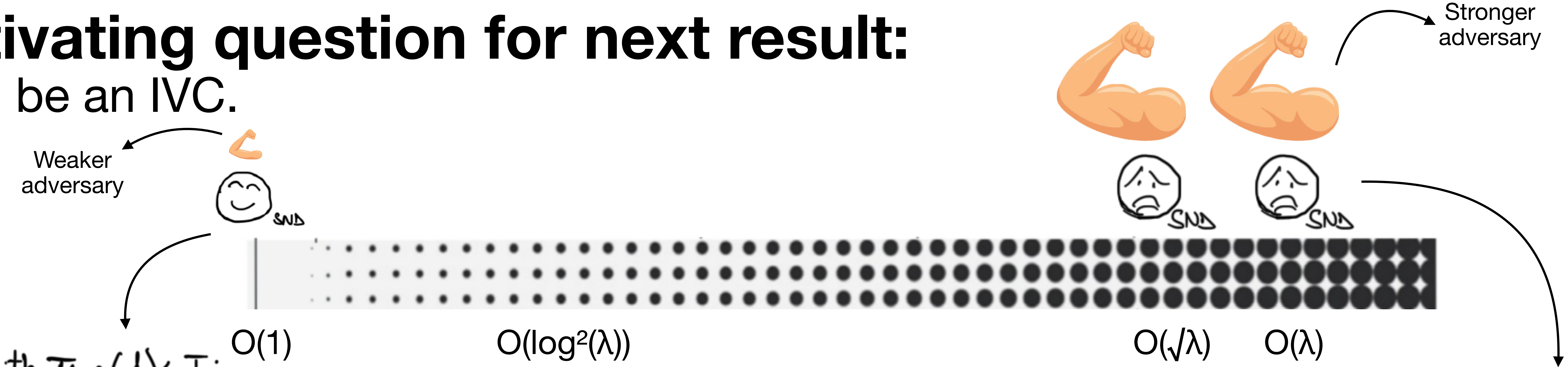

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Our Results
(continued)

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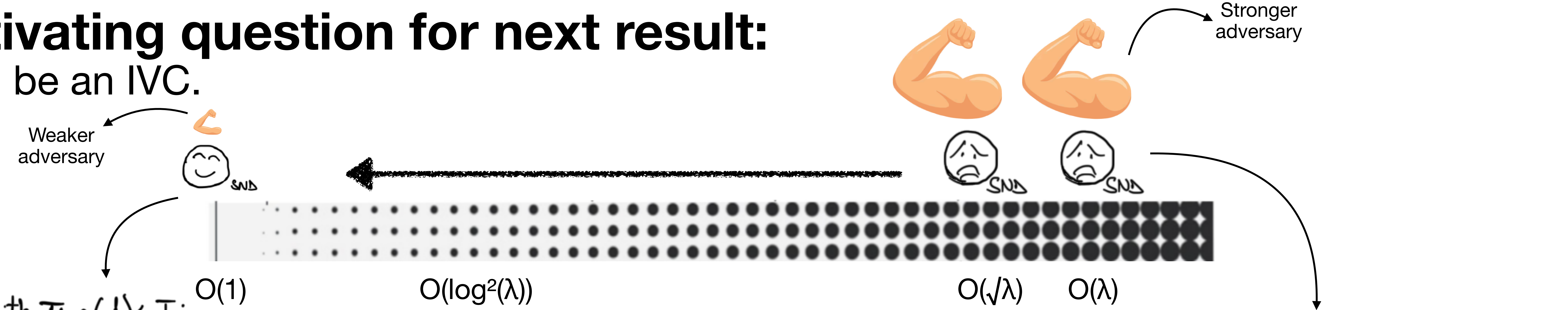

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Case 2: insecure somewhere.

Our Results

(continued)

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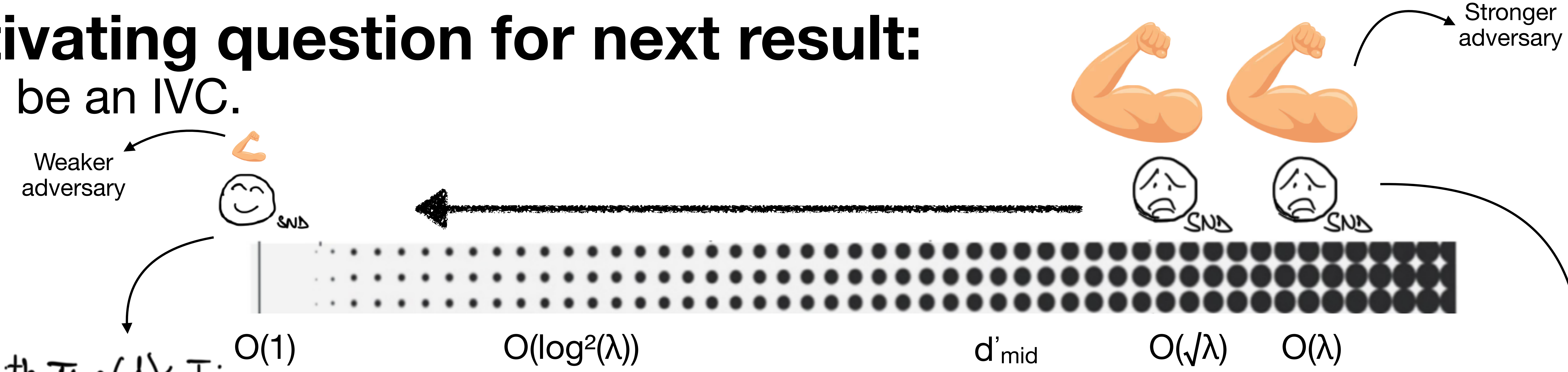

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FOR poly $P(\cdot)$, INFINITELY MANY λ-s

Case 2: insecure somewhere.

Our Results
(continued)

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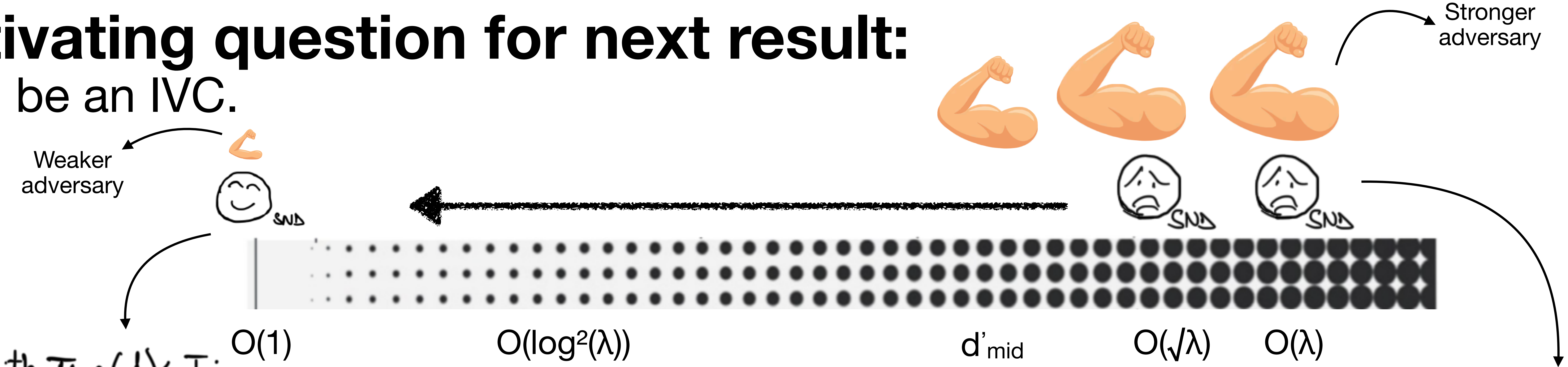

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Case 2: insecure somewhere.

Our Results
(continued)

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Case 2: insecure somewhere.

Our Results
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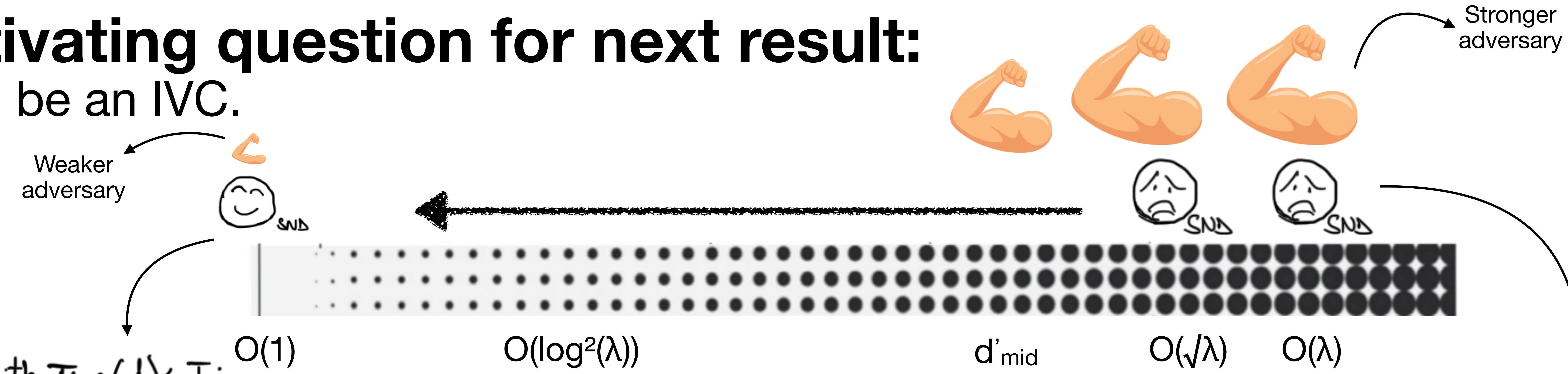

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FOR poly $p(\cdot)$, INFINITELY MANY λ-s

Case 2: insecure somewhere.

Our Results
(continued)

Motivating question for next result:

Let Π be an IVC.

Case 2: insecure somewhere.

Our Results
(continued)

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Our Results
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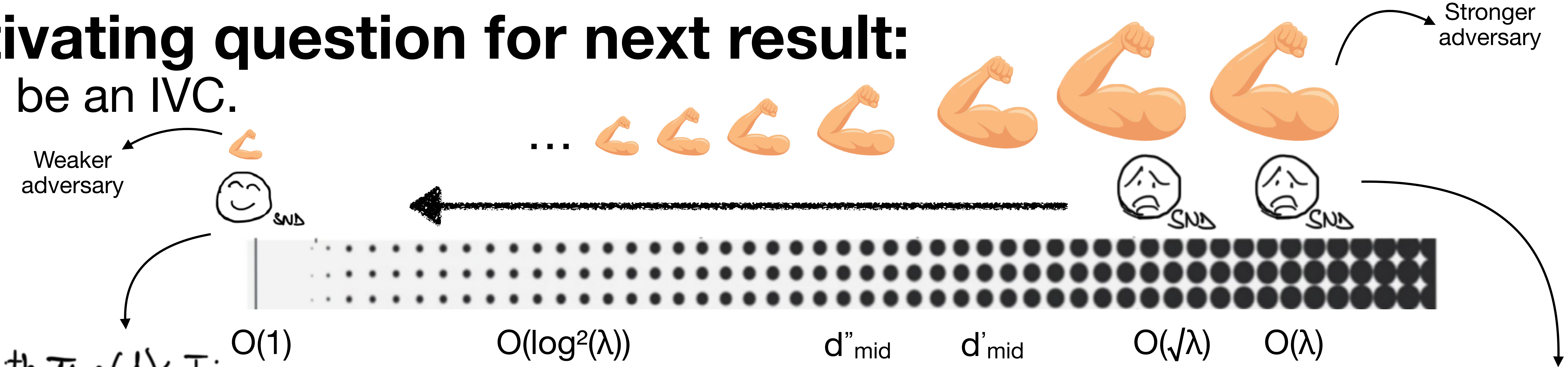

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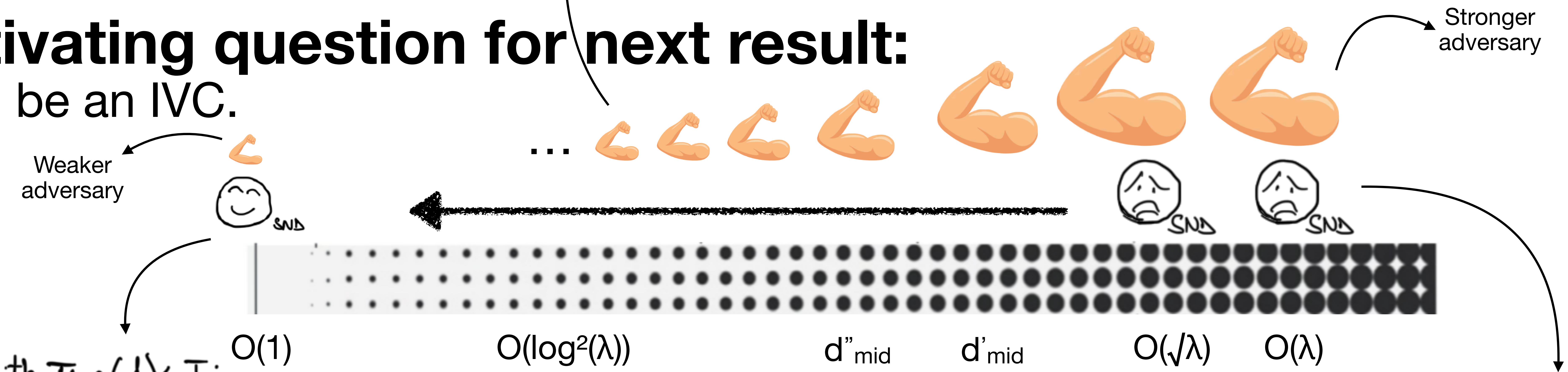
Case 2: insecure somewhere.

Our Results
(continued)

We call this (potential) pattern in IVC
graceful security degradation

Motivating question for next result:

Let Π be an IVC.



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FOR poly $P(\cdot)$, INFINITELY MANY λ-s

Case 2: insecure somewhere.

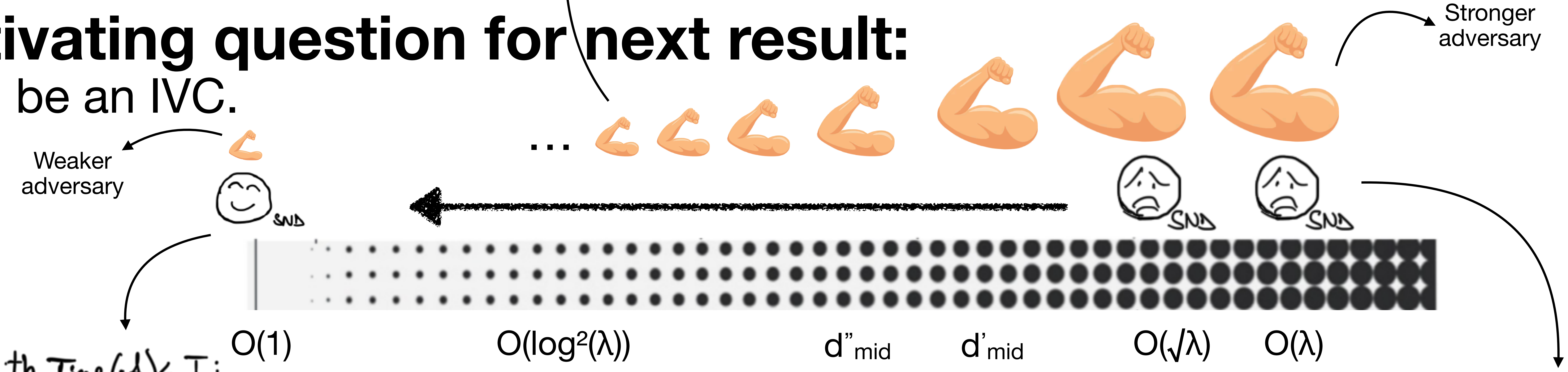
Our Results
(continued)

Q: Can an IVC exhibit it?

We call this (potential) pattern in IVC **graceful security degradation**

Motivating question for next result:

Let Π be an IVC.



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FOR poly $p(\cdot)$, INFINITELY MANY λ-s

Case 2: insecure somewhere.

A practical framing around graceful sec. degradation:

Our Results (continued)

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Motivating question for next result:

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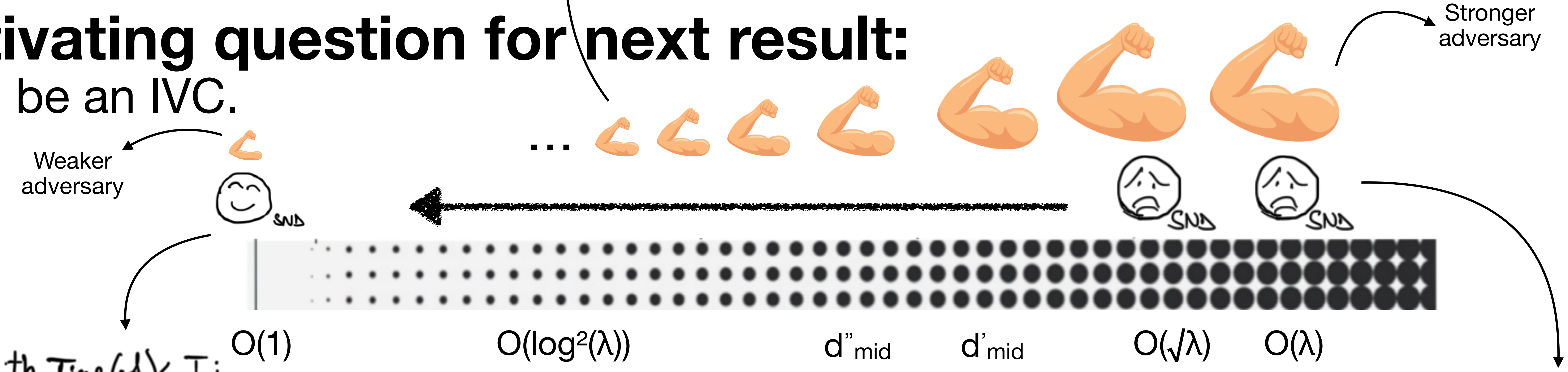

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FOR poly $p(\cdot)$, INFINITELY MANY λ-s

Case 2: insecure somewhere.

Our Results (continued)

Q: Can an IVC exhibit it?

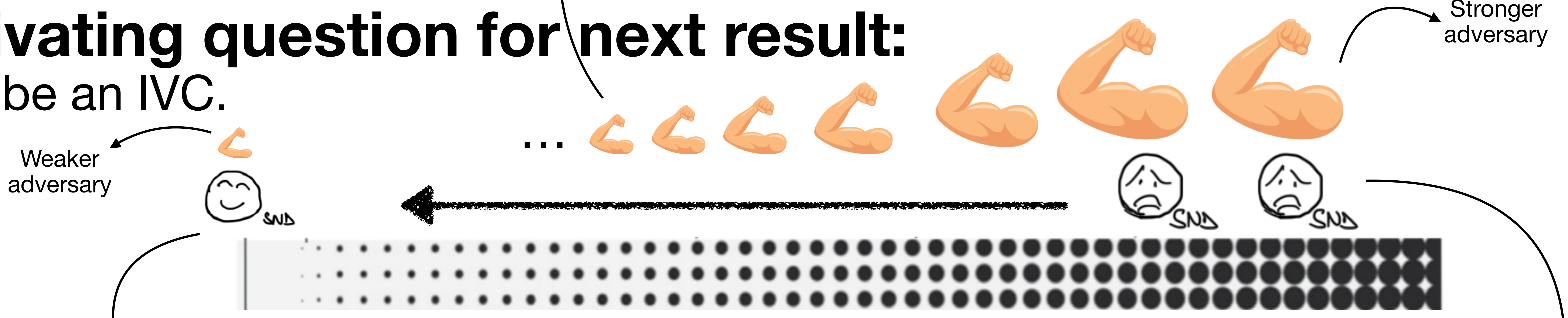
We call this (potential) pattern in IVC **graceful security degradation**

A practical framing around graceful sec. degradation:

💪💪💪💪💪💪 ≈ better and better inverse poly-s

Motivating question for next result:

Let Π be an IVC.



O(1) O(log²(λ)) d”mid d’mid O(√λ) O(λ)

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FOR poly $p(\cdot)$, INFINITELY MANY λ-S

Case 2: insecure somewhere.

Our Results (continued)

Q: Can an IVC exhibit it?

We call this (potential) pattern in IVC **graceful security degradation**

A practical framing around graceful sec. degradation:

$\approx$ better and better inverse poly-s

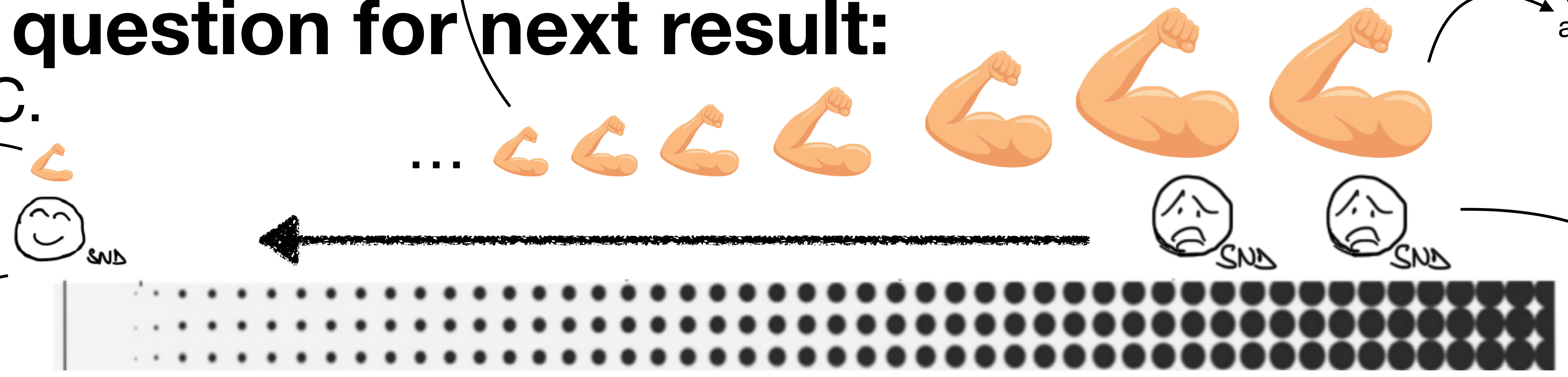
And cryptographers do sometimes work with inverse poly sec.

Motivating question for next result:

Let Π be an IVC.

Weaker adversary

Stronger adversary



O(1) — $O(\log^2(\lambda))$ — d''_{mid} — d'_{mid} — $O(\sqrt{\lambda})$ — $O(\lambda)$

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FOR poly $p(\cdot)$, INFINITELY MANY λ-s

Case 2: insecure somewhere.

Our Results (continued)

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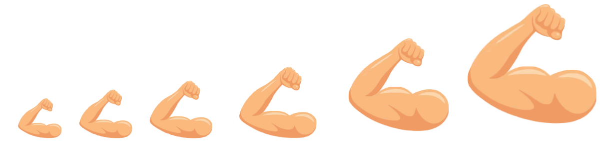
A practical framing around graceful sec. degradation:



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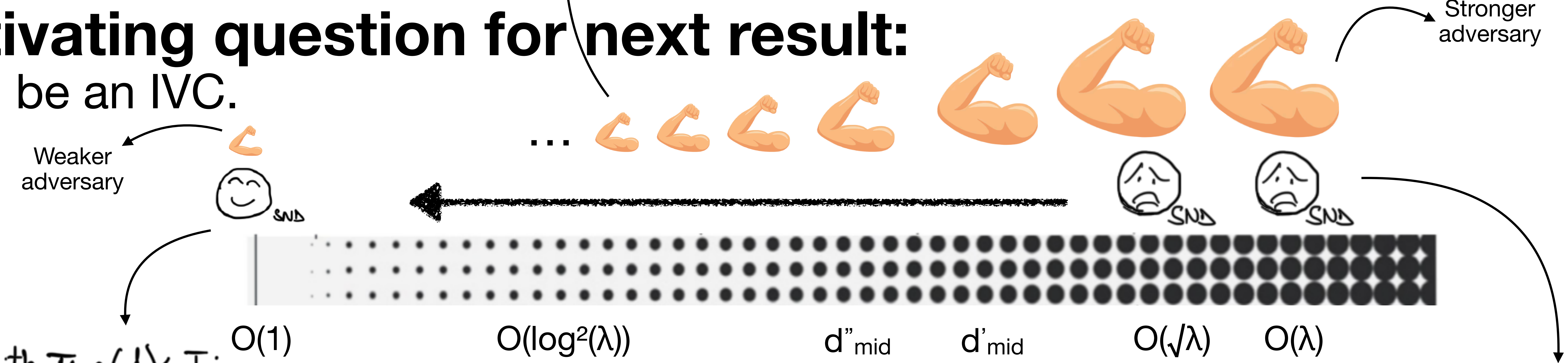

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FOR poly $p(\cdot)$, INFINITELY MANY λ-s

Our Results (continued)

Q: Can an IVC exhibit it?

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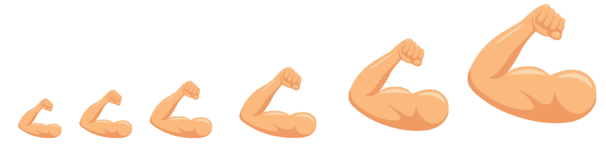 ≈ better and better inverse poly-s

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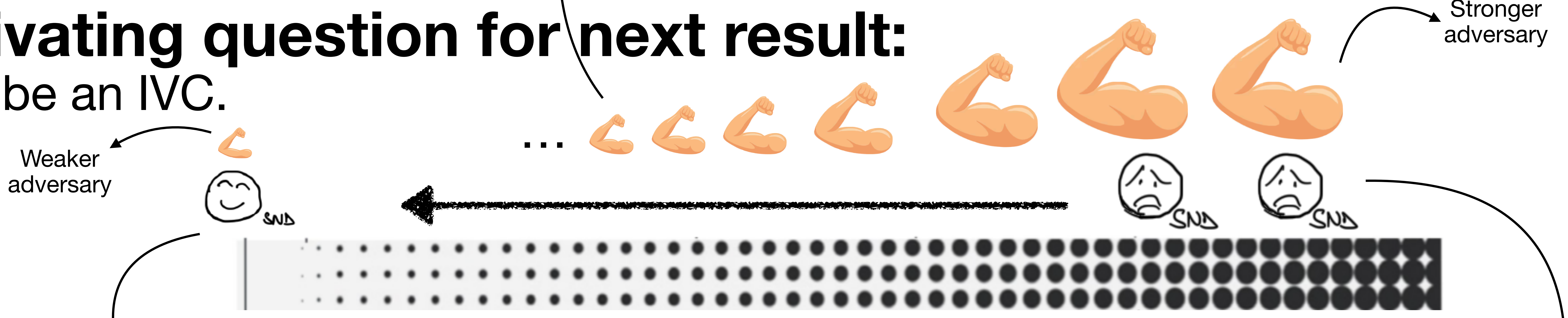

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Case 2: insecure somewhere.

Result ("no free snack" theorem):

Let Π be an IVC. Then:

Our Results (continued)

Q: Can an IVC exhibit it?

We call this (potential) pattern in IVC **graceful security degradation**

A practical framing around graceful sec. degradation:

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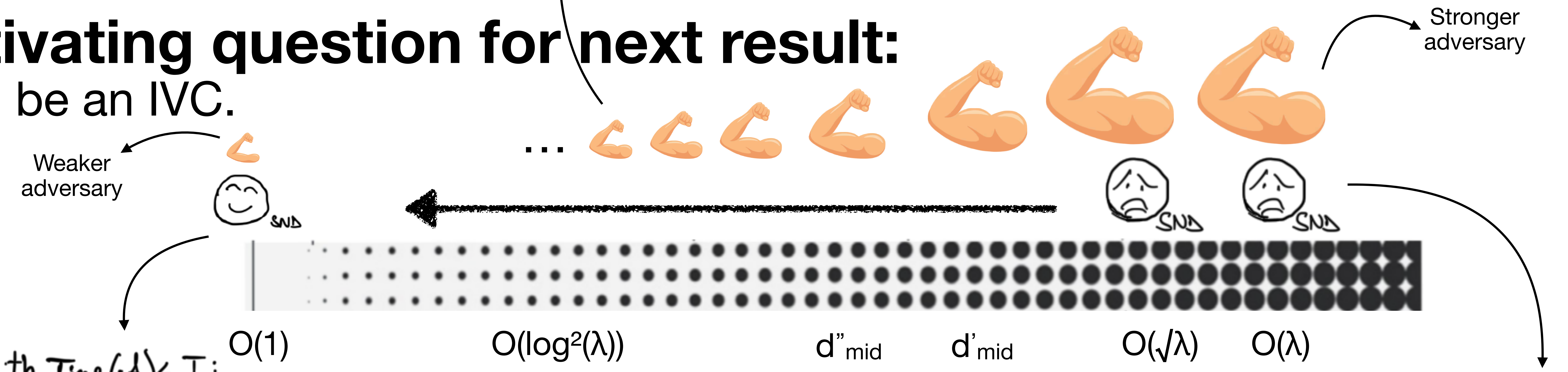

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FOR poly $p(\cdot)$, INFINITELY MANY λ-s

Case 2: insecure somewhere.

Result ("no free snack" theorem):

Let Π be an IVC. Then:

- **<u>either</u> Π is secure at arbitrary polynomial depths,**

Our Results
(continued)

Q: Can an IVC exhibit it?

We call this (potential) pattern in IVC **graceful security degradation**

A practical framing around graceful sec. degradation:

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Motivating question for next result:

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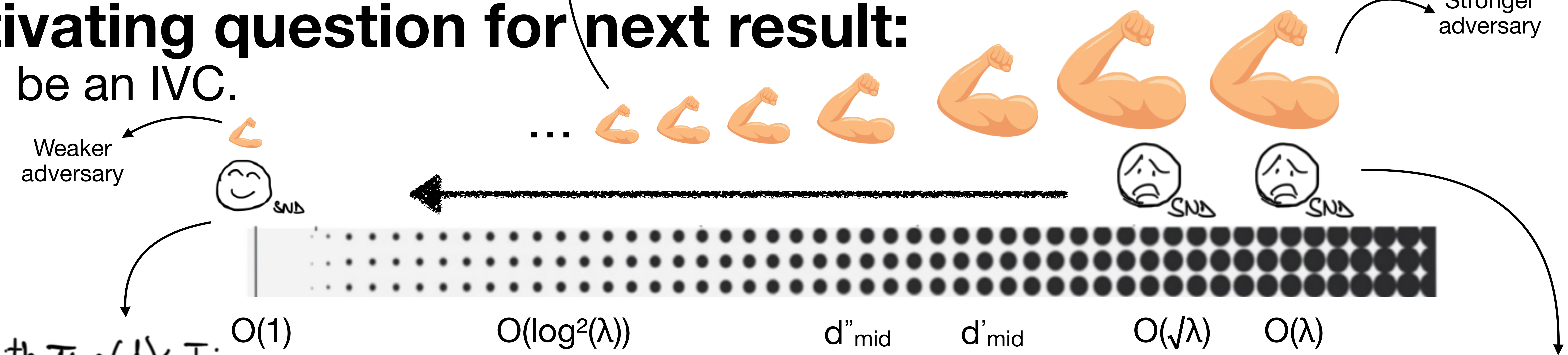

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FOR poly $P(\cdot)$, INFINITELY MANY λ-s

Case 2: insecure somewhere.

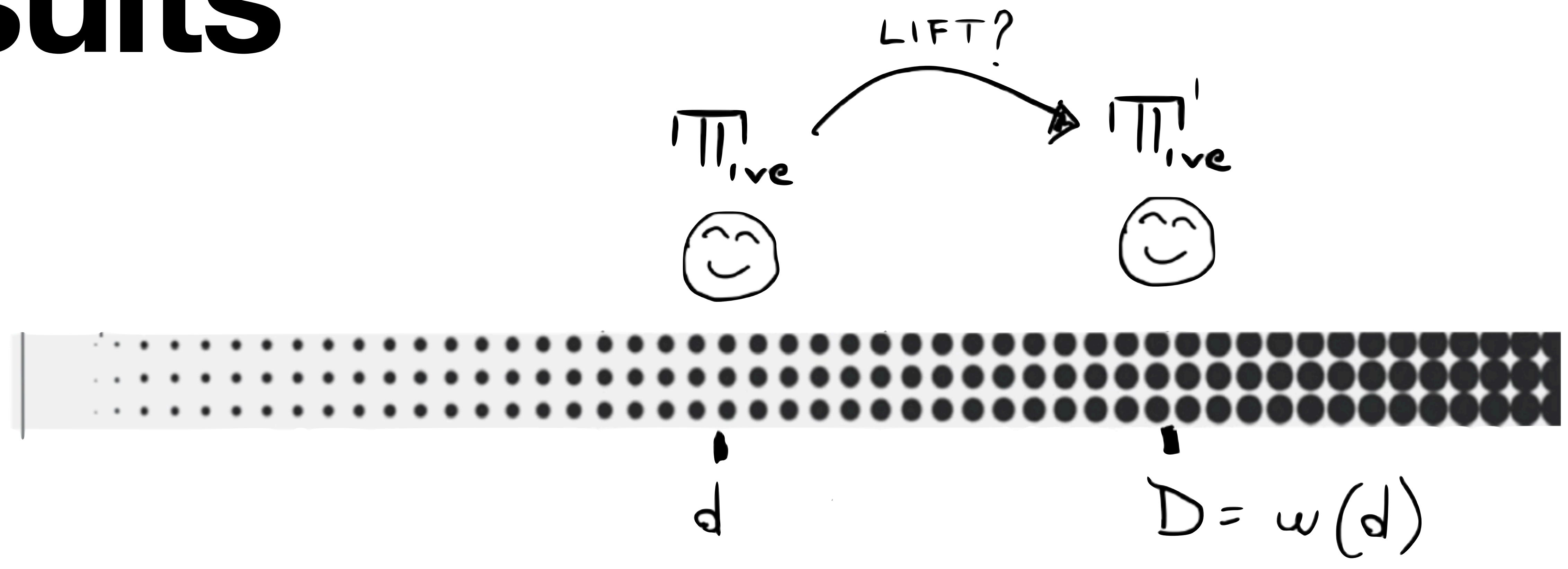
Result ("no free snack" theorem):

Let Π be an IVC. Then:

- **<u>either</u> Π is secure at arbitrary polynomial depths,**
- **<u>or</u> Π <u>cannot</u> exhibit graceful security degradation.**

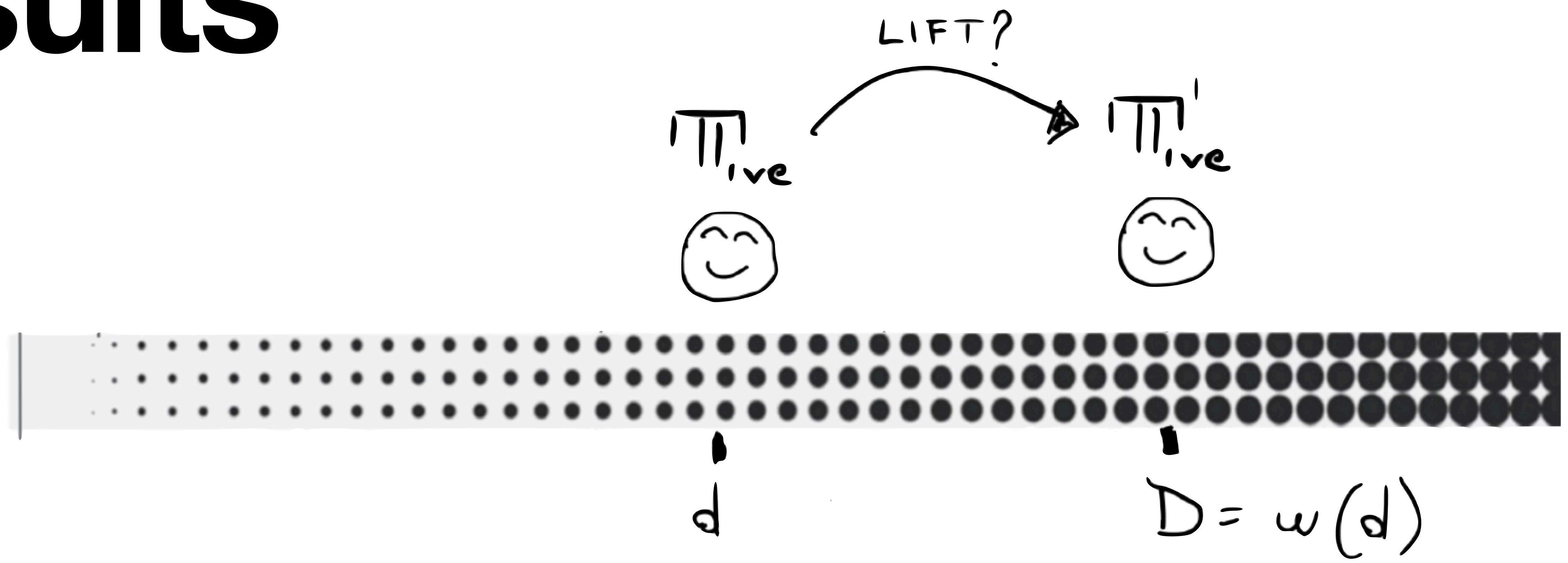
Our Results
(continued)

Our Results
(continued)



Our Results
(continued)

NB: We are interested in:
- <u>black-box</u> lifting results,
- and that preserve performance.



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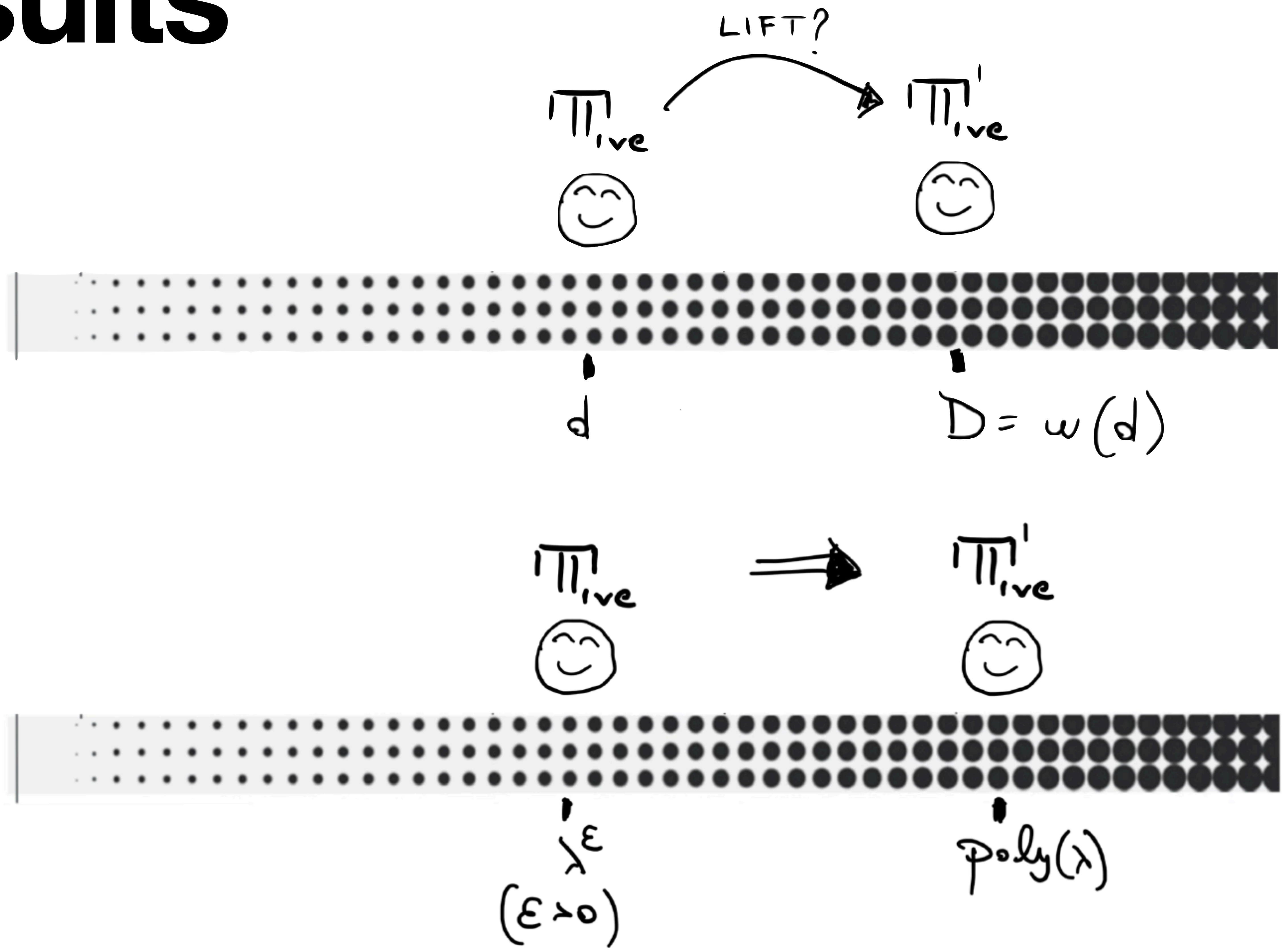

Our Results
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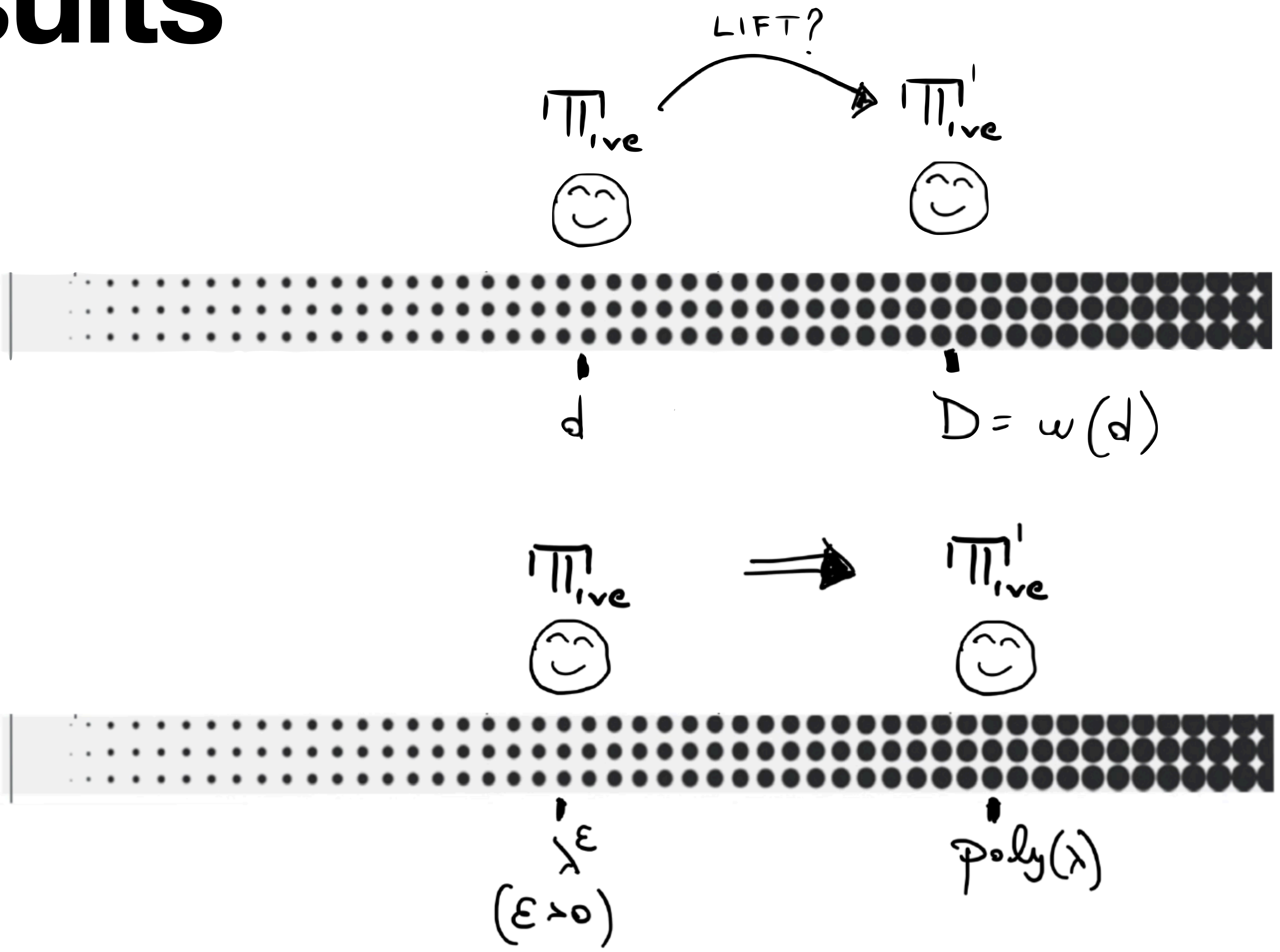

Theorem (sublinear depths):

∃ IVC Π SND at depth λ^{ε} (for some ε>0)
⇒ ∃ IVC Π' SND at arbitrary depth.

Overhead for P/V/proof size in Π' is $O_{\lambda}(1)$.

Our Results

(continued)

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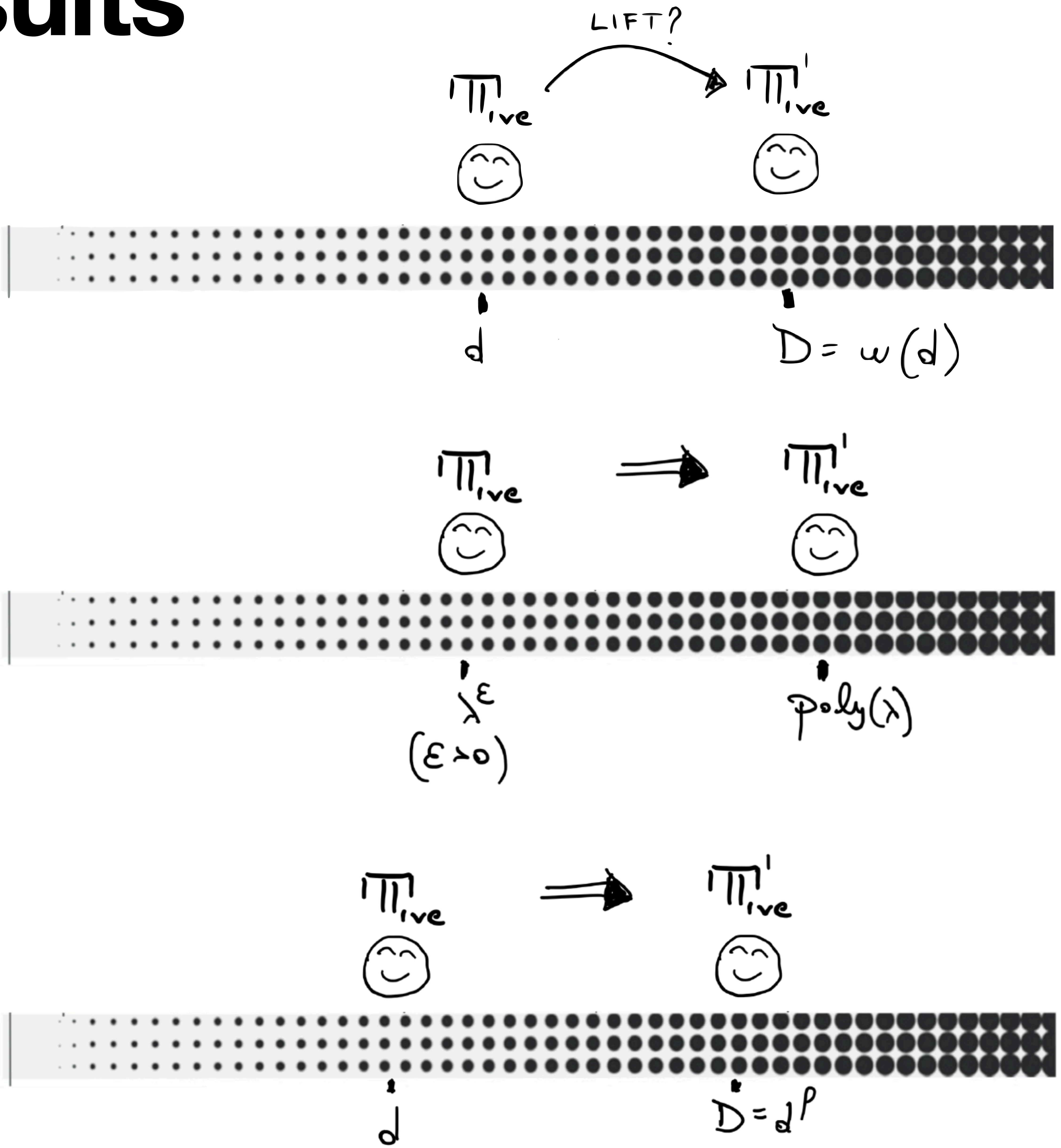

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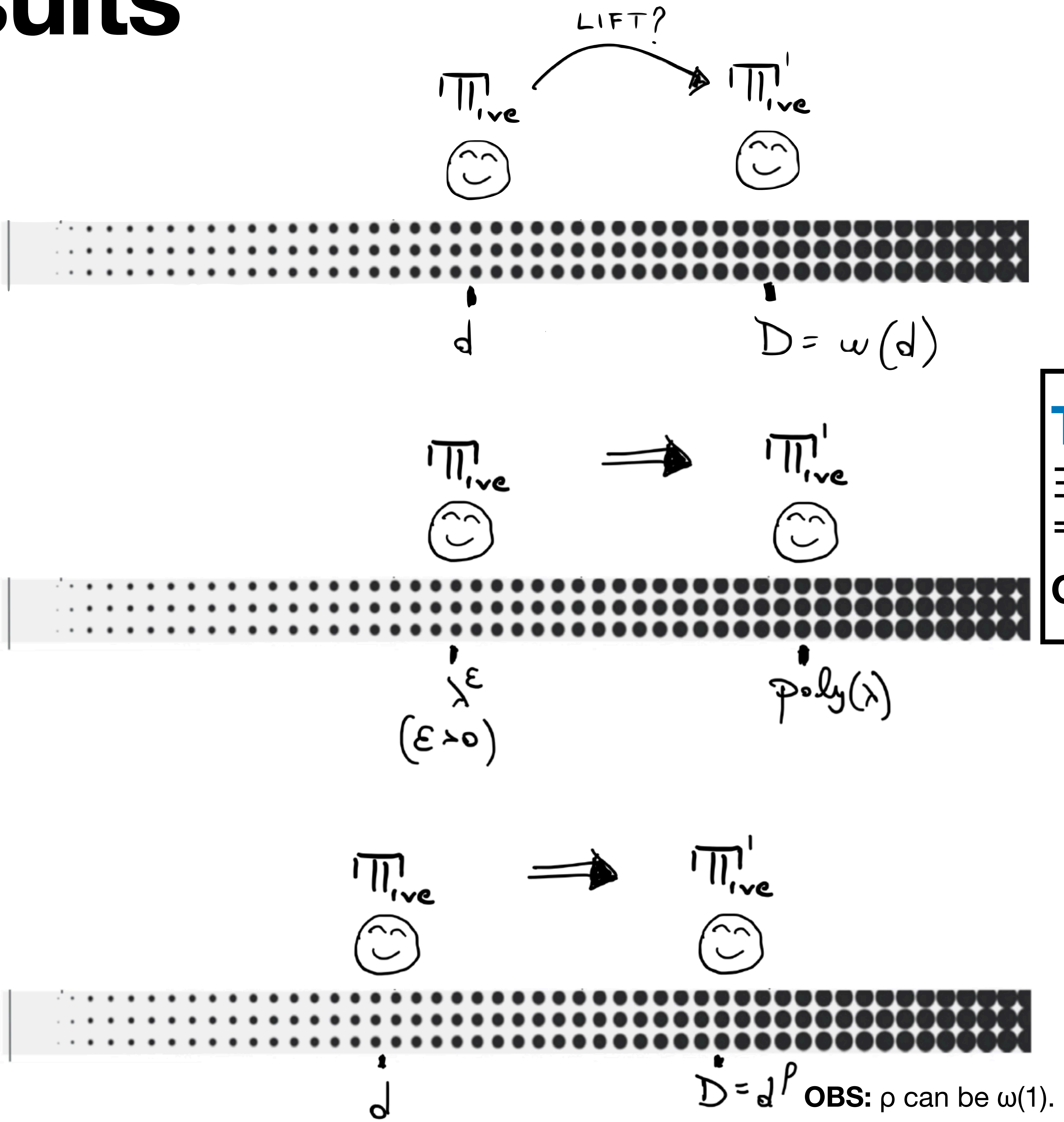

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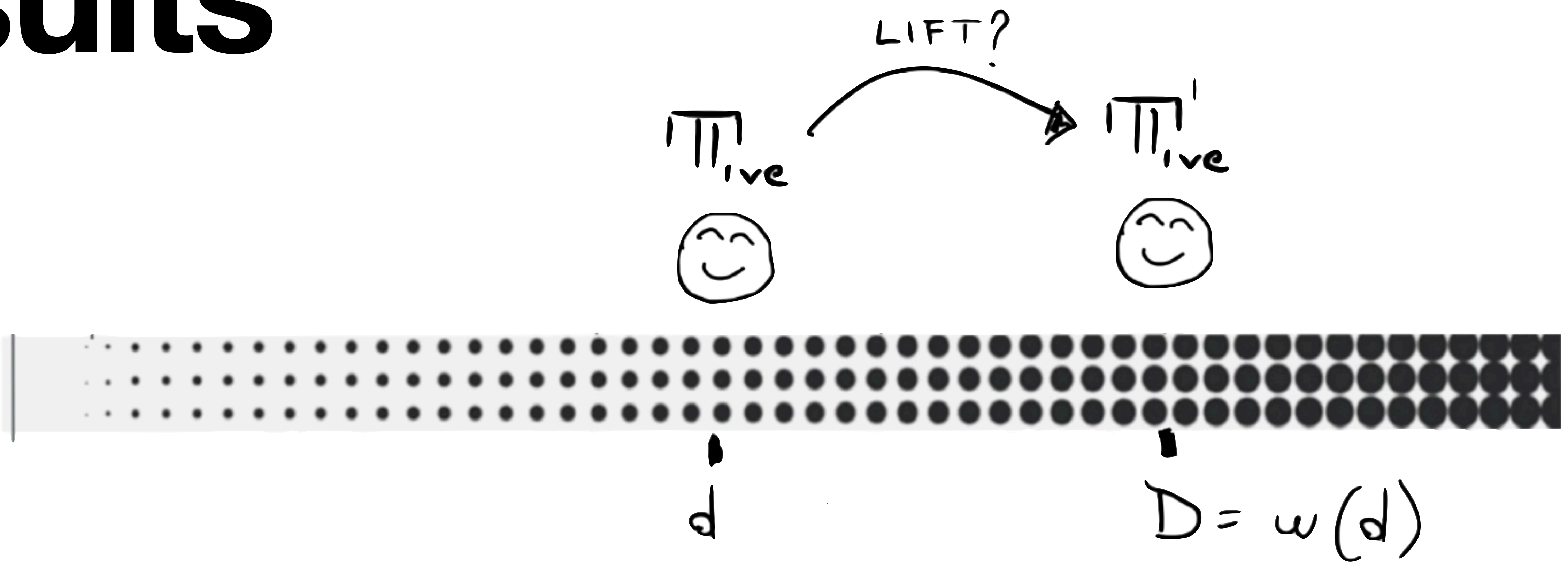

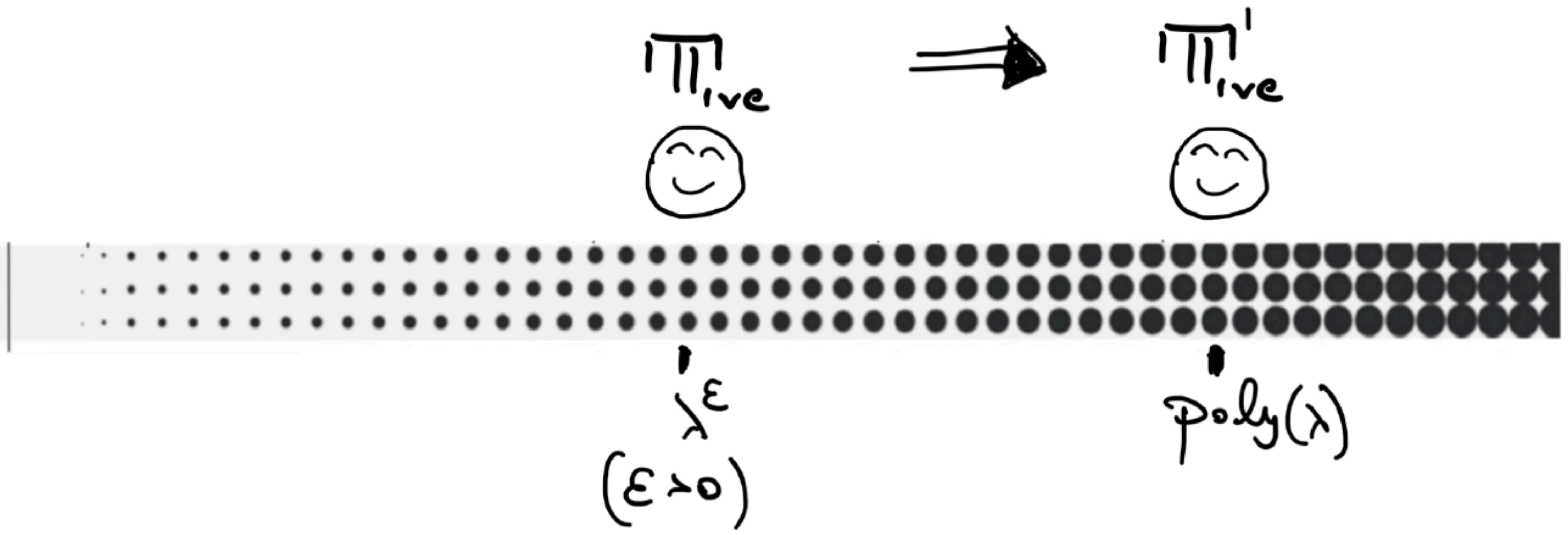

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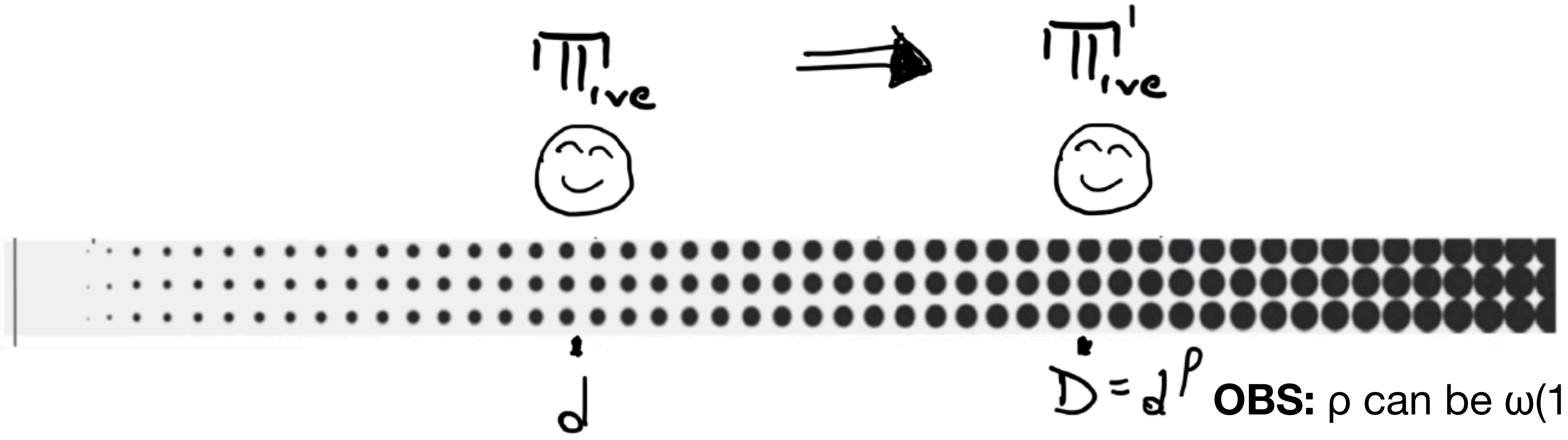

OBS: ρ can be ω(1).

Theorem (general lifting):
∃ IVC Π SND at depth d
⇒ ∃ IVC Π' SND at depth $D = d^{\rho}$.

Overhead* for P/V/proof size in Π' is $O_\lambda(\rho)$

Our Results
(continued)

NB: We are interested in:
- black-box lifting results,
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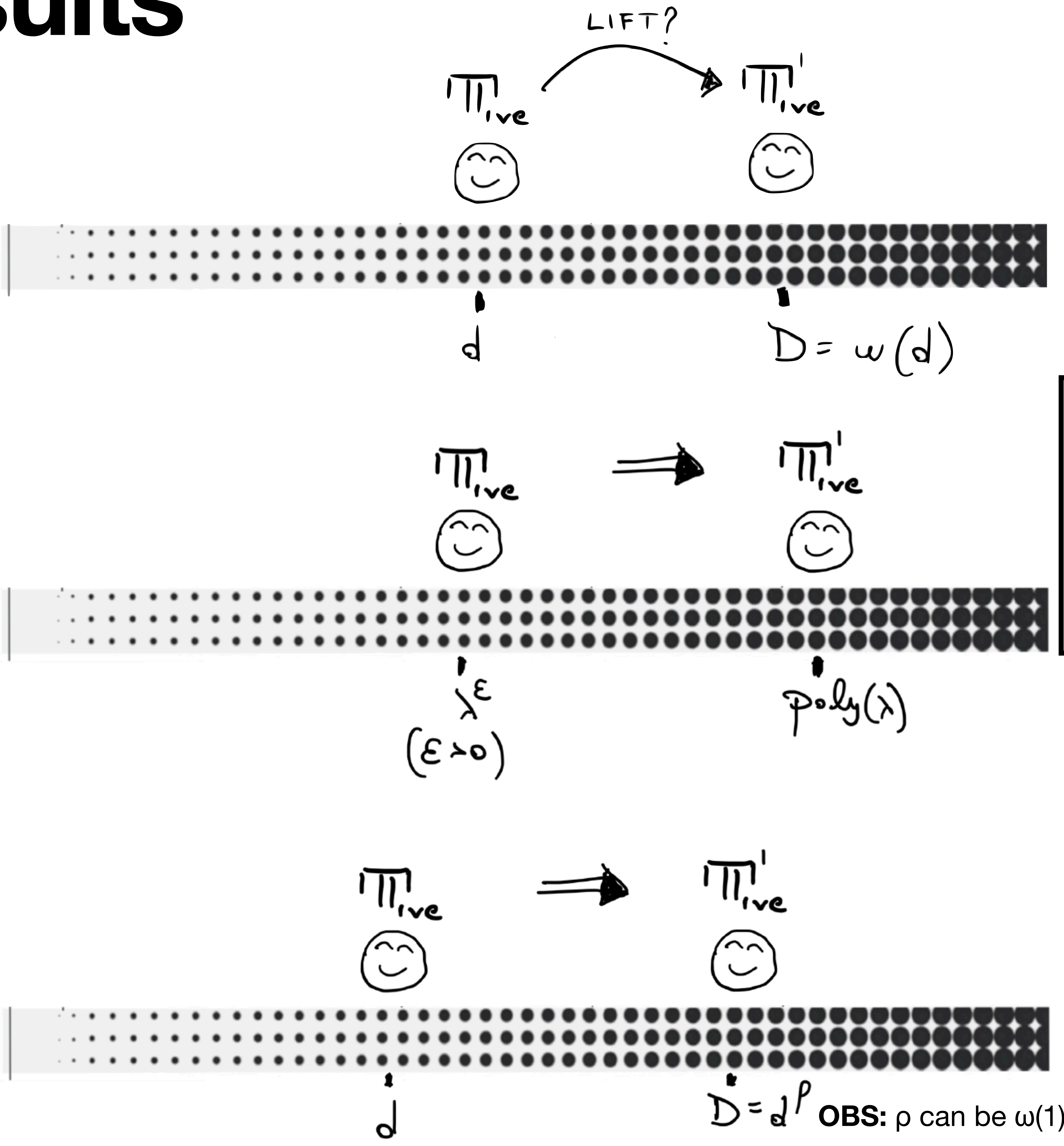

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⇒ ∃ IVC Π' SND at arbitrary depth.

Overhead for P/V/proof size in Π' is $O_\lambda(1)$.

Theorem (general lifting):

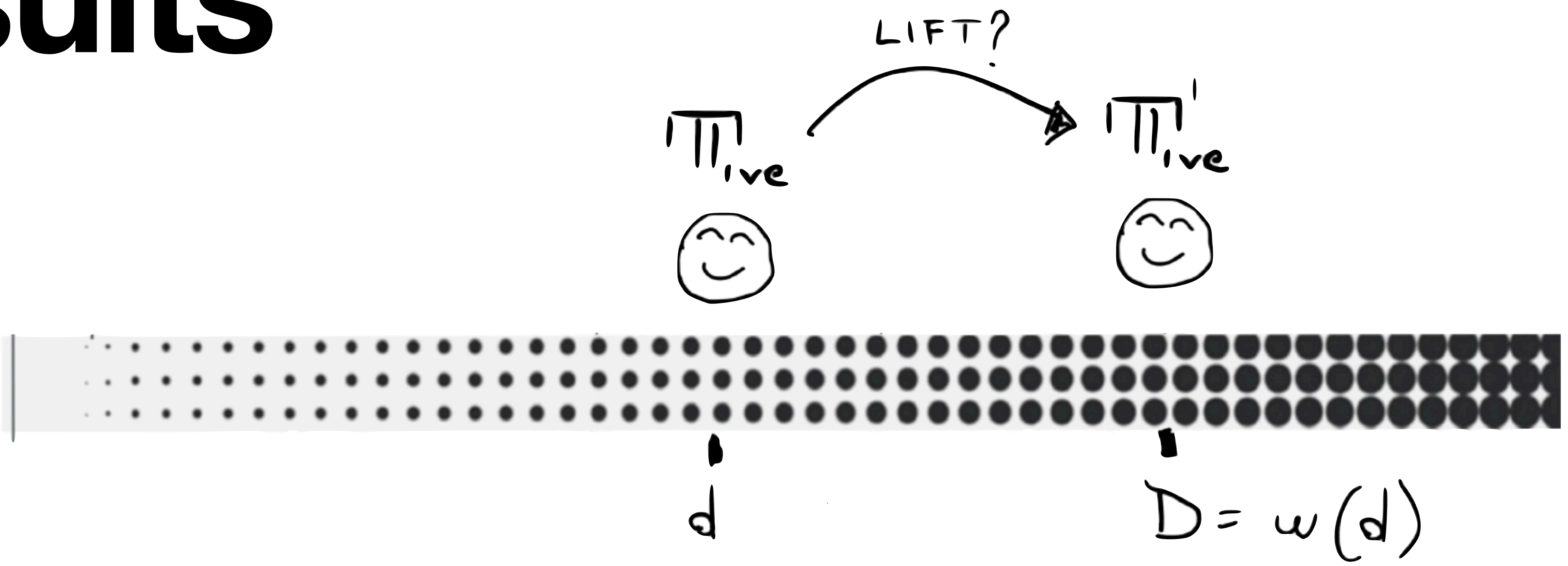
∃ IVC Π SND at depth d
⇒ ∃ IVC Π' SND at depth D = d^ρ.

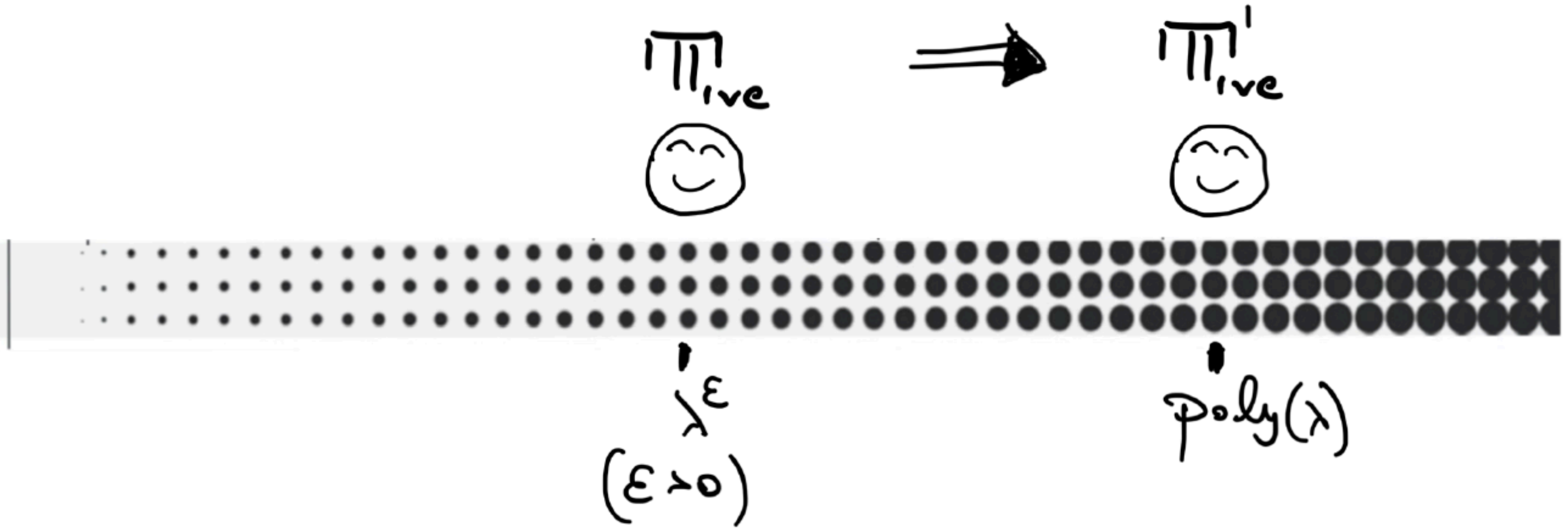
Overhead* for P/V/proof size in Π' is $O_\lambda(\rho)$

*: amortized prover time; applies for linear $T_P(\Pi)$
(if not linear additional polylog overhead).

Our Results
(continued)

NB: We are interested in:
- black-box lifting results,
- and that preserve performance.





Theorem (sublinear depths):
∃ IVC Π SND at depth λ^{ε} (for some $\varepsilon>0$)
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Corollary:
∃ IVC SND at O(1) ⇒
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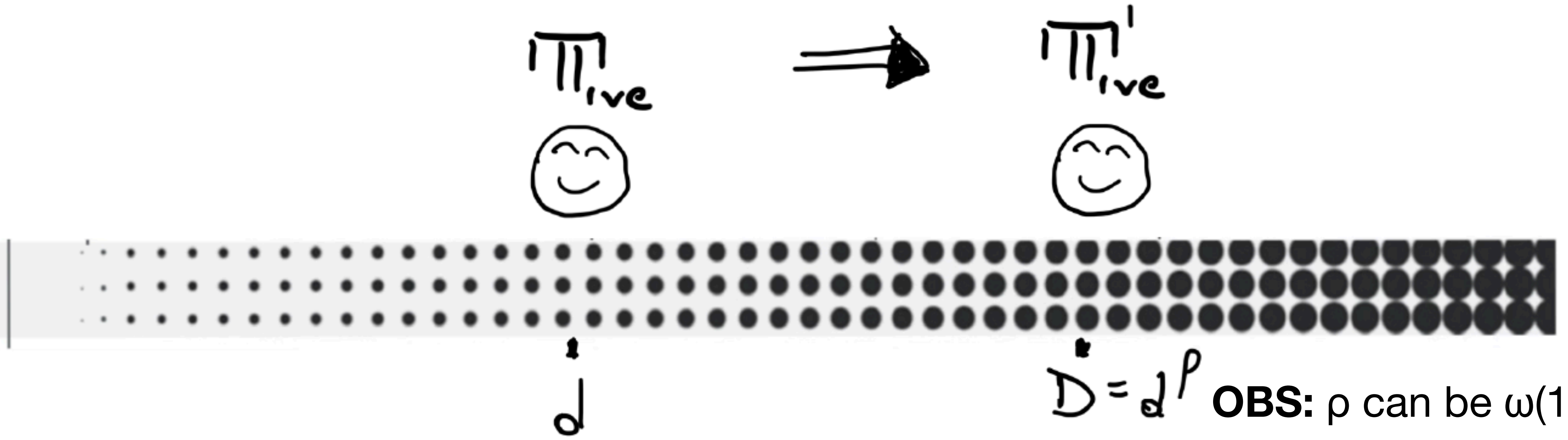

OBS: ρ can be ω(1).

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(continued)

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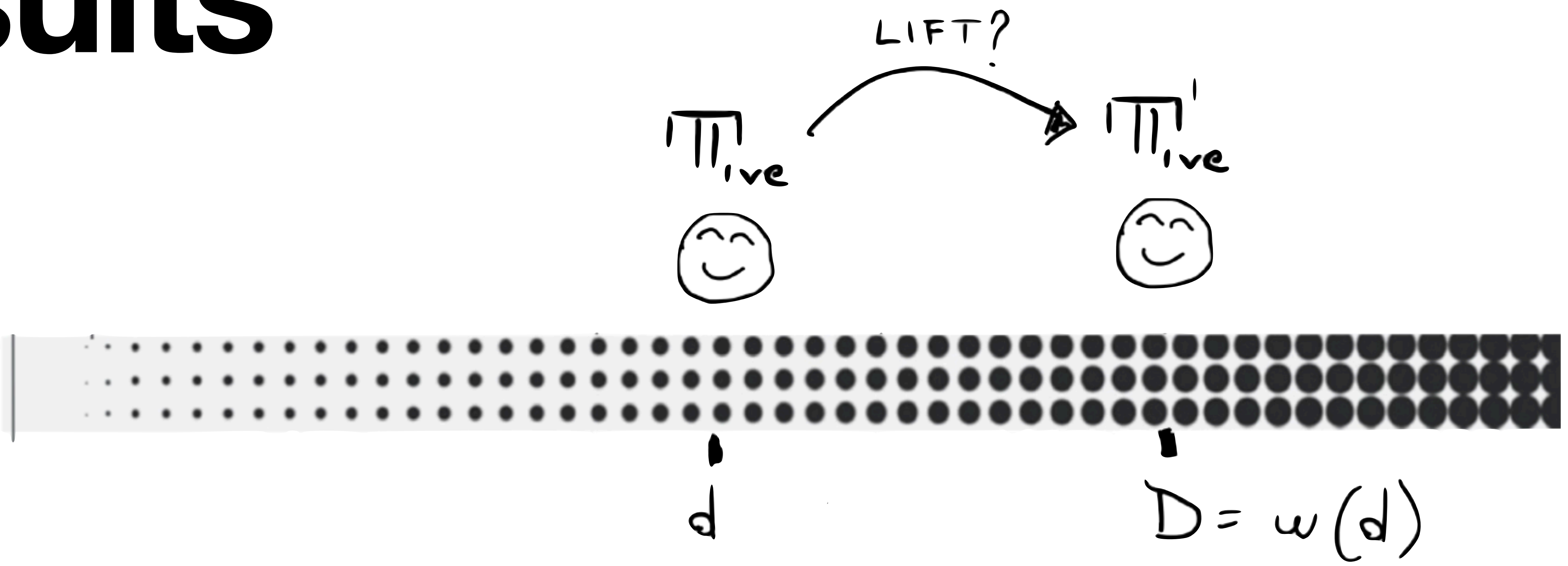

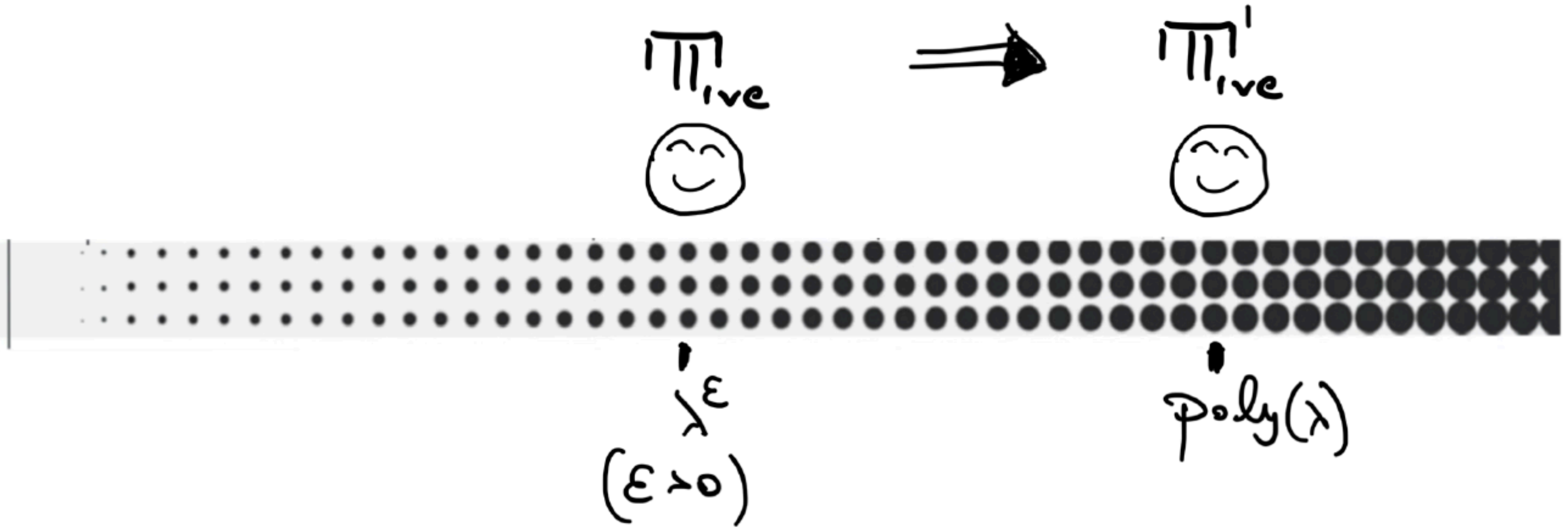

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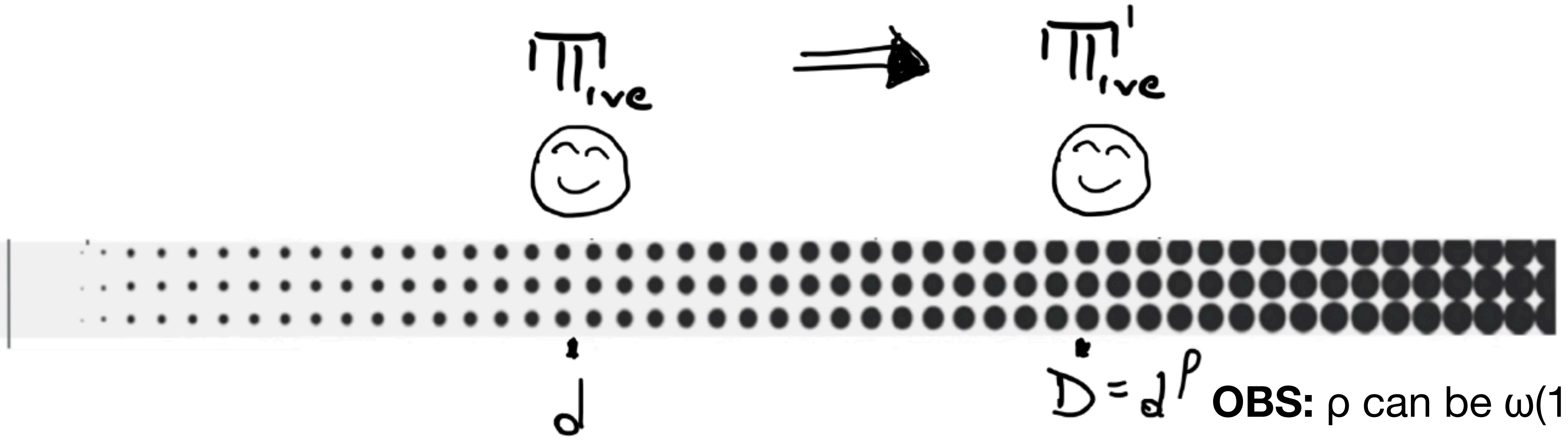
↑

Special case: d = O(1); ρ = O(logλ)



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When Do Our Results Apply?

For what security notions do they hold?

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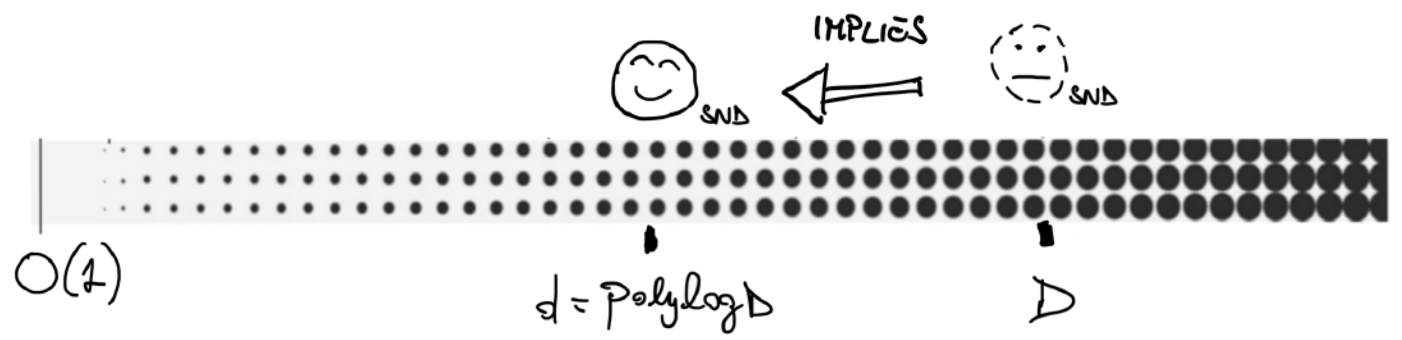
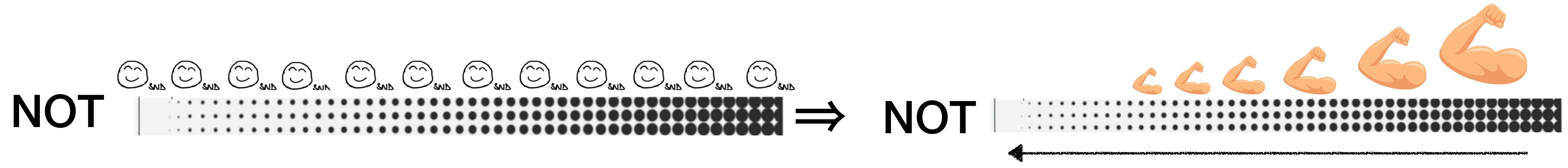
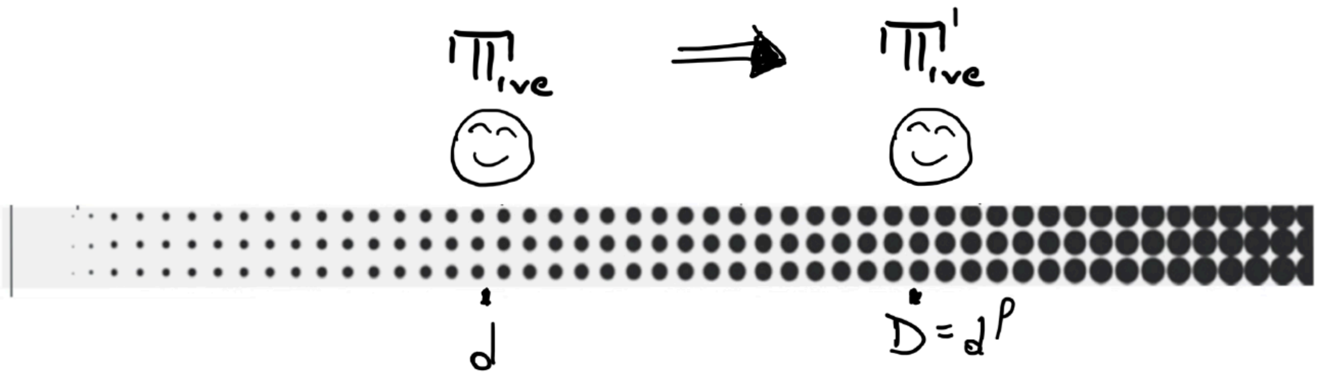


<u>Insecure IVCs cannot exhibit graceful sec. degradation</u>



<u>Black-box lifting with low overhead</u>



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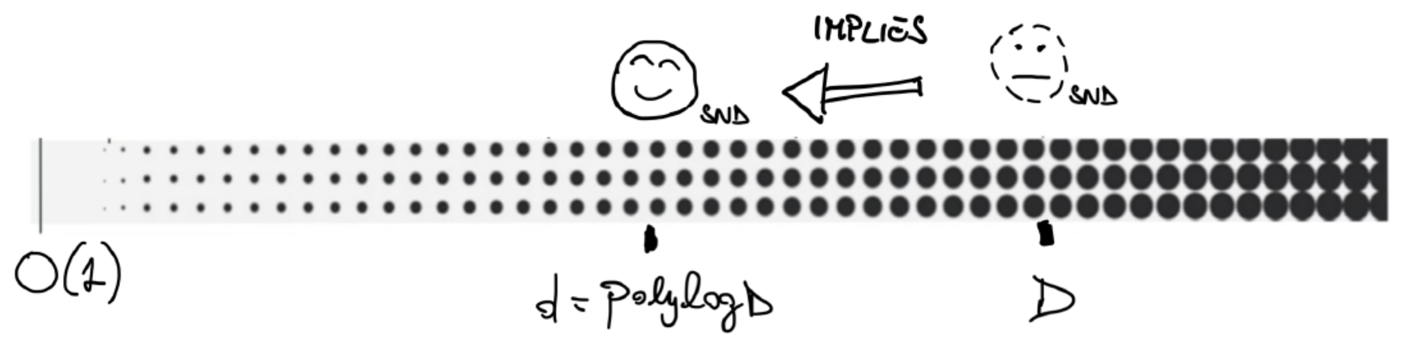

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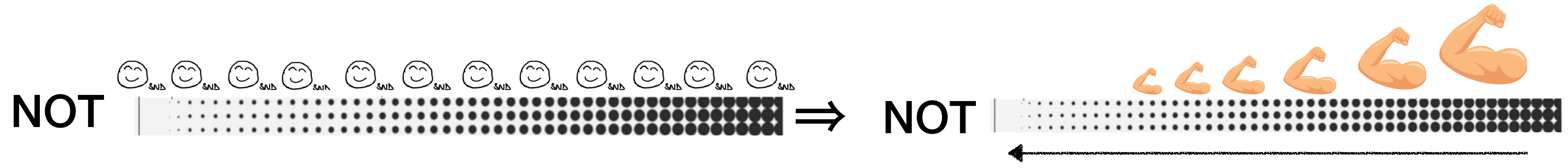

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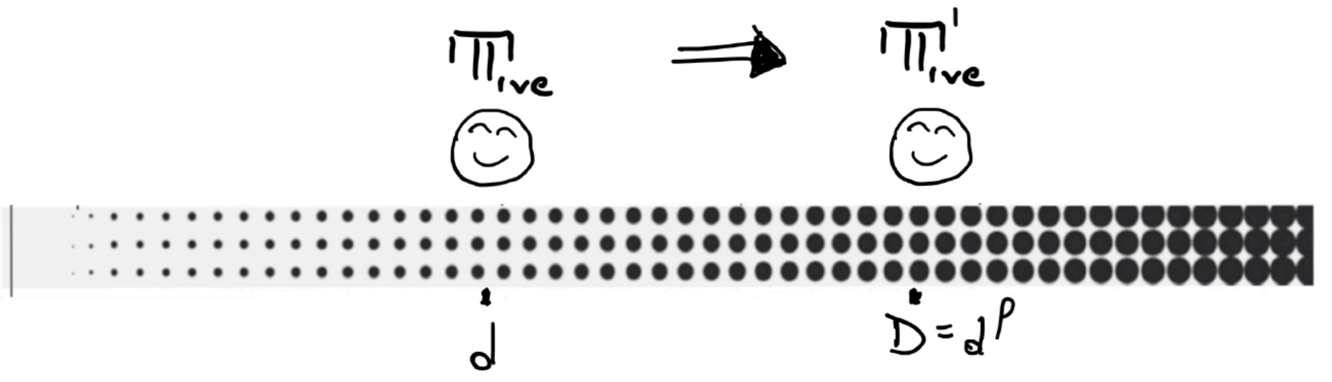

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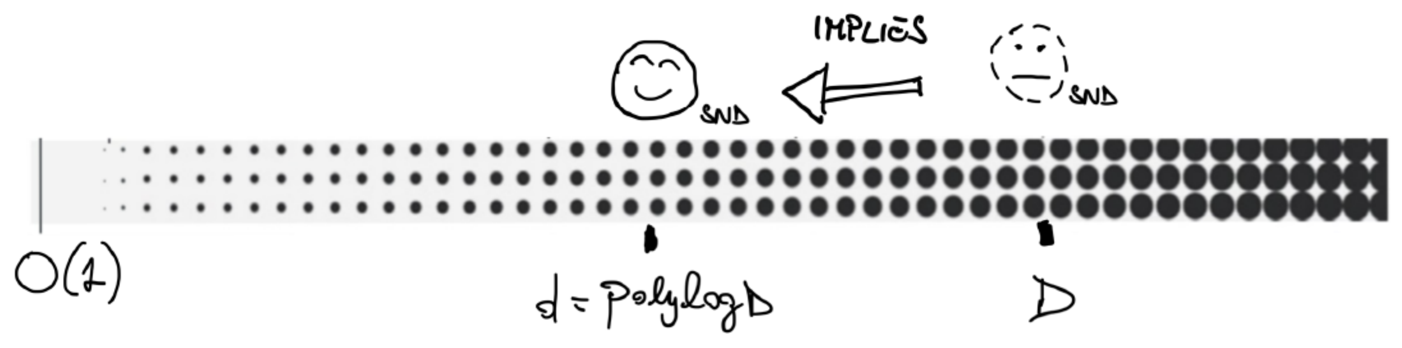

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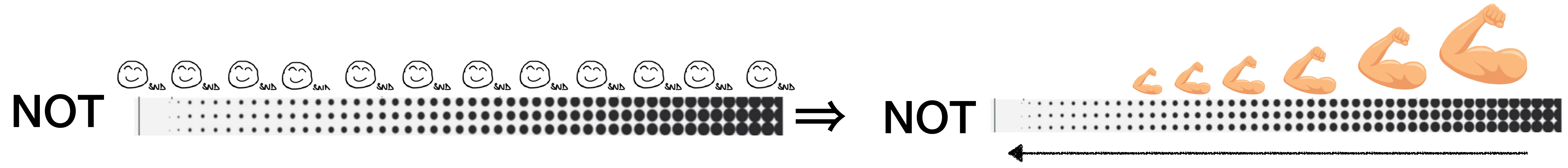

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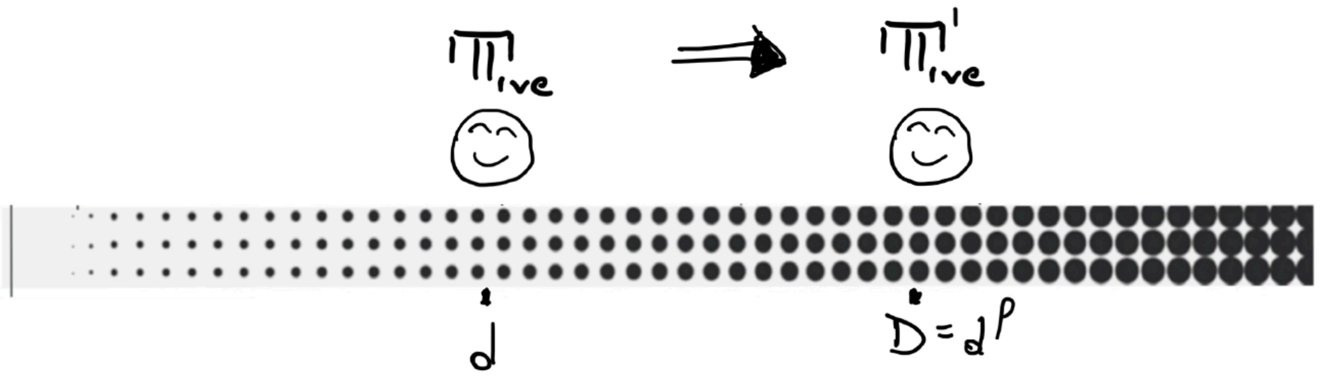

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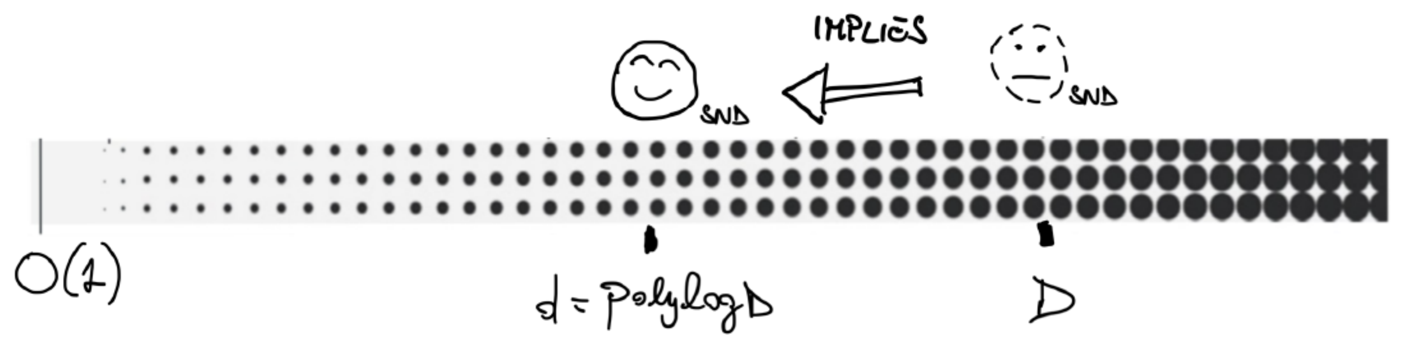

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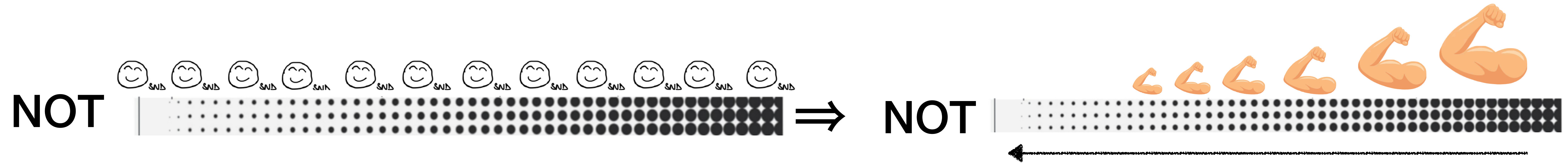

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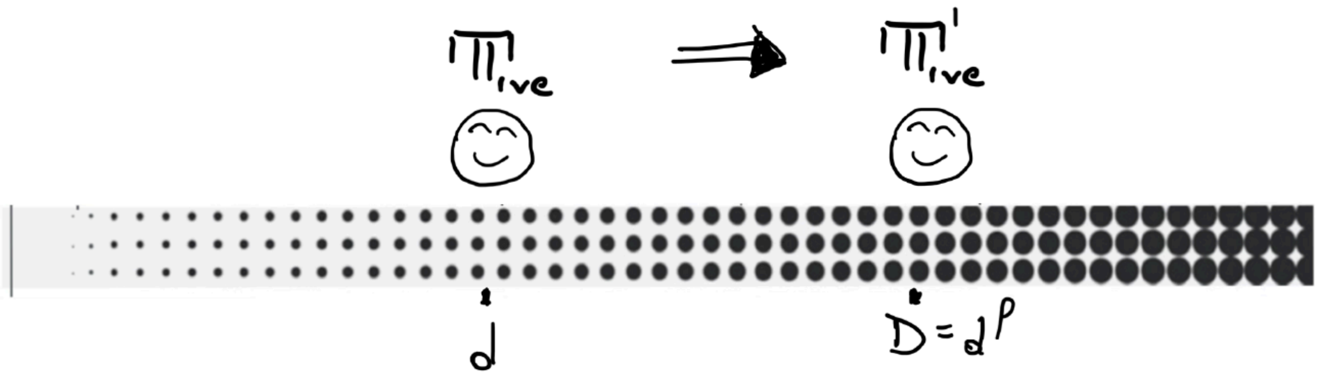

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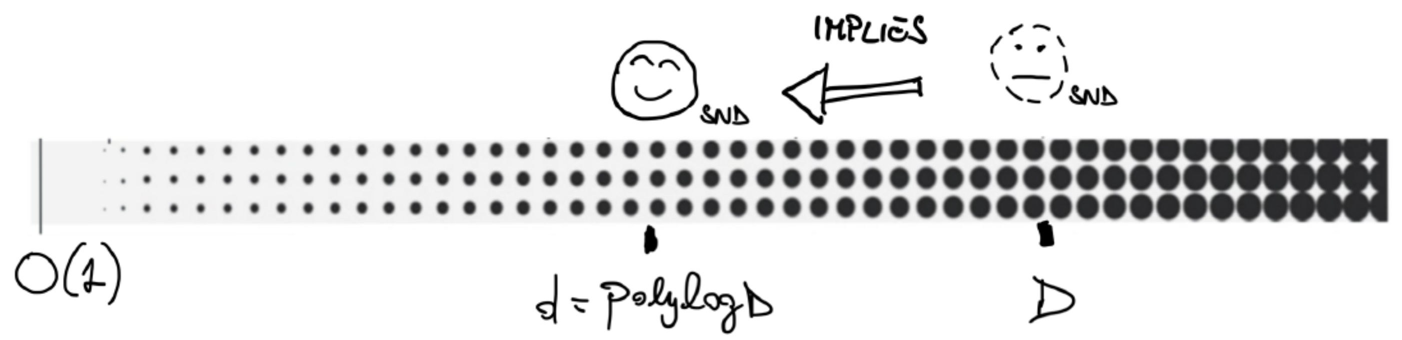

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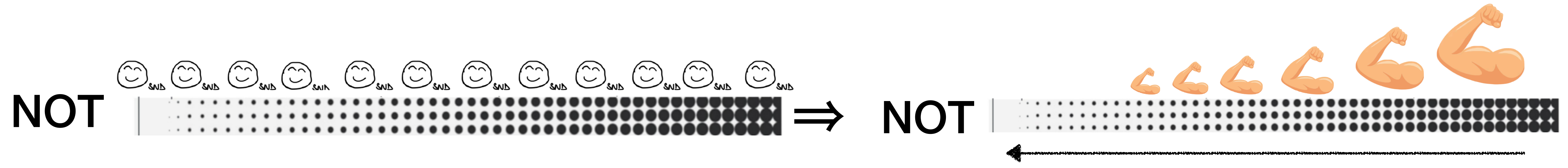

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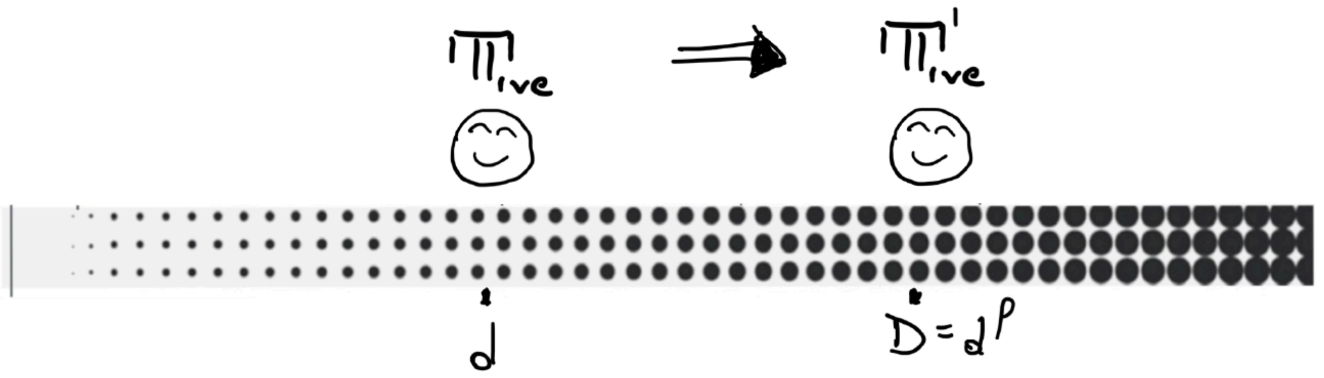

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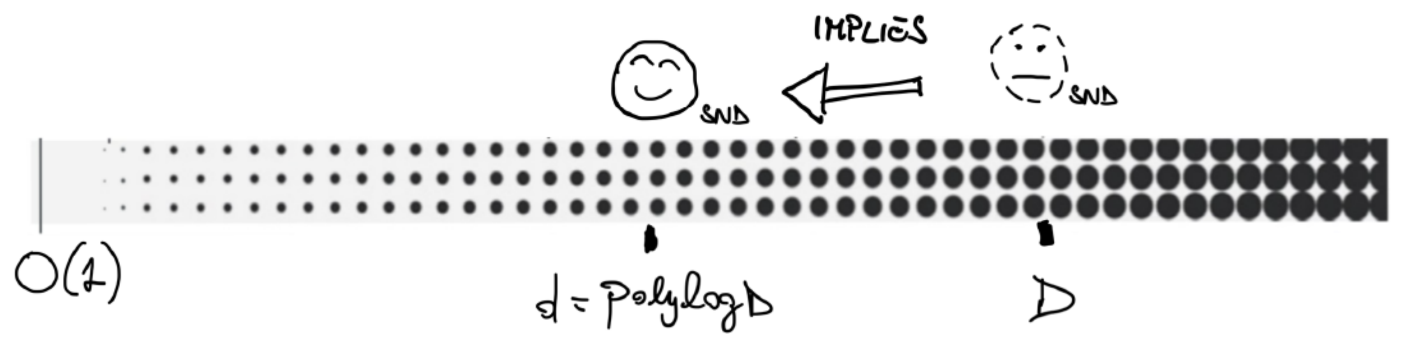

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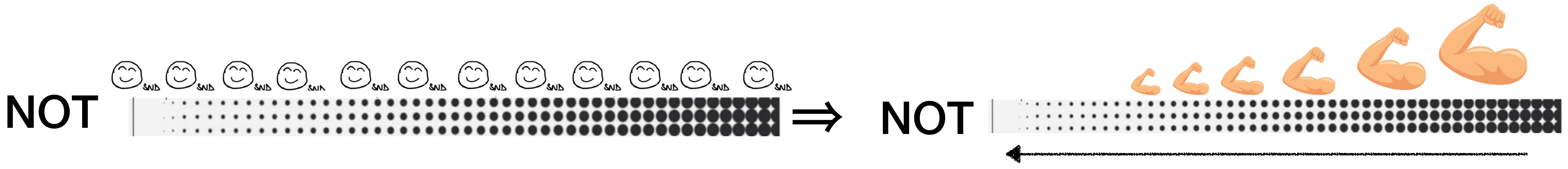

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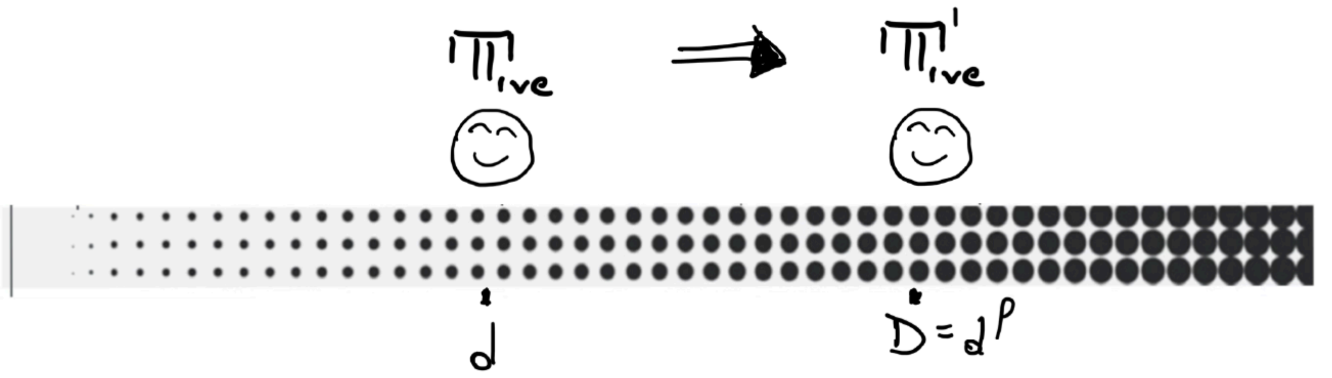

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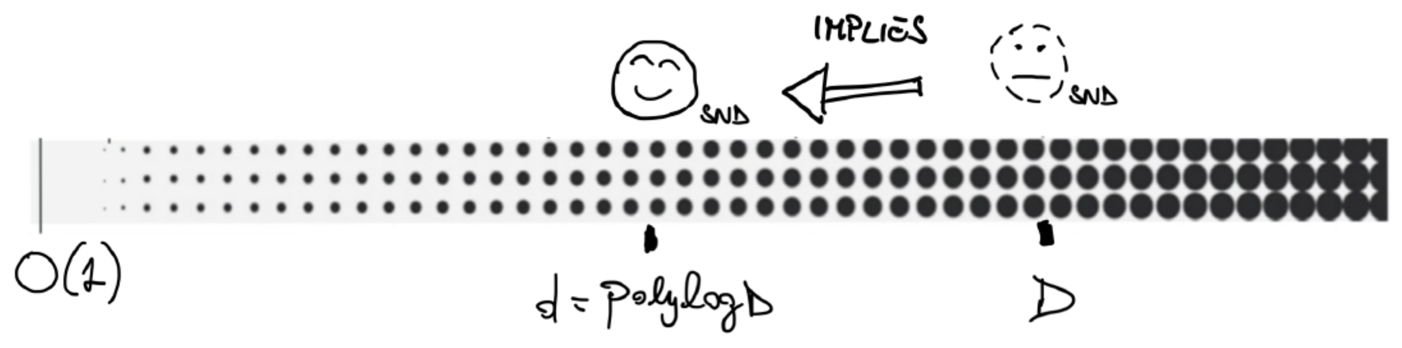

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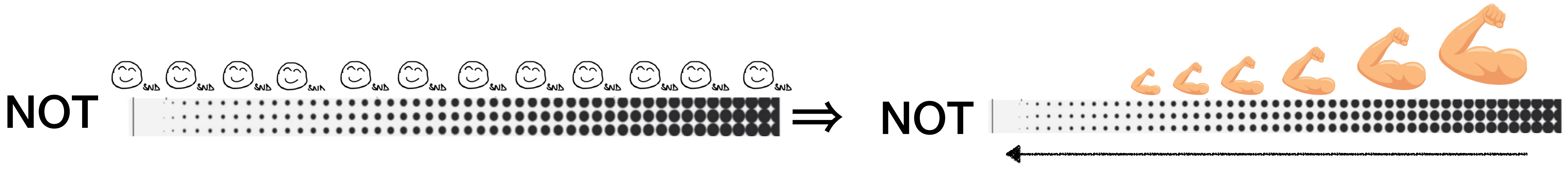

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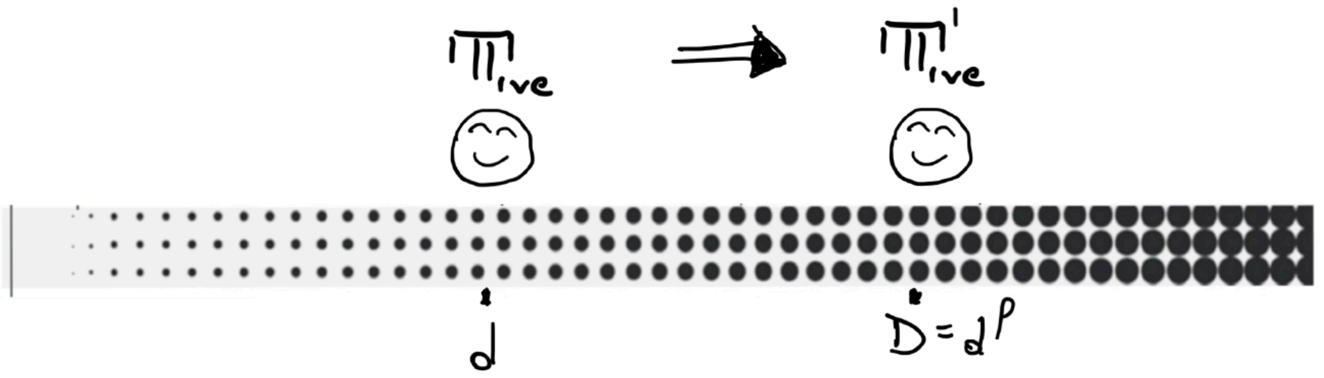

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  - the result on graceful sec. degradation does not apply mostly because definitions do not translate immediately.

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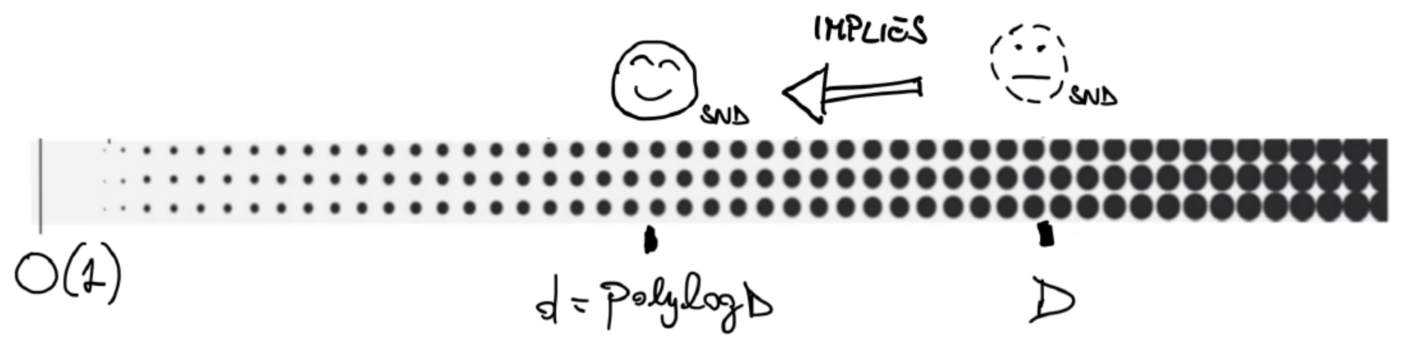

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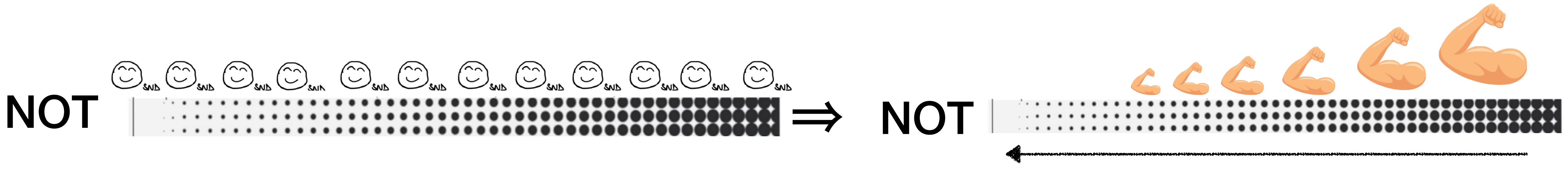

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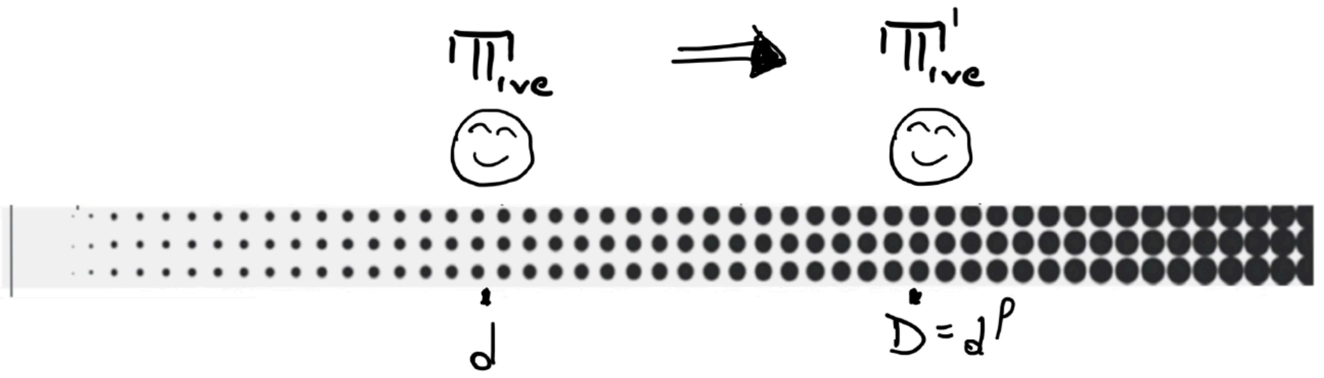

New Notion: Incremental Functional Commitments

What are Functional Commitments? (FC)

Server (Prover)

Client (Verifier)

Credit to Dario Fiore for the graphics in the center.

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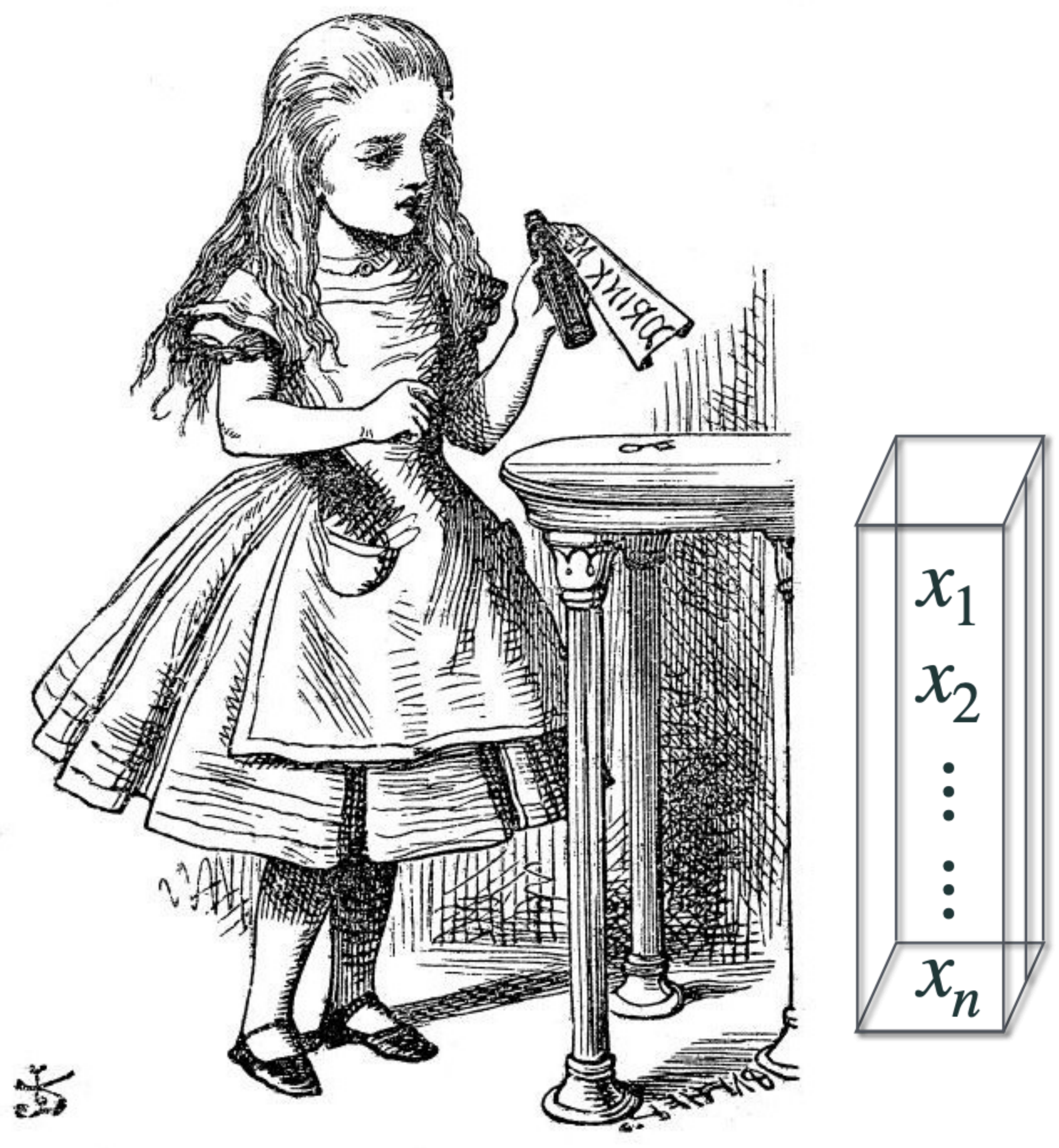

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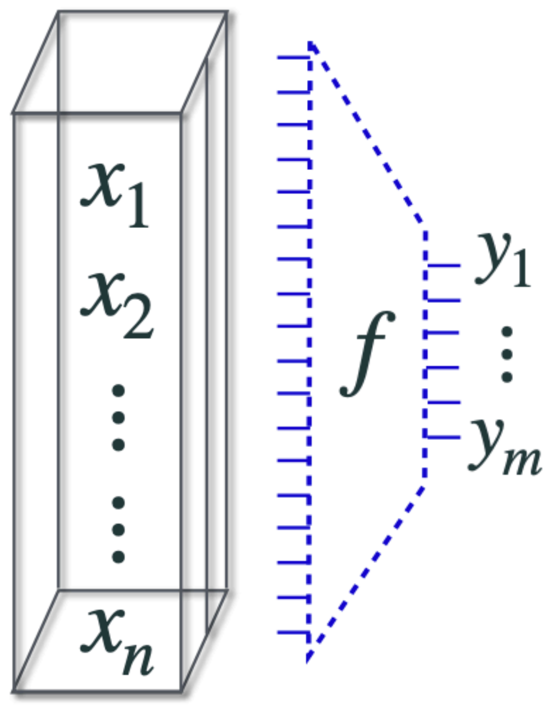

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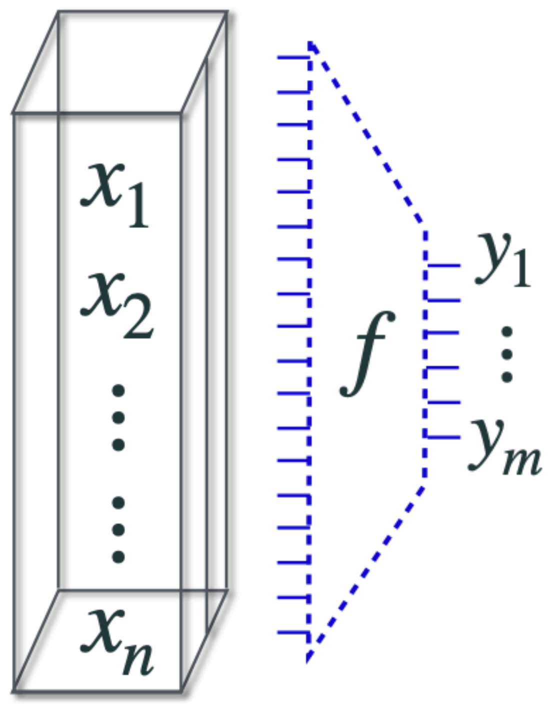

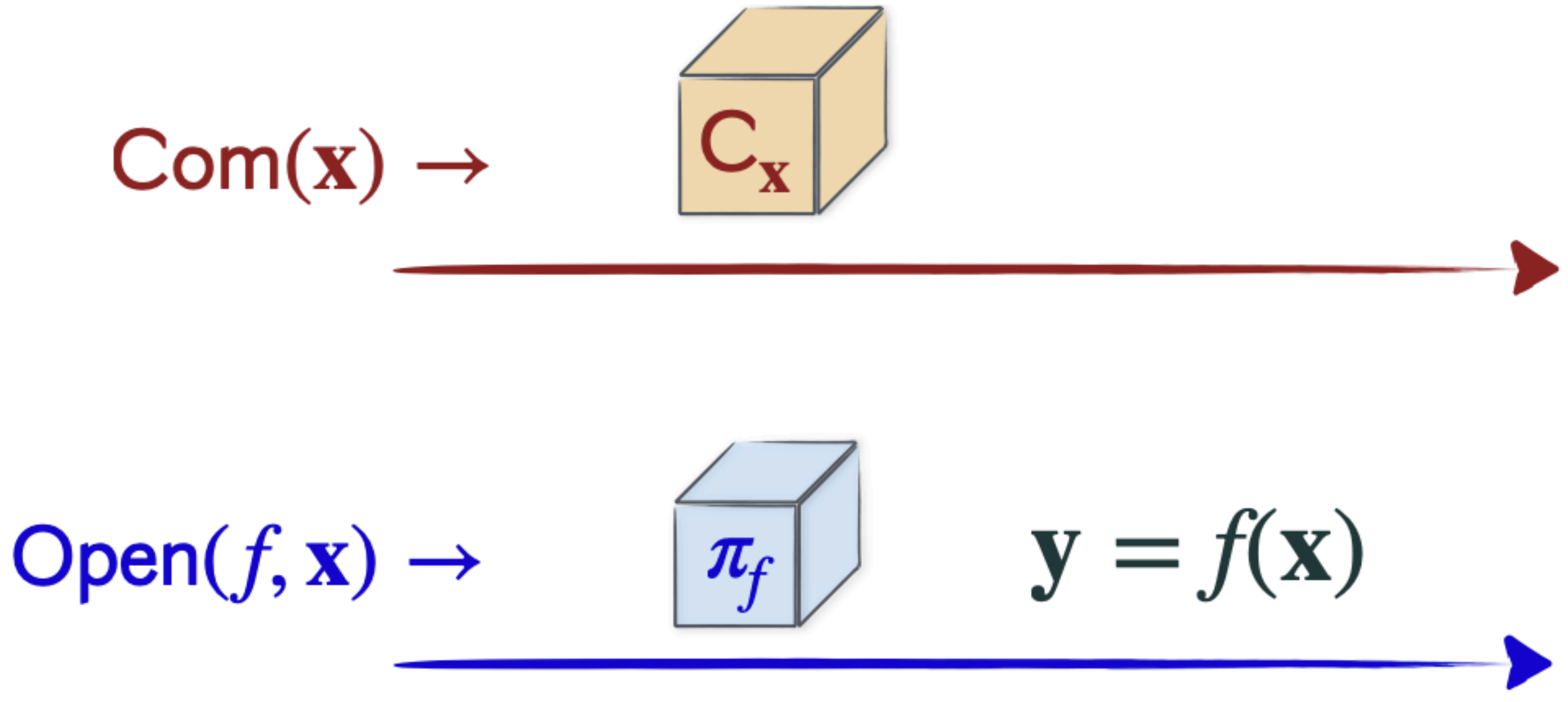

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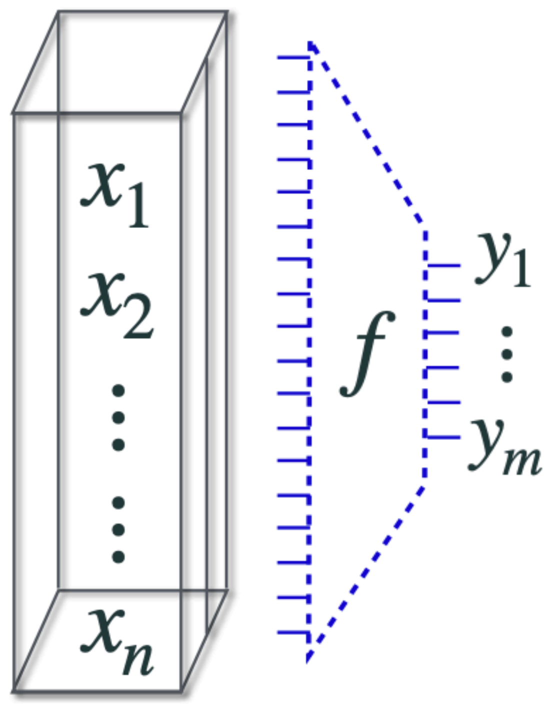

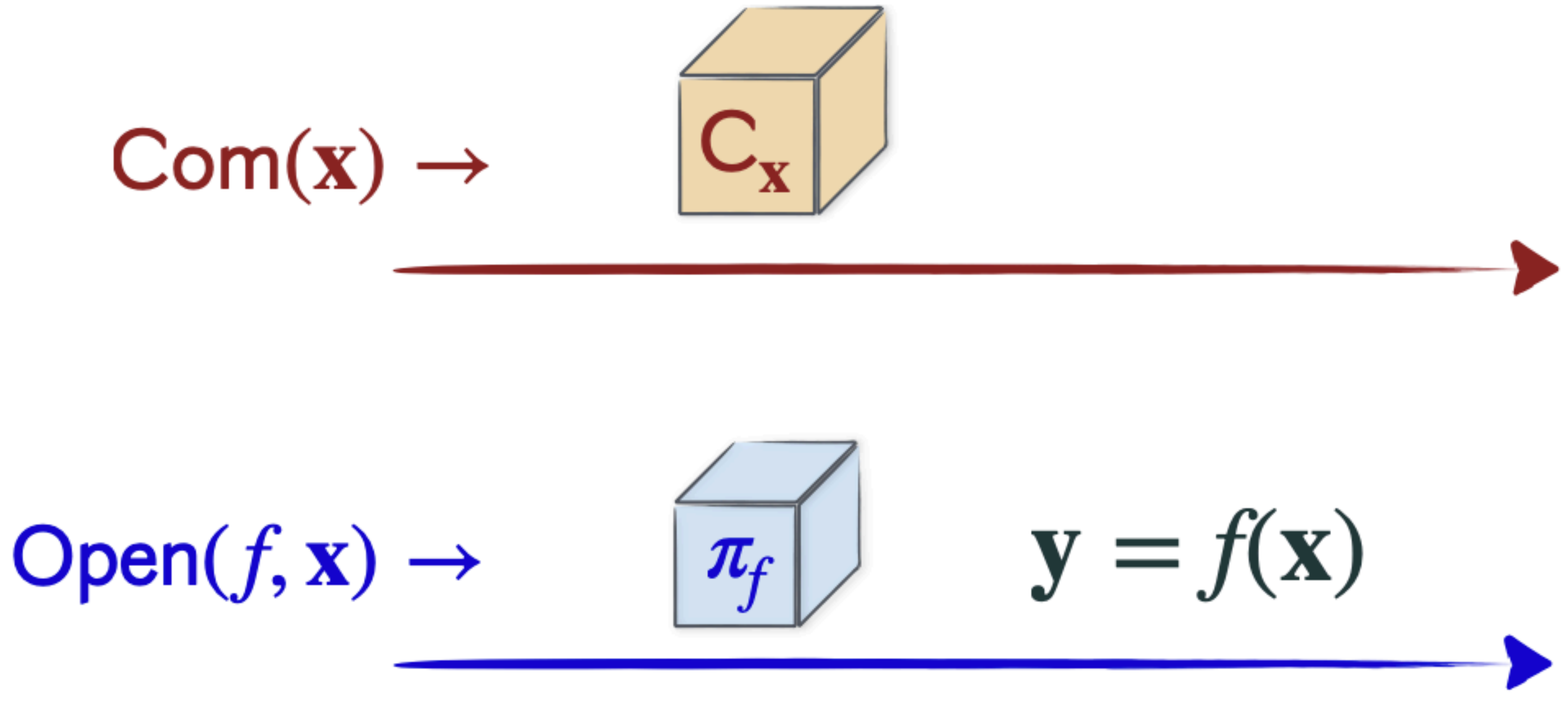

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$\mathsf{Ver}(\mathsf{C}_{\mathbf{x}}, f, \mathbf{y}, \pi_f) \stackrel{?}{=} 1$

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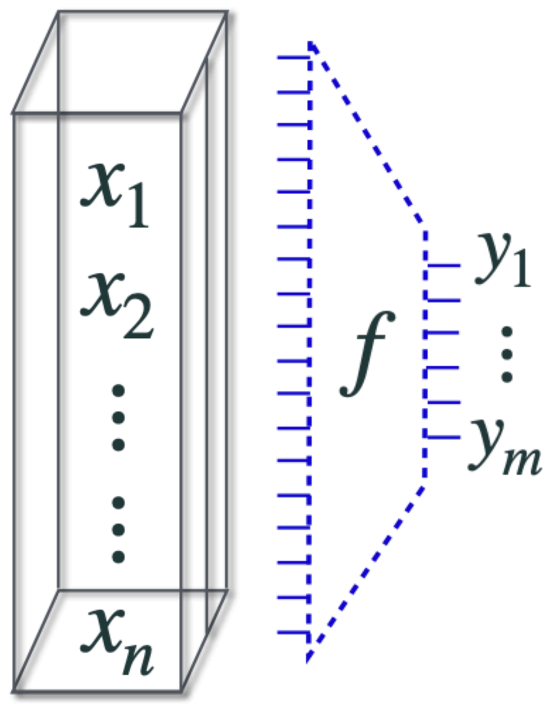

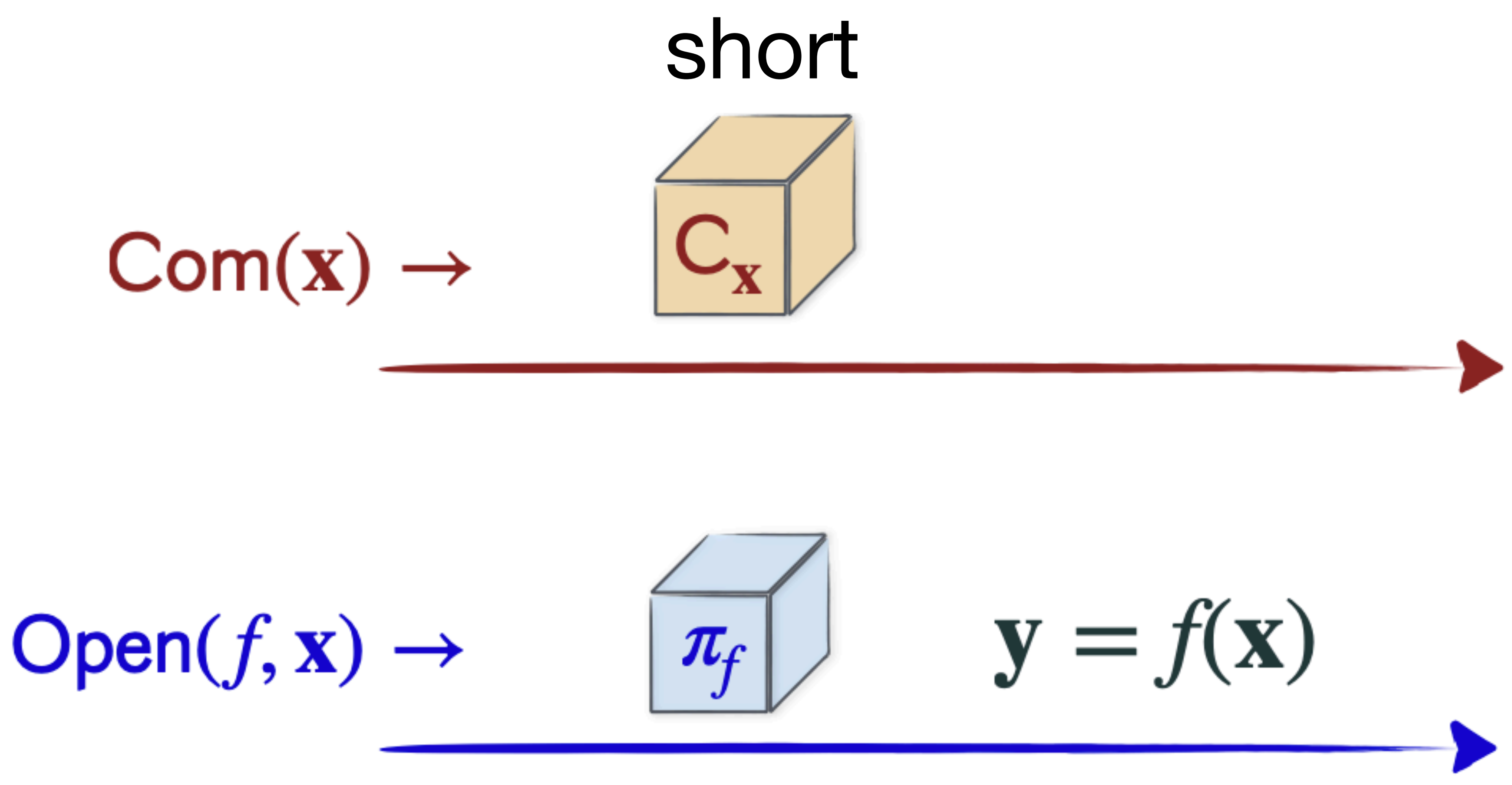

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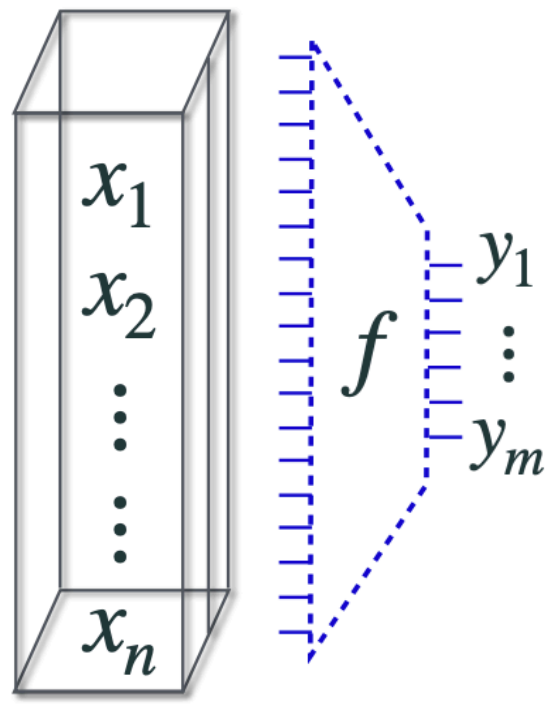

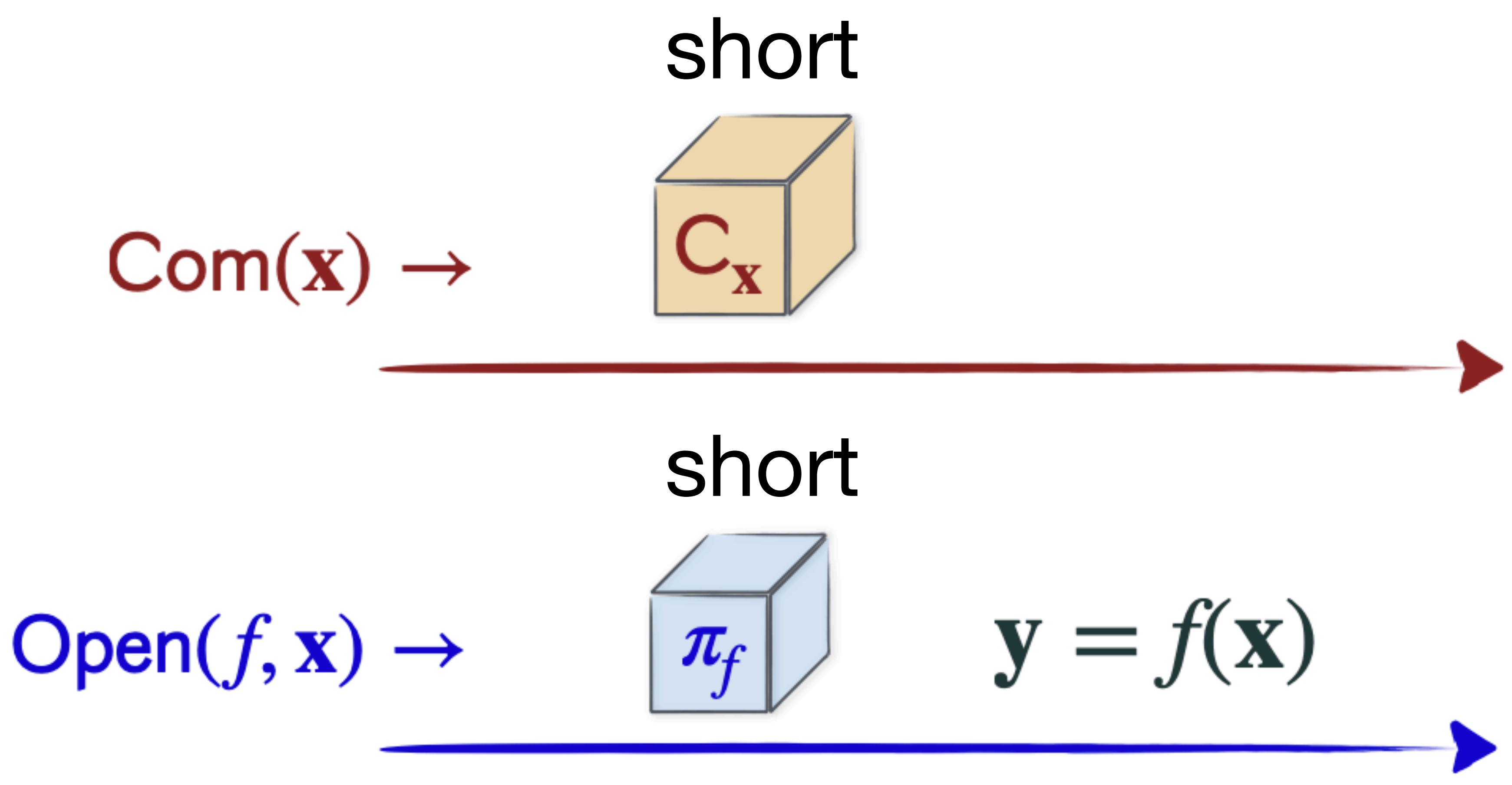

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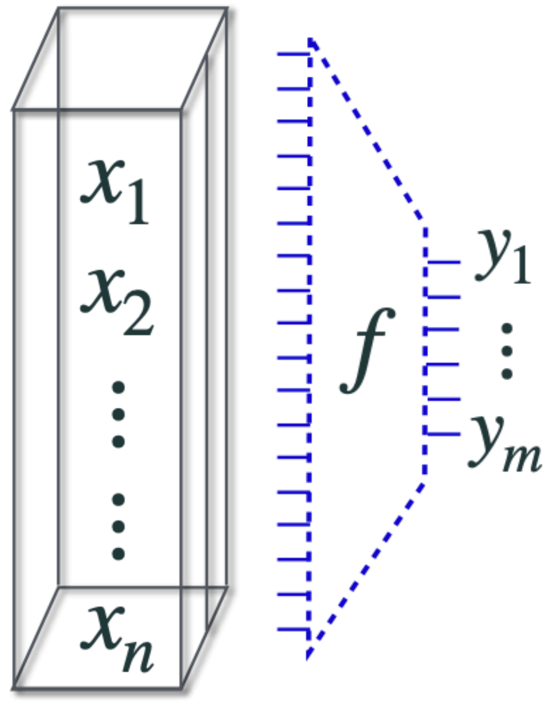

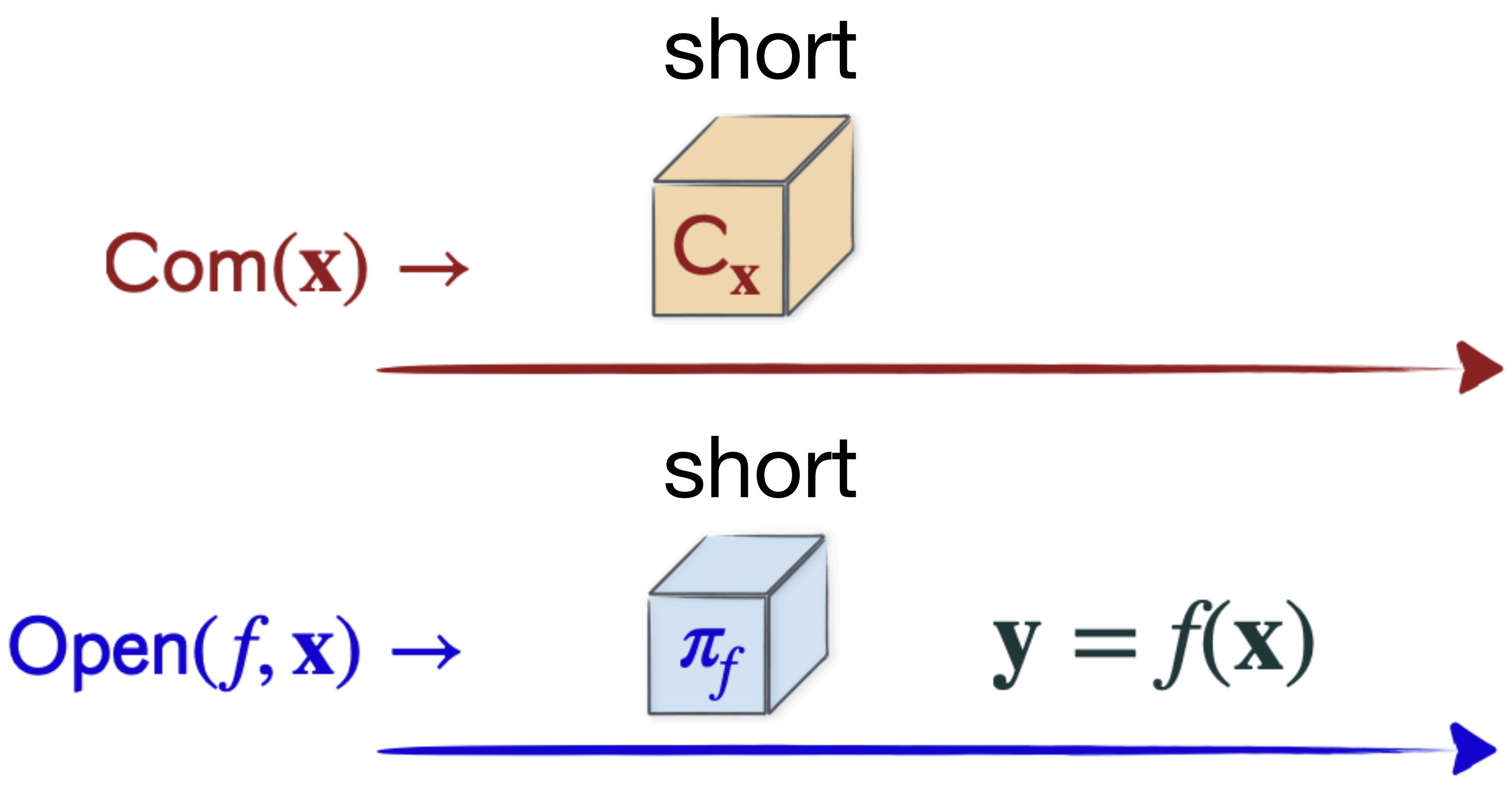

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Functional commitments generalize polynomial and vector commitments.

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Security of Functional Commitments

Evaluation Binding

Malicious Prover

Client (Verifier)

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No adversary can succeed in providing inconsistent valid-looking outputs.

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Security of Functional Commitments

Evaluation Binding

$\mathsf{C}_{\mathbf{x}} \quad f, \quad \pi_f, \mathbf{y}, \quad \pi'_f, \mathbf{y}'$ $\longrightarrow$

$\mathbf{y} \neq \mathbf{y}'$

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NB: intuitively stronger than deterministic and non-deterministic soundness (but weaker than extractability).

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Incrementality in Functional Commitments

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Our goal:

committing and (especially) proving should be doable in an incremental manner.

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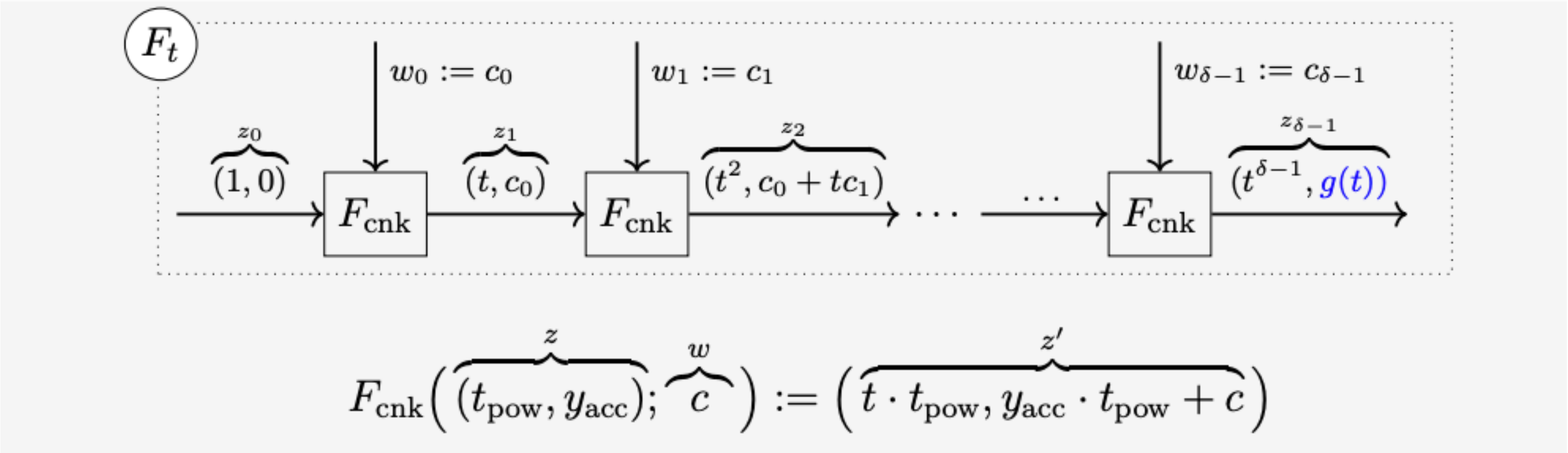

“Incremental” polynomial

Incrementality in Functional Commitments

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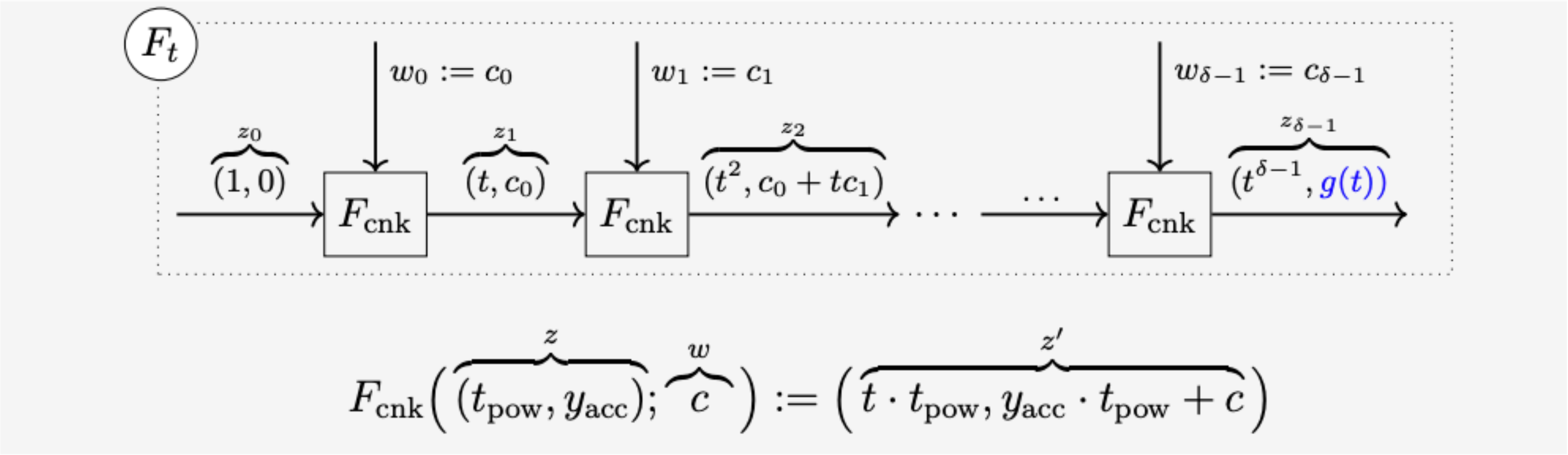
Our contributions for IFC:

modeling, canonical construction,
security proofs, connections to other results.



“Incremental” polynomial

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Summary and, where could one go from here?

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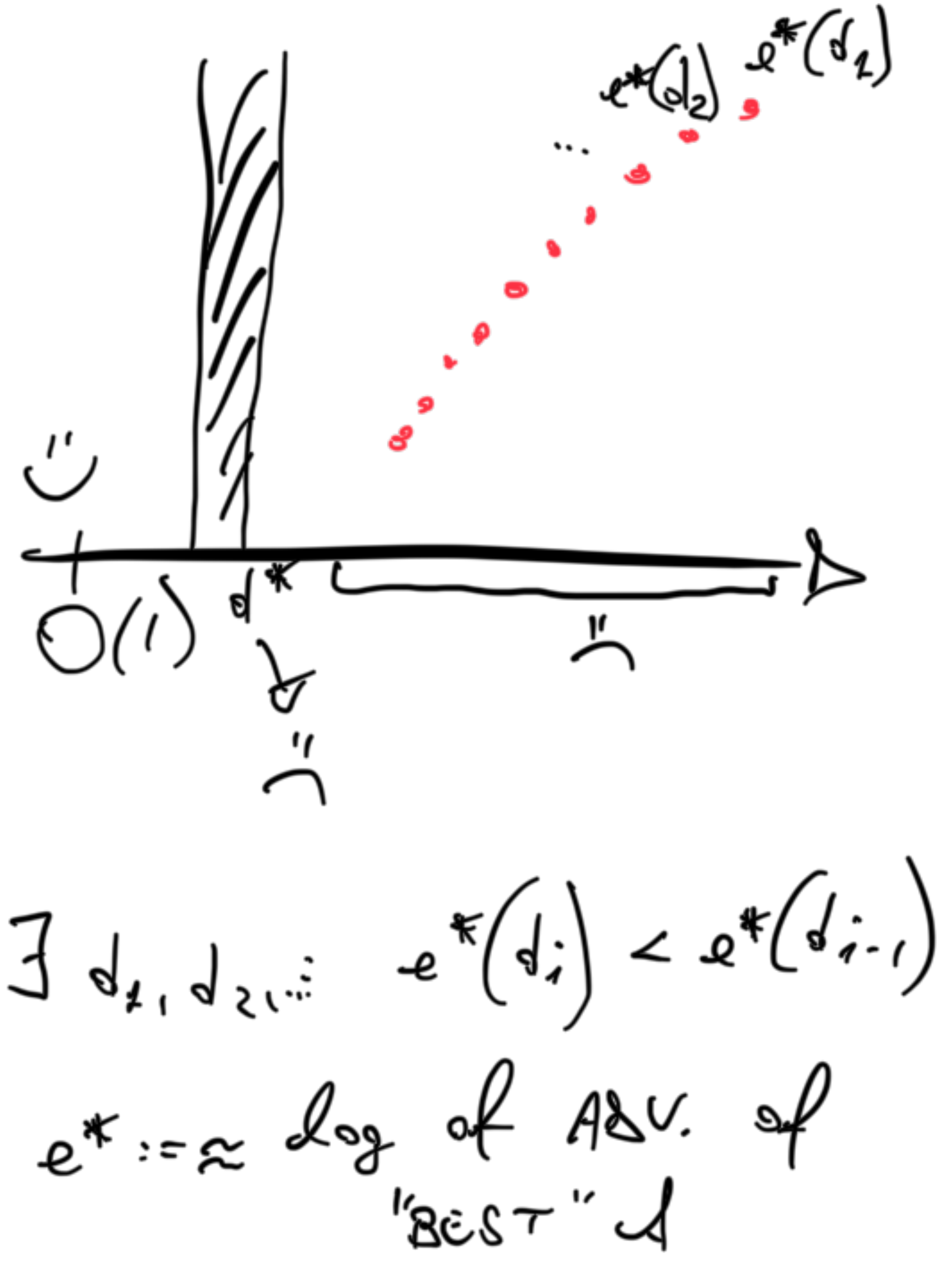
Extra slide on graceful sec. degradation



Theorem 6. *Given any sequence of superconstant—i.e., $\omega(1)$—depth bounds $R_0, R_1, R_2, \ldots$, there always exists a superconstant depth bound L such that for all i, $R_i \succeq L$.*

Extra slide on io-soundness

Theorem (Informal statement of Corollary 1). *Let Π be an* IVC *scheme and* $\mathsf{D} = \omega(1)$ *be a depth bound. Let* $E \subseteq \mathbb{N}$ *be an infinite and "exponentially sparse" set of security parameters where* Π *achieves negligible soundness at depth bound* D*. Then there exists a depth bound* $d = \omega(1)$ *where* Π *achieves (standard) negligible soundness.*

Theorem (Informal statement of Corollary 2). *Let* $\Pi, \mathsf{D} = \omega(1)$, *and* E *as in the previous theorem. Then:*

- E *exponentially sparse* $\implies d = O(\log \mathsf{D})$.
- E *sub-exponentially sparse* $\implies d = O(\mathrm{polylog}\mathsf{D})$.

Theorem 3. *Let* $E = \{\lambda_1 < \lambda_2 < \cdots\} \subseteq \mathbb{N}$ *be a constructible* (2^{κ^T})*-sparse set for some* T *with* $0 < T \leq 1$*. Let* Π *be an IVC that is i.o-sound with respect to* E *for depth bound* $\mathsf{D}(\cdot)$*. Let* $d'(\cdot)$ *be a depth bound. If for all* $i \in \mathbb{N}$,

$$d'(\lambda_{i+1} - 1) \leq \mathsf{D}(\lambda_i), \qquad (\blacktriangle)$$

then Π *is (almost-everywhere) sound for depth bound* d' *if appropriately parameterized (Definition 3). The resulting proving time, verification time and proof size are like those originally in* Π *(up to constant factors).*