Ph.D. Proposal

Software Side-Channel Analysis

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UCSB

INTRODUCTION

What is a side channel?

What is a side channel?

TIME

Monday, Aug. 13, 1990

And Bomb The Anchovies

By Paul Gray

Delivery people at various Domino's pizza outlets in and around Washington claim that they have learned to anticipate big news baking at the White House or the Pentagon by the upsurge in takeout orders. Phones usually start ringing some 72 hours before an official announcement. "We know," says one pizza runner. "Absolutely. Pentagon orders doubled up the night before the Panama attack; same thing happened before the Grenada invasion." Last Wednesday, he adds, "we got a lot of orders, starting around midnight. We figured something was up." This time the big news arrived quickly: Iraq's surprise invasion of Kuwait.

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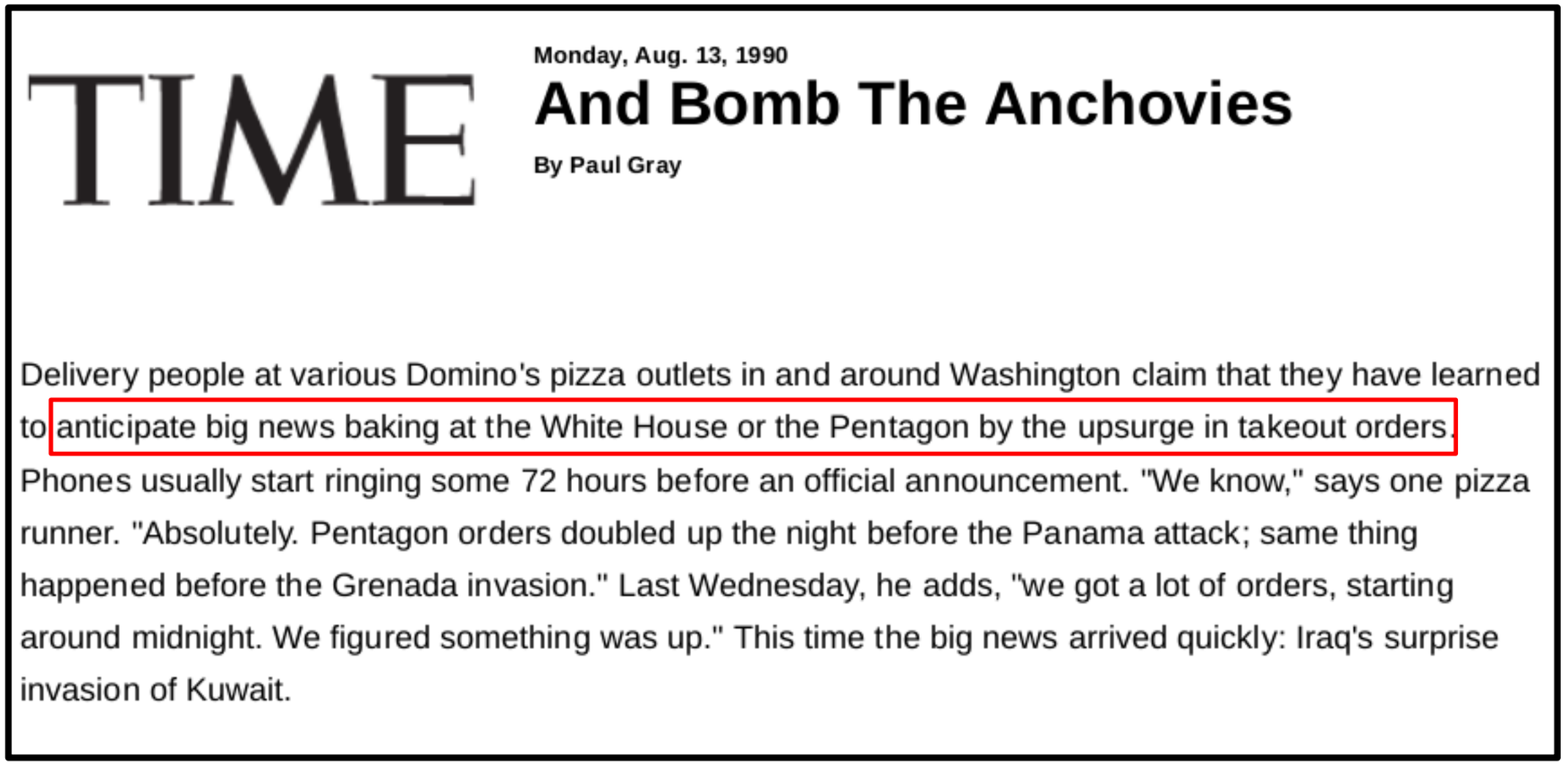

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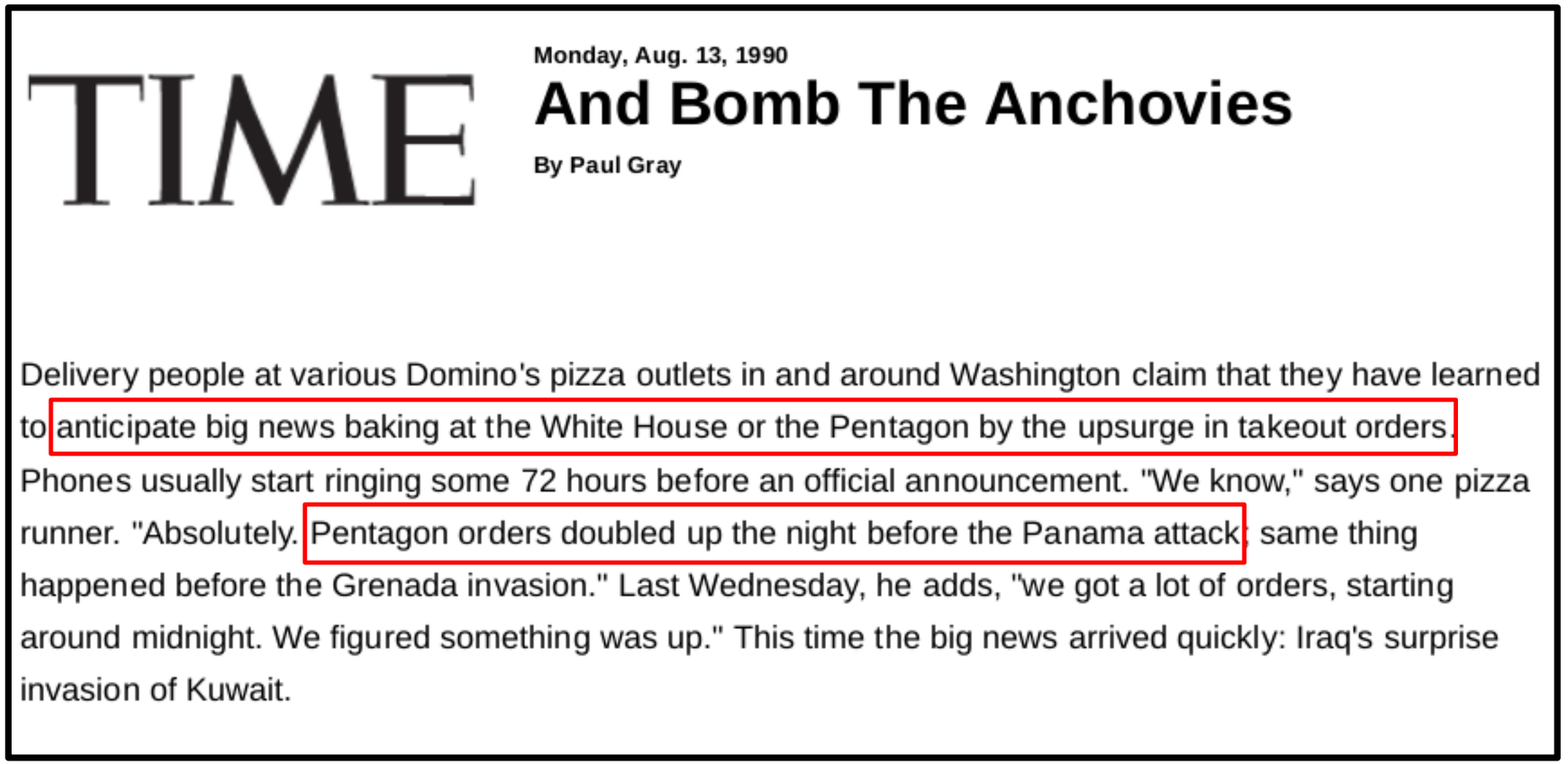

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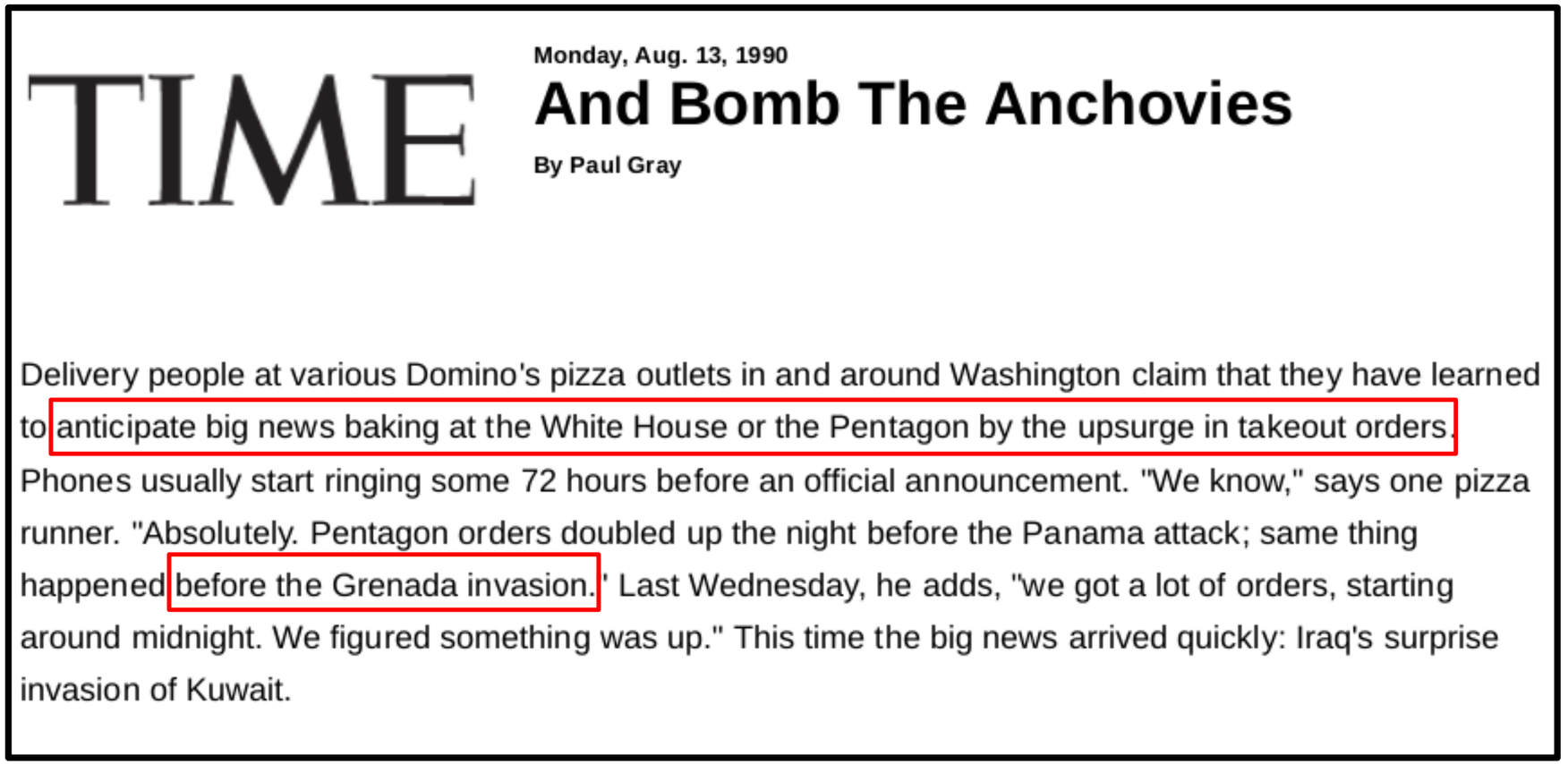

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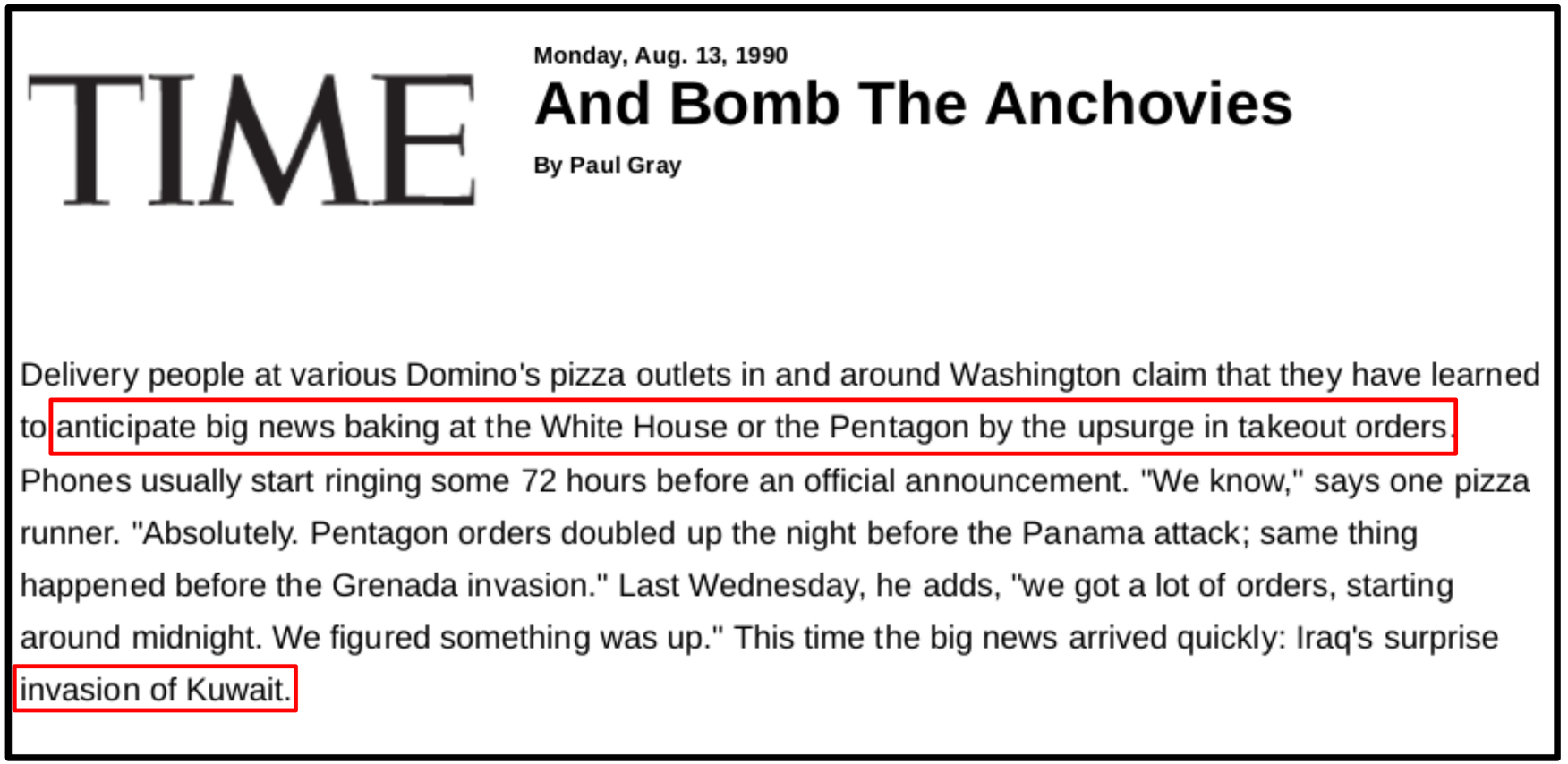

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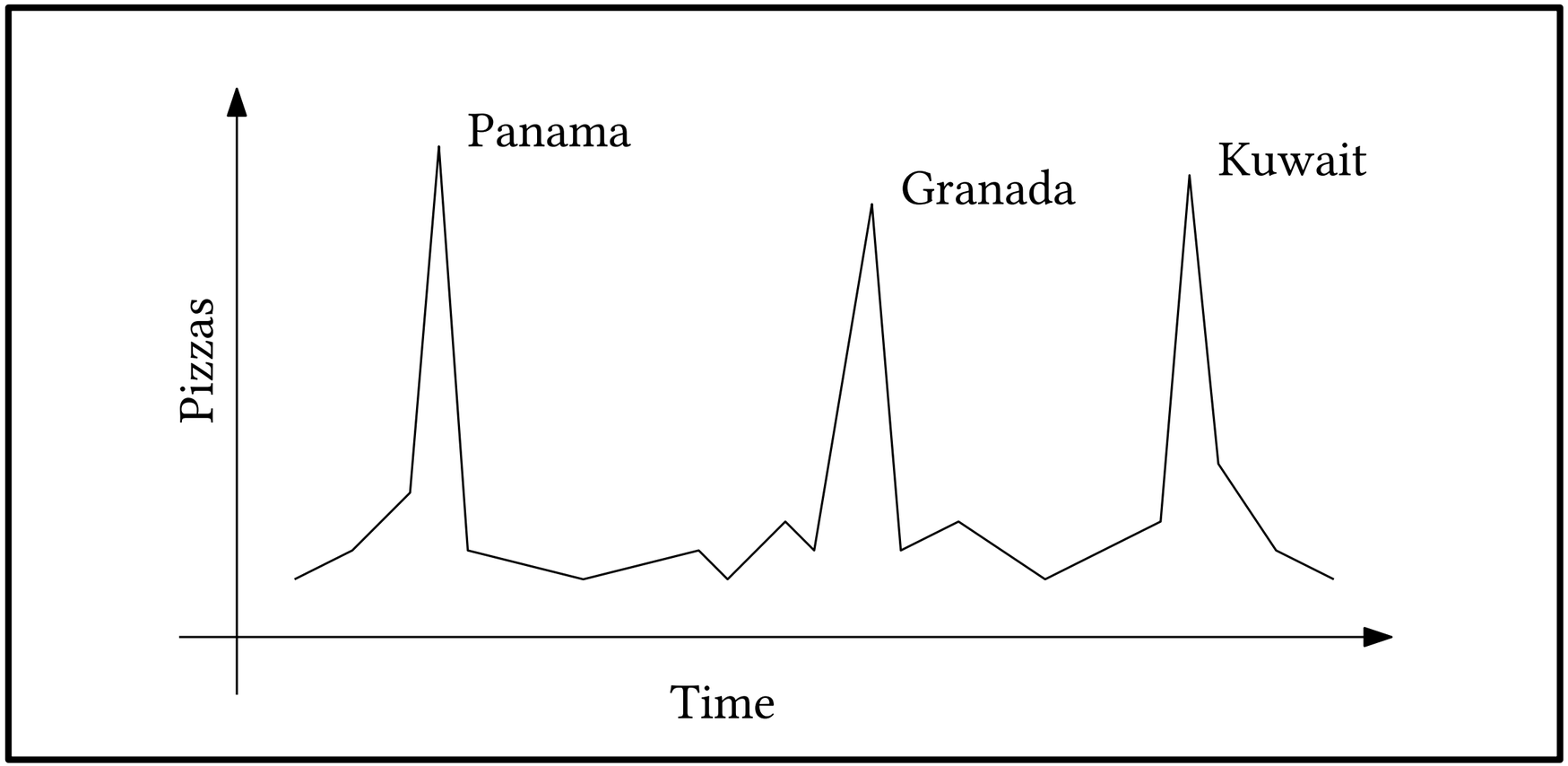

Side channel: learn secrets through indirect observation.

secret information correlates with observation ⟹ reveal secrets

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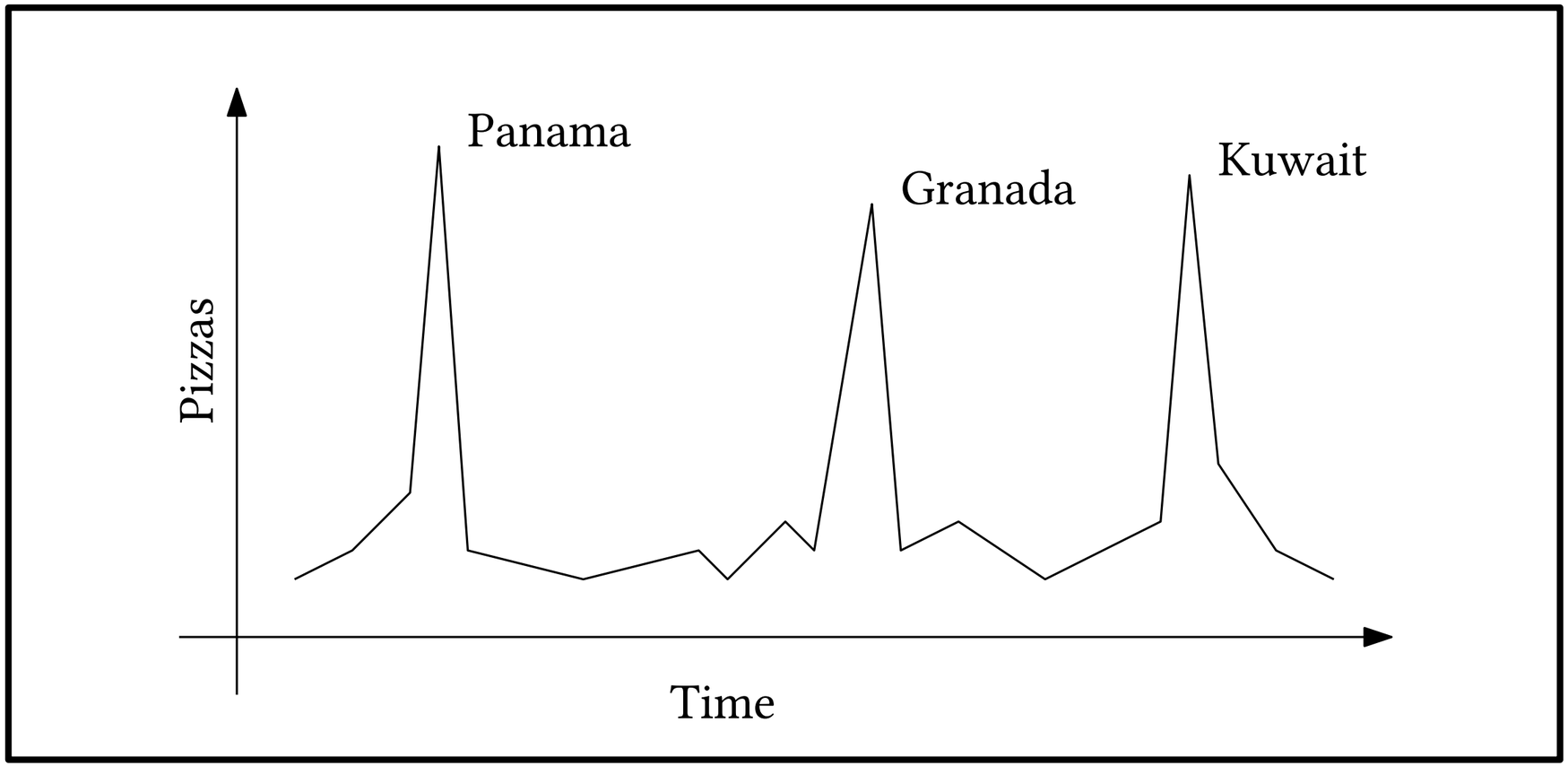

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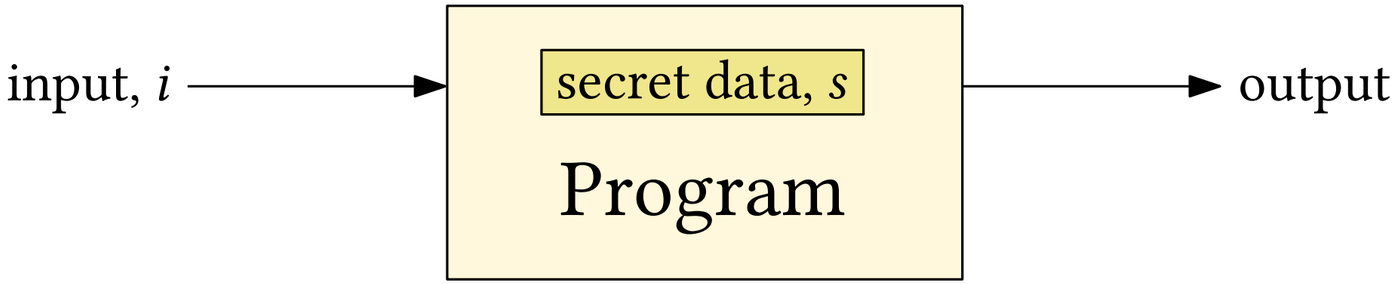

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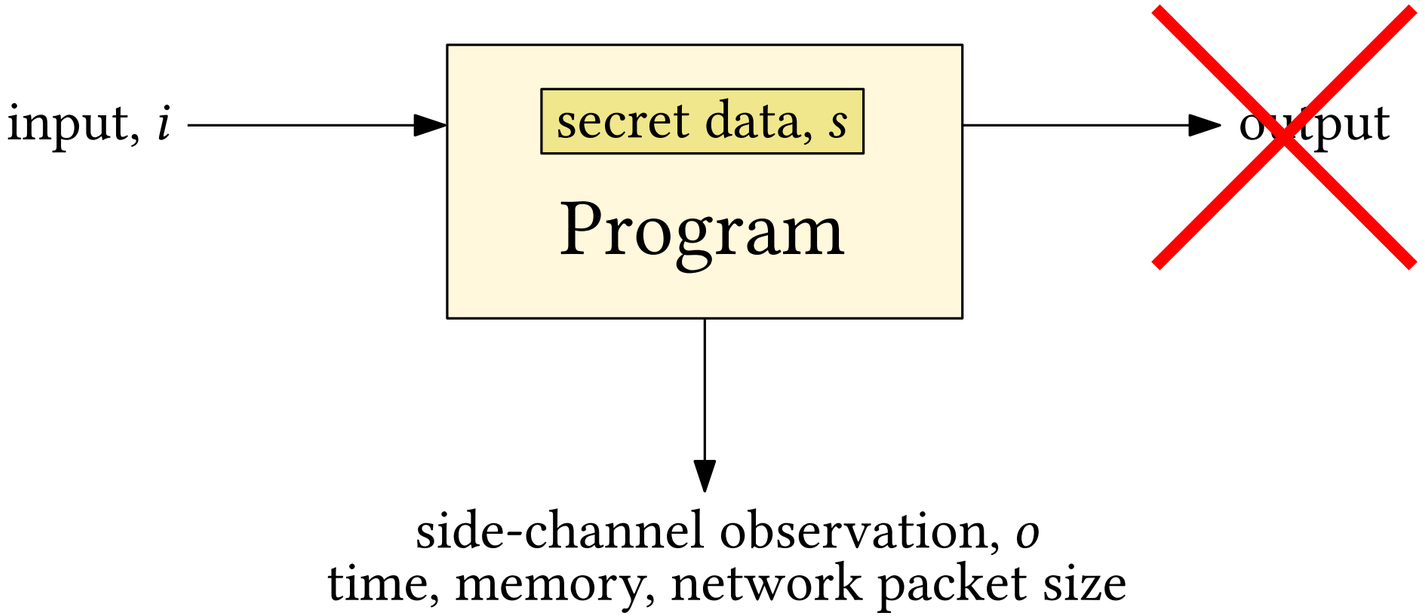

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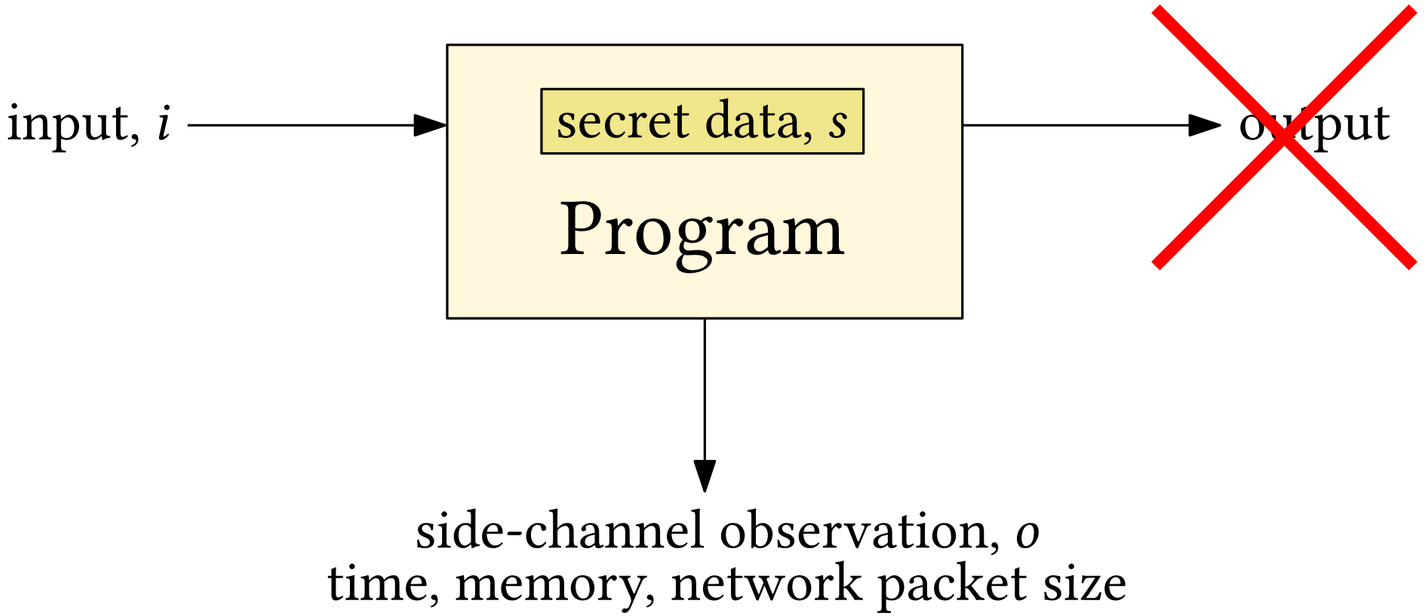
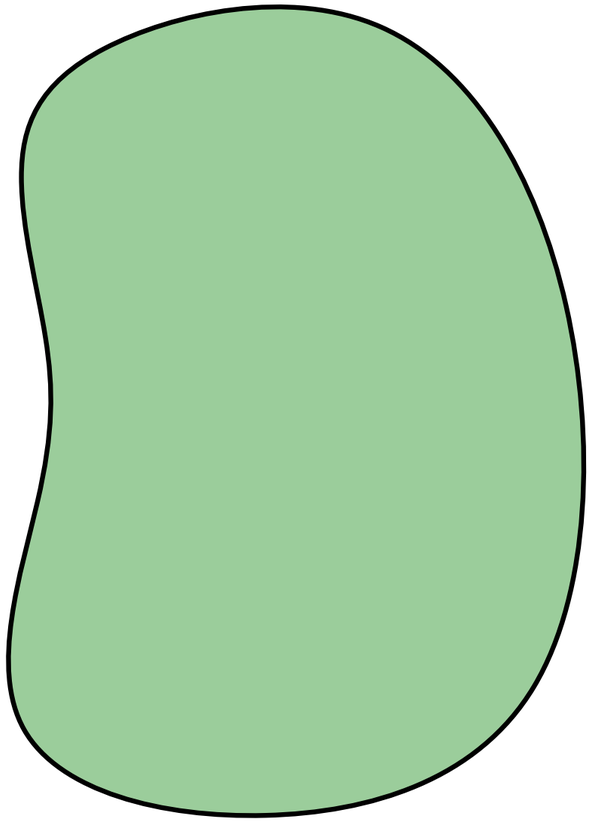


correlation between (i, o) and $s \Rightarrow$ vulnerability

Side Channels and Searching

$i_0 \in I$

secret $s \in S$



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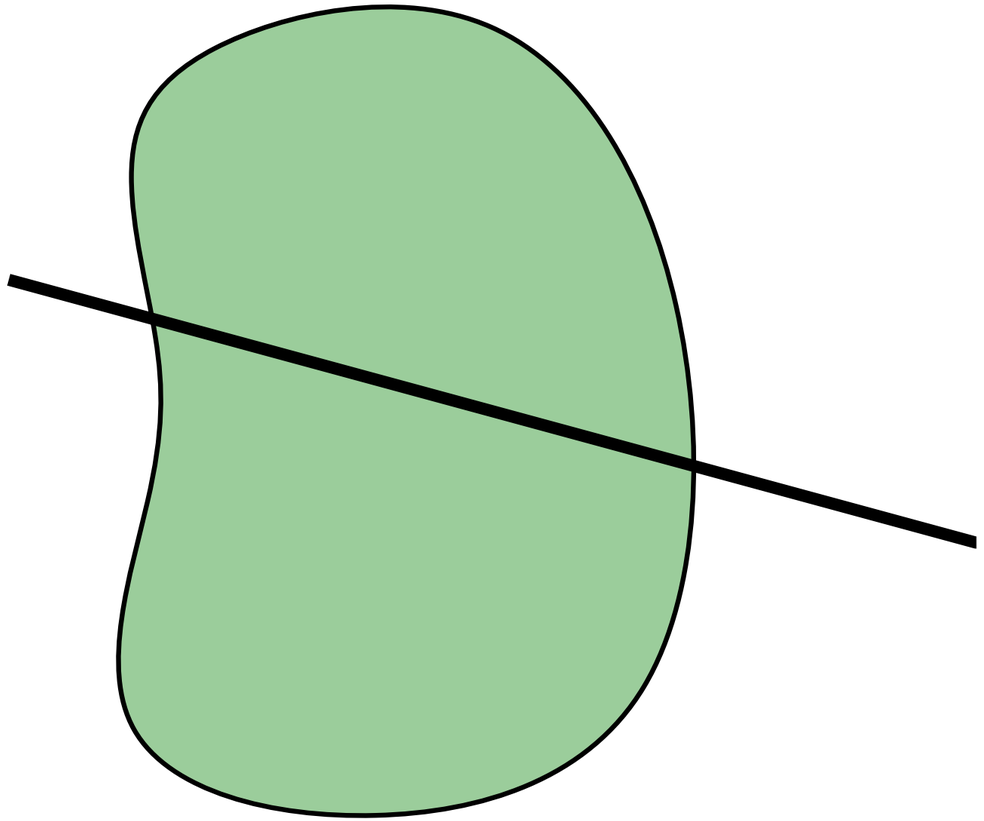

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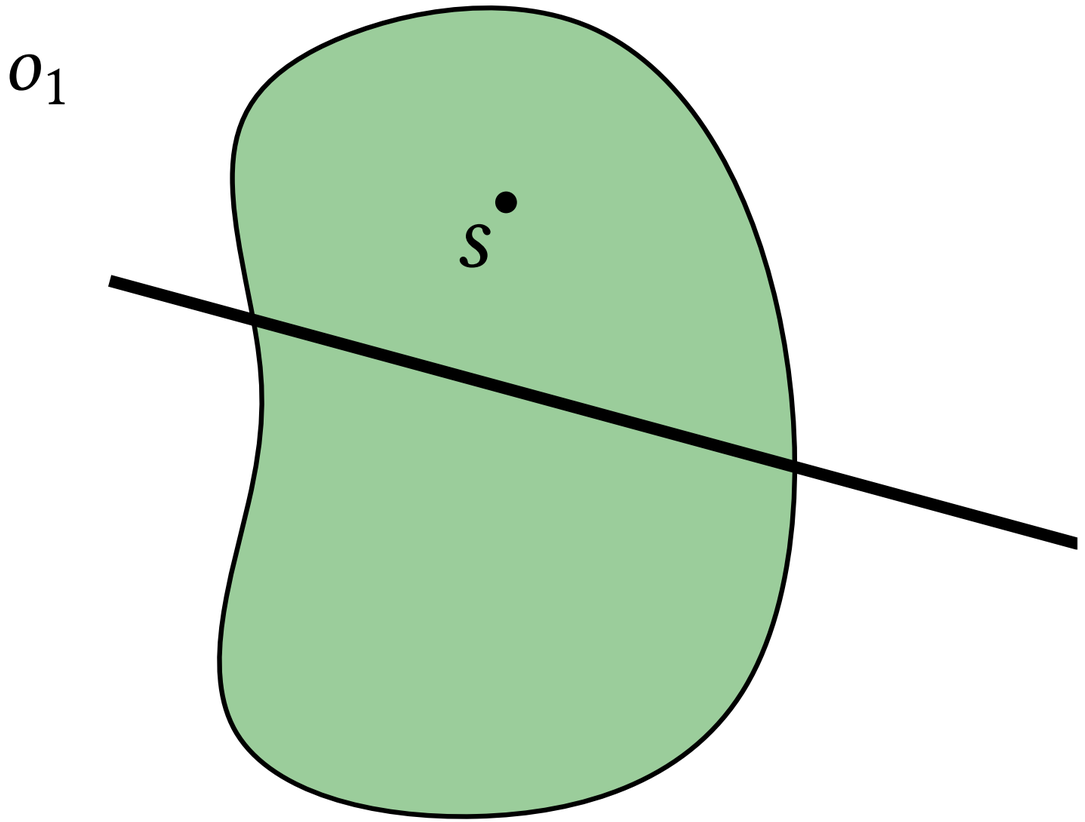

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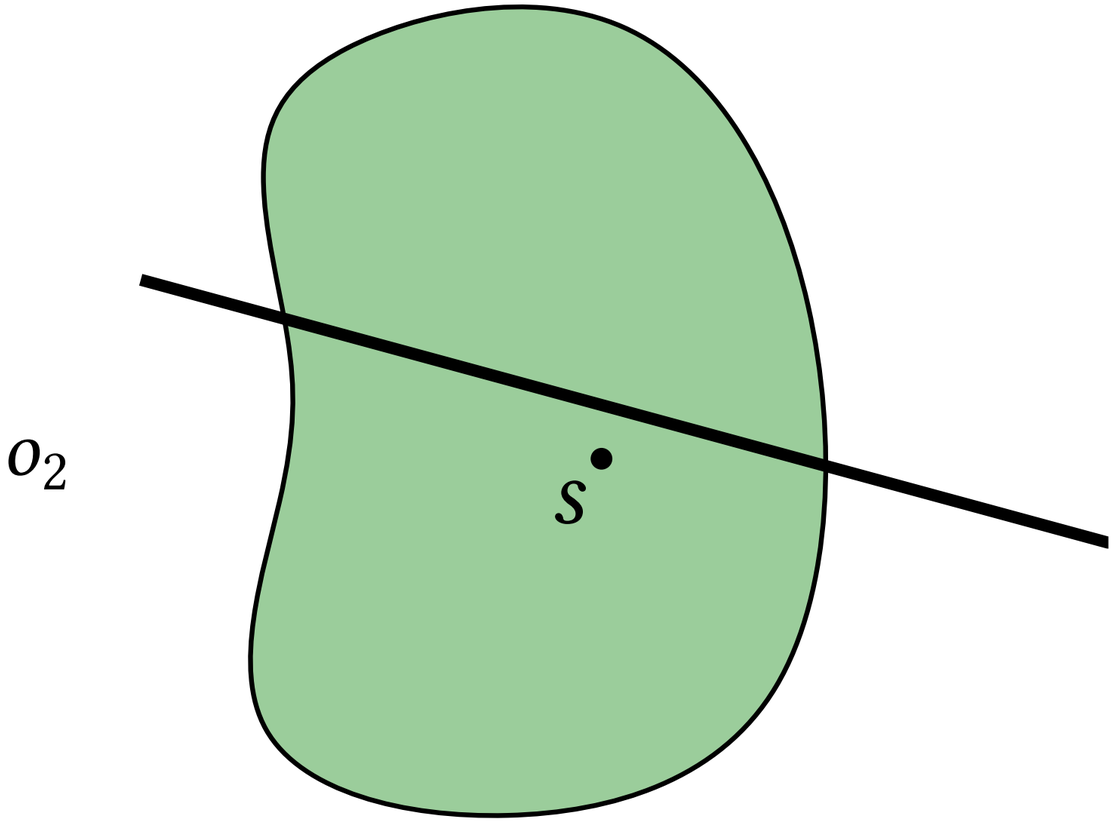

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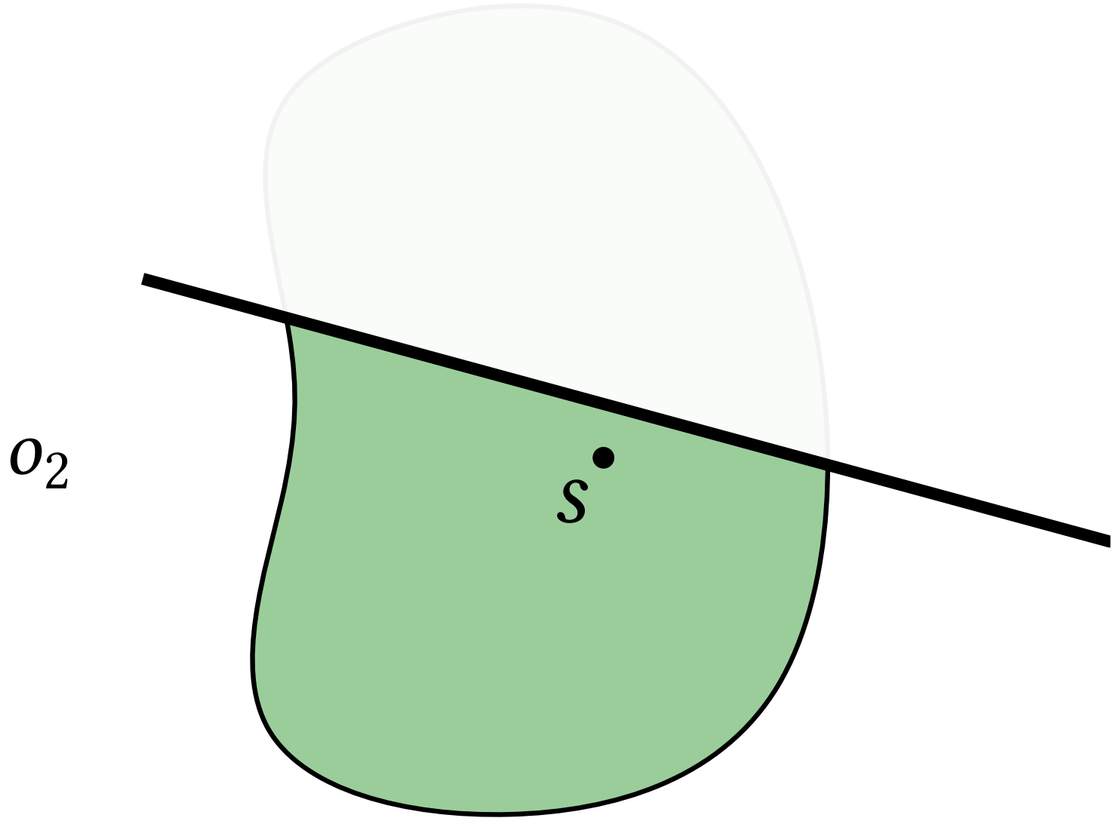

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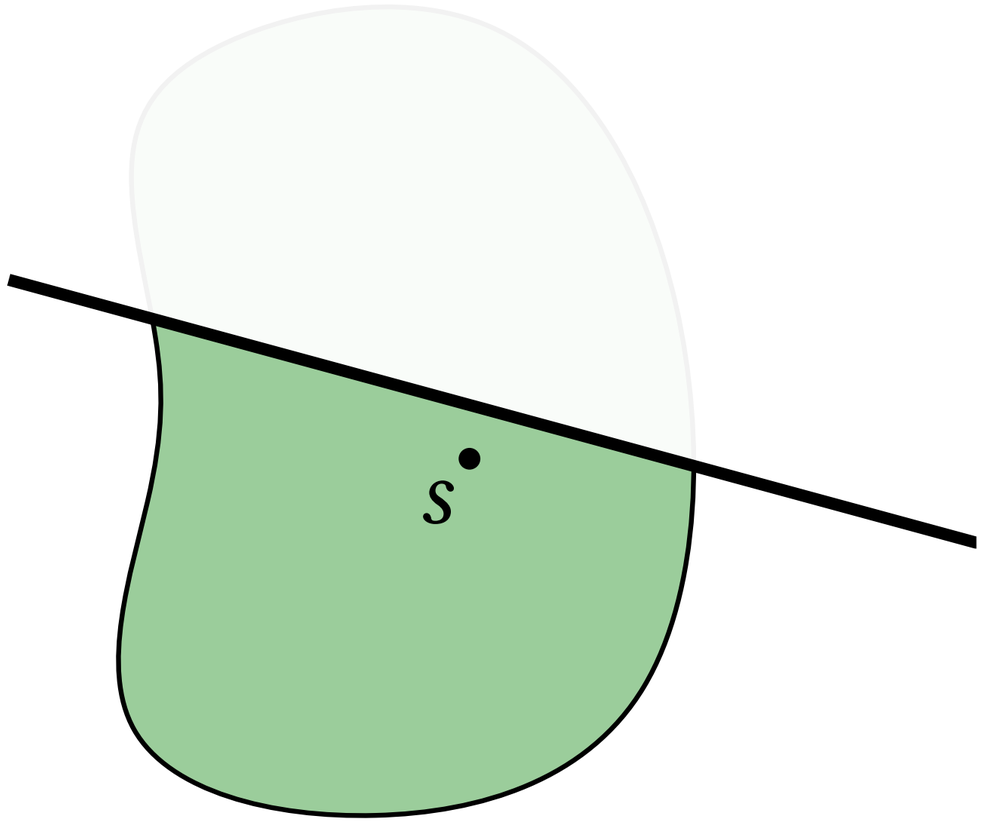

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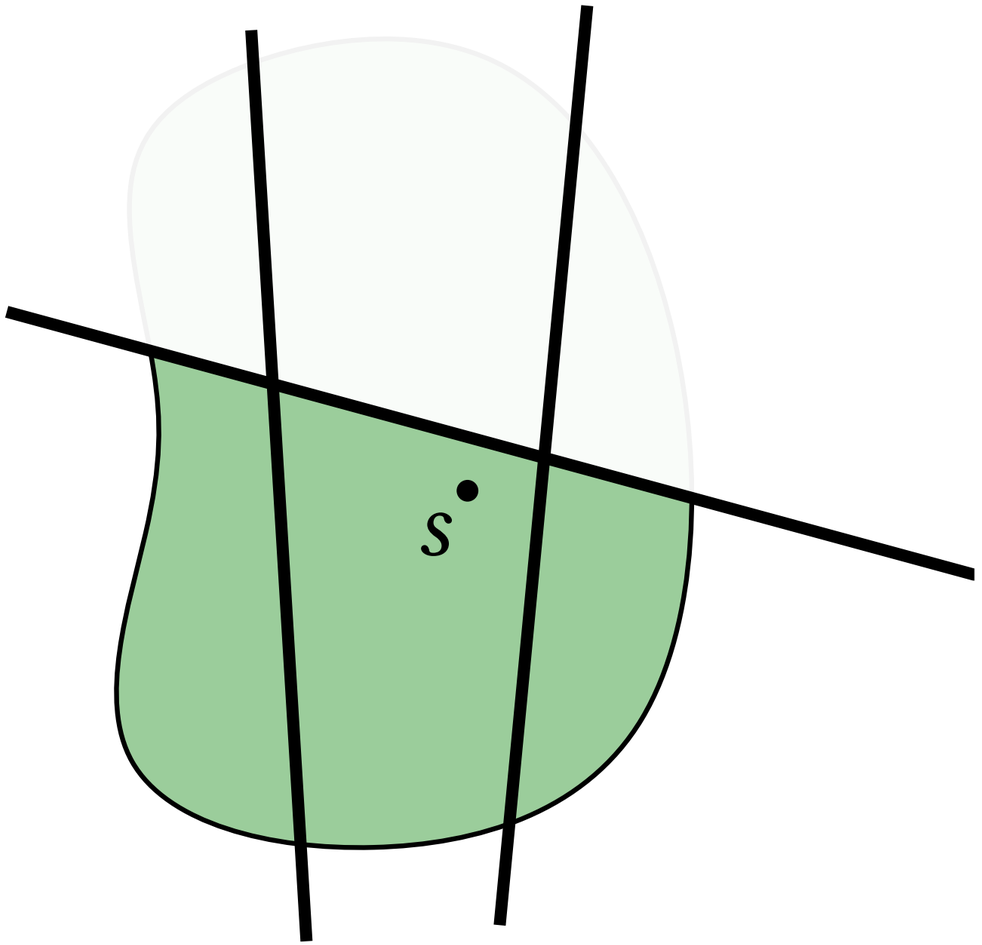

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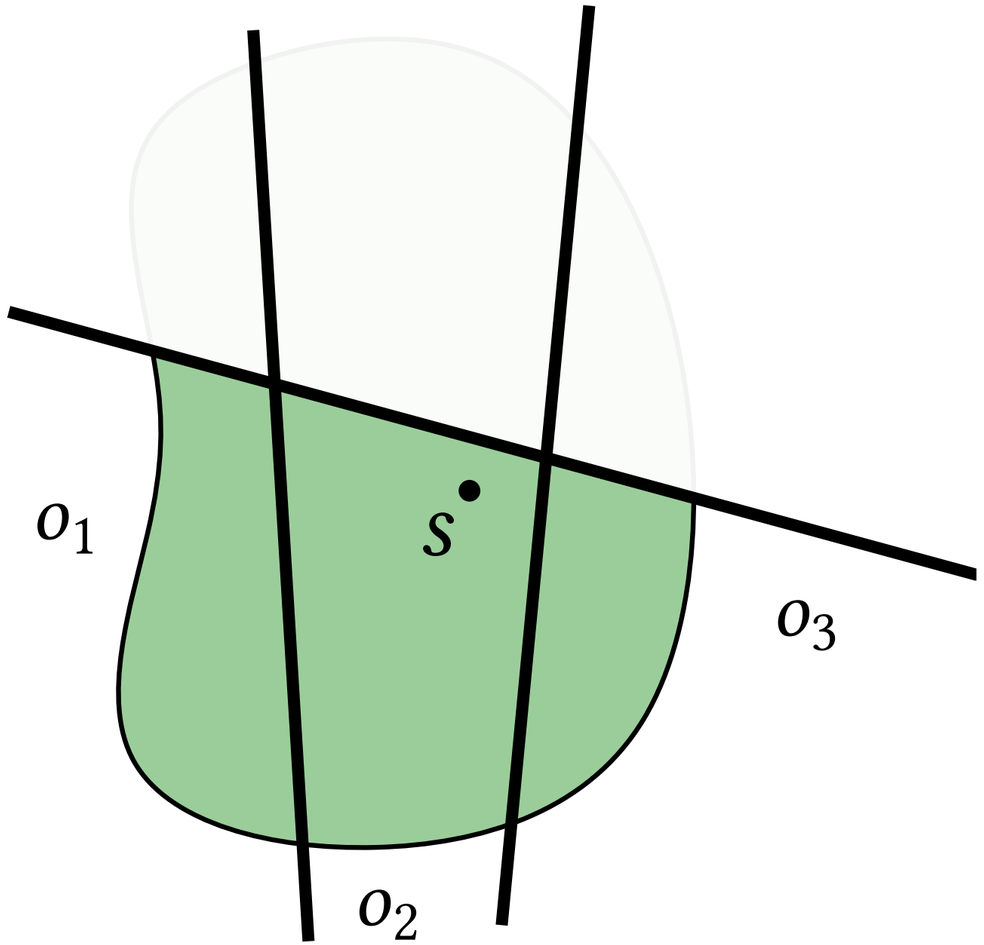

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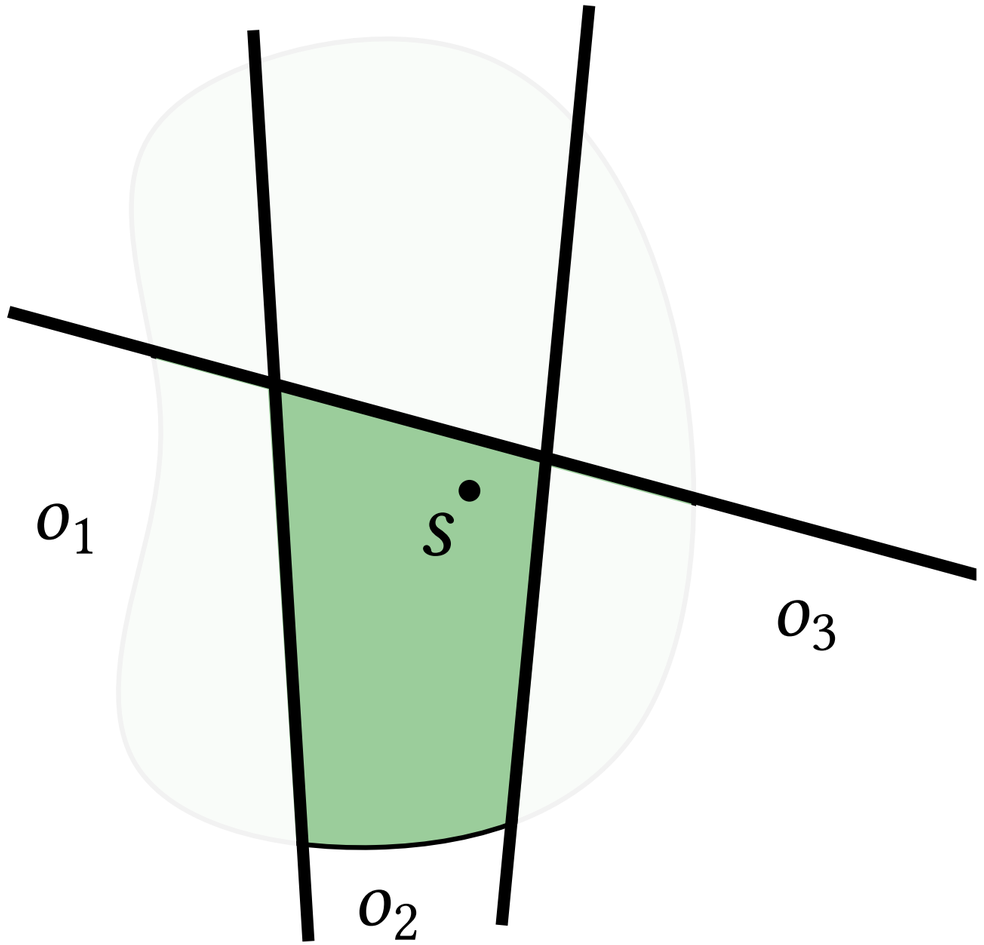

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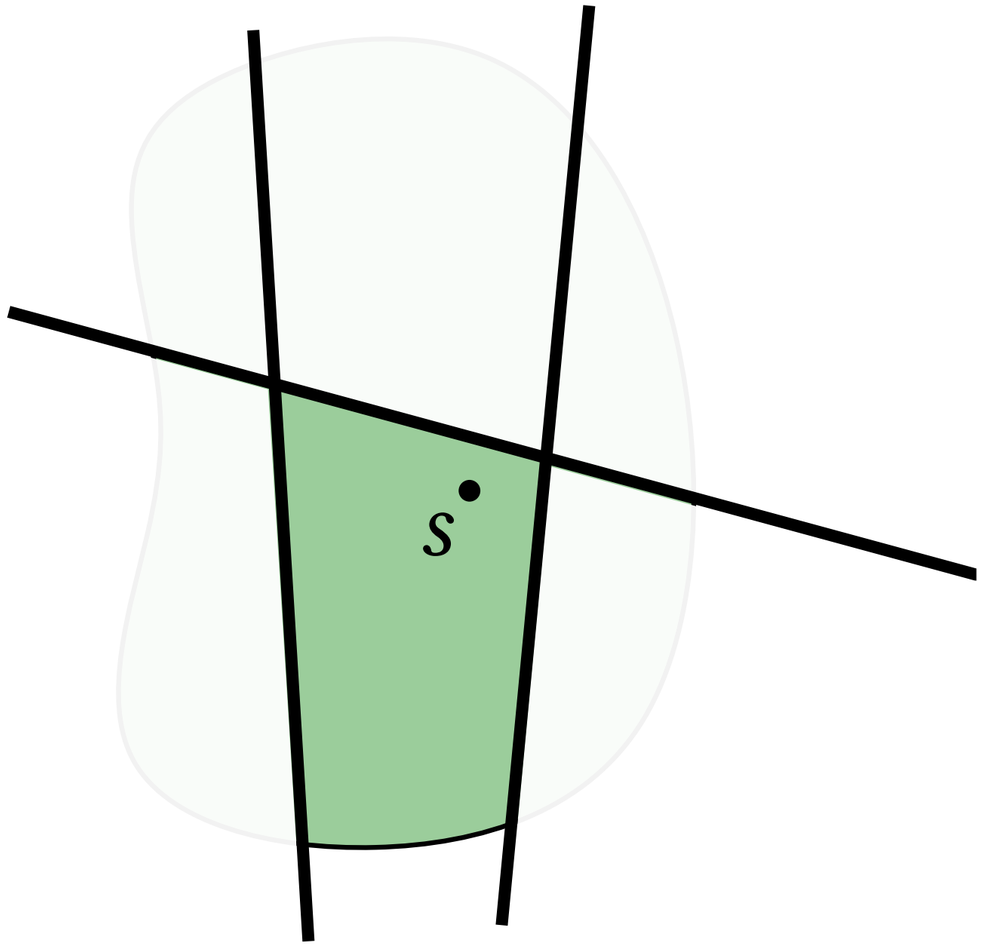

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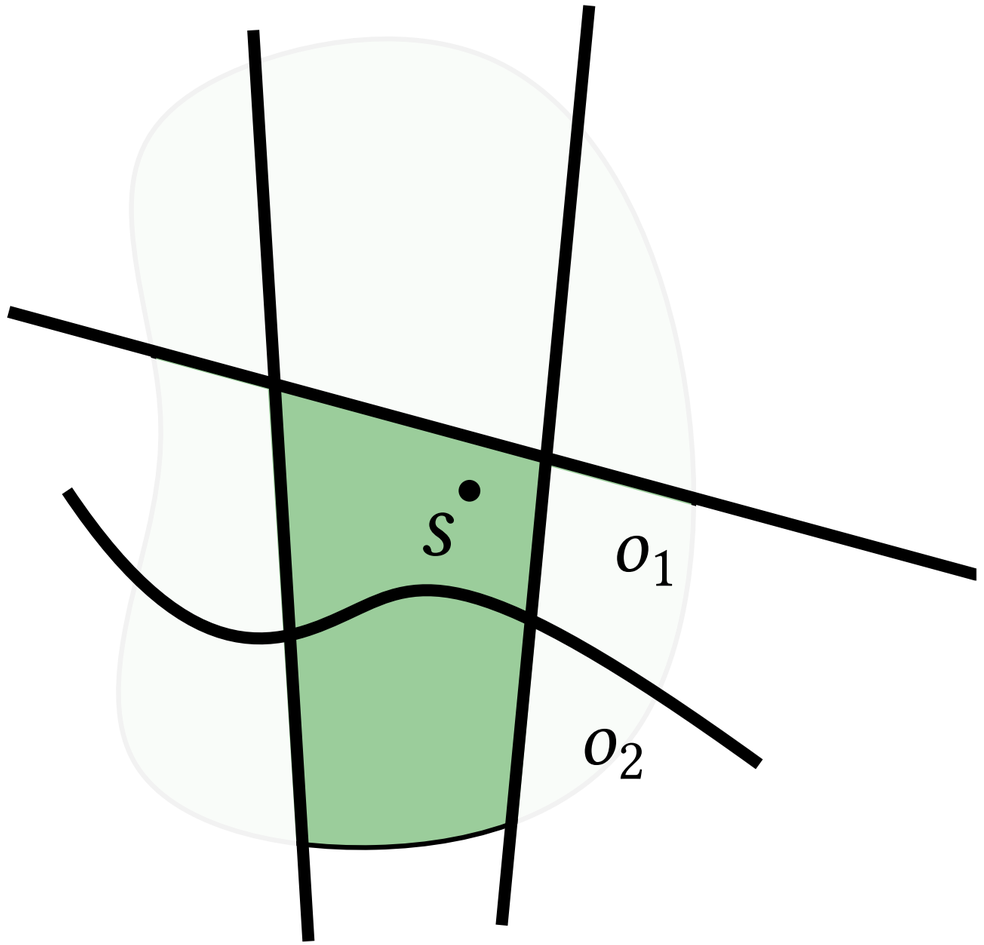

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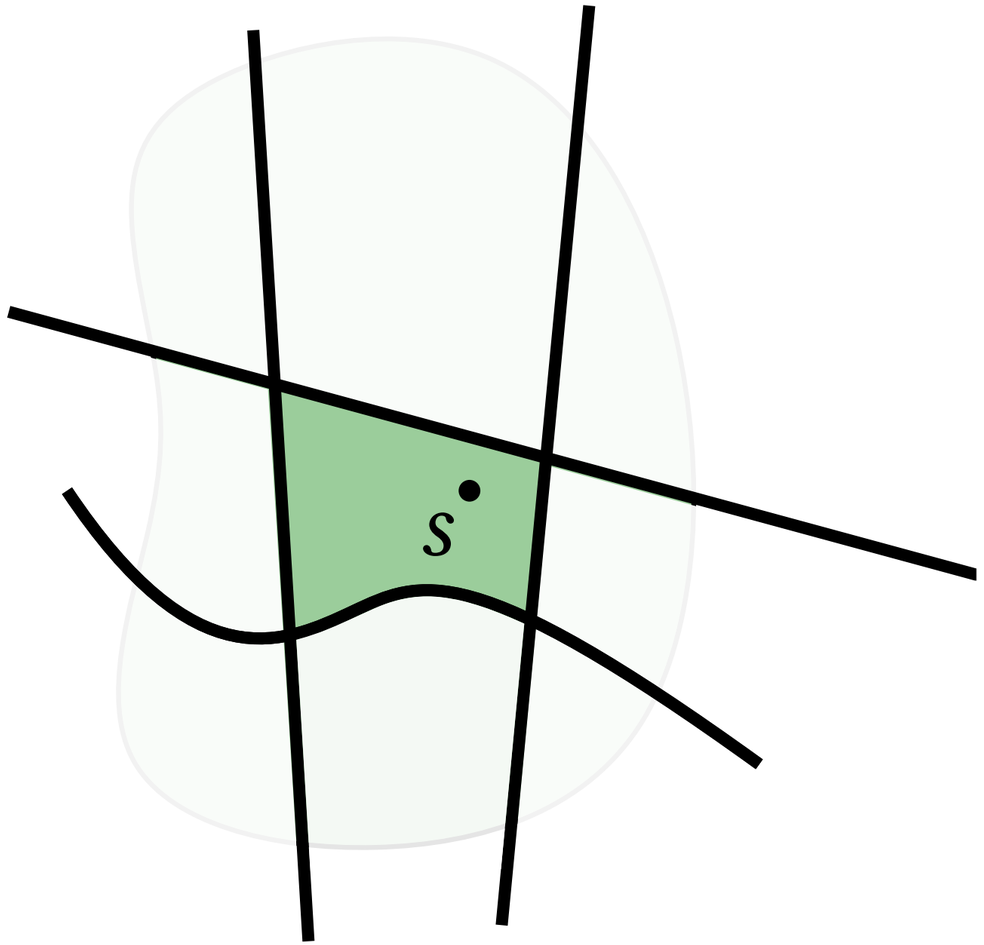

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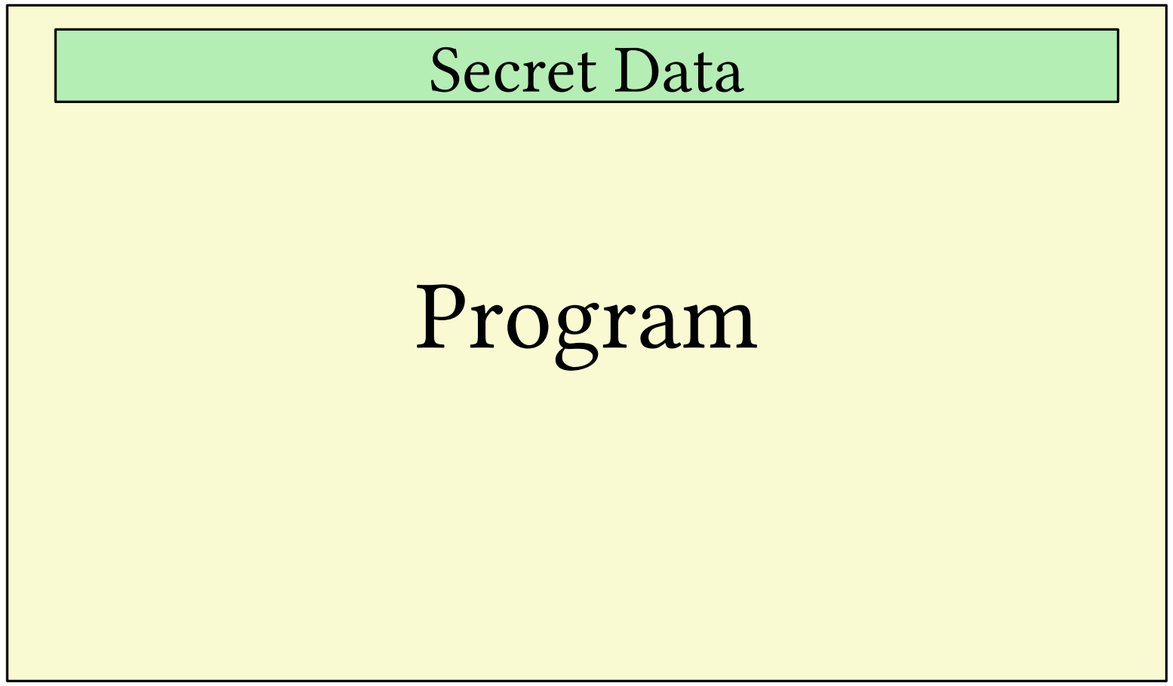

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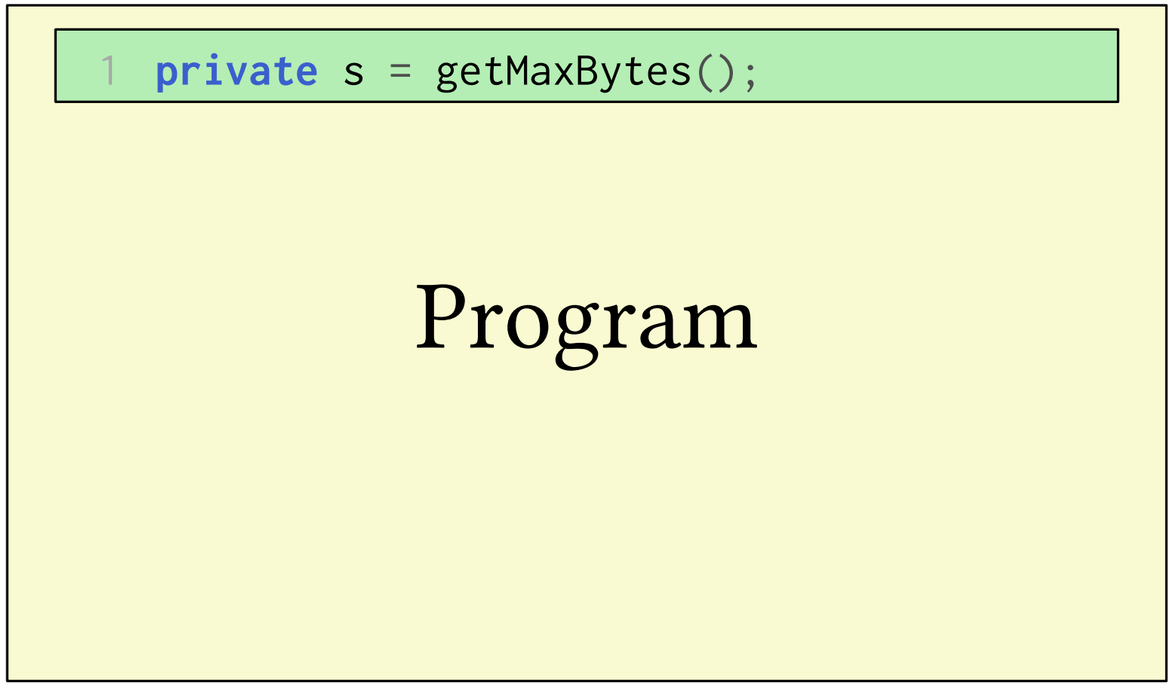

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4  public int compare(int i){
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input, i →

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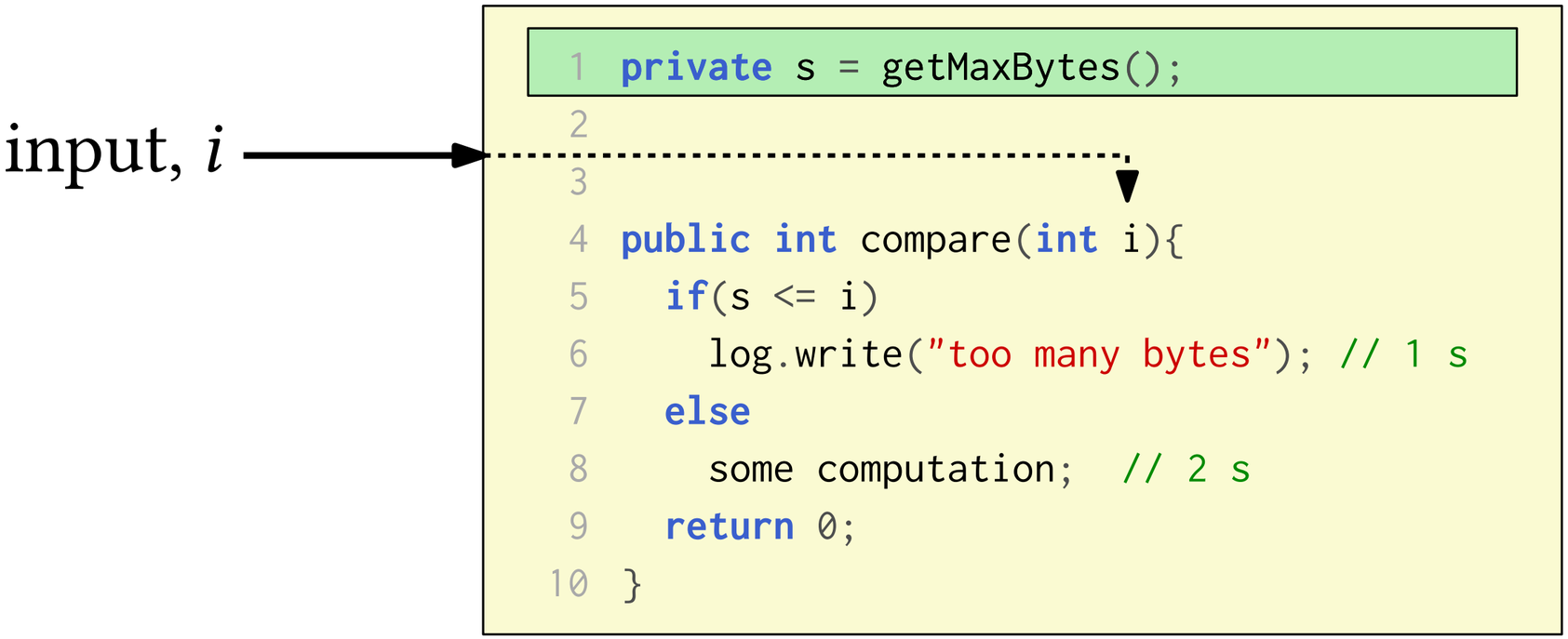

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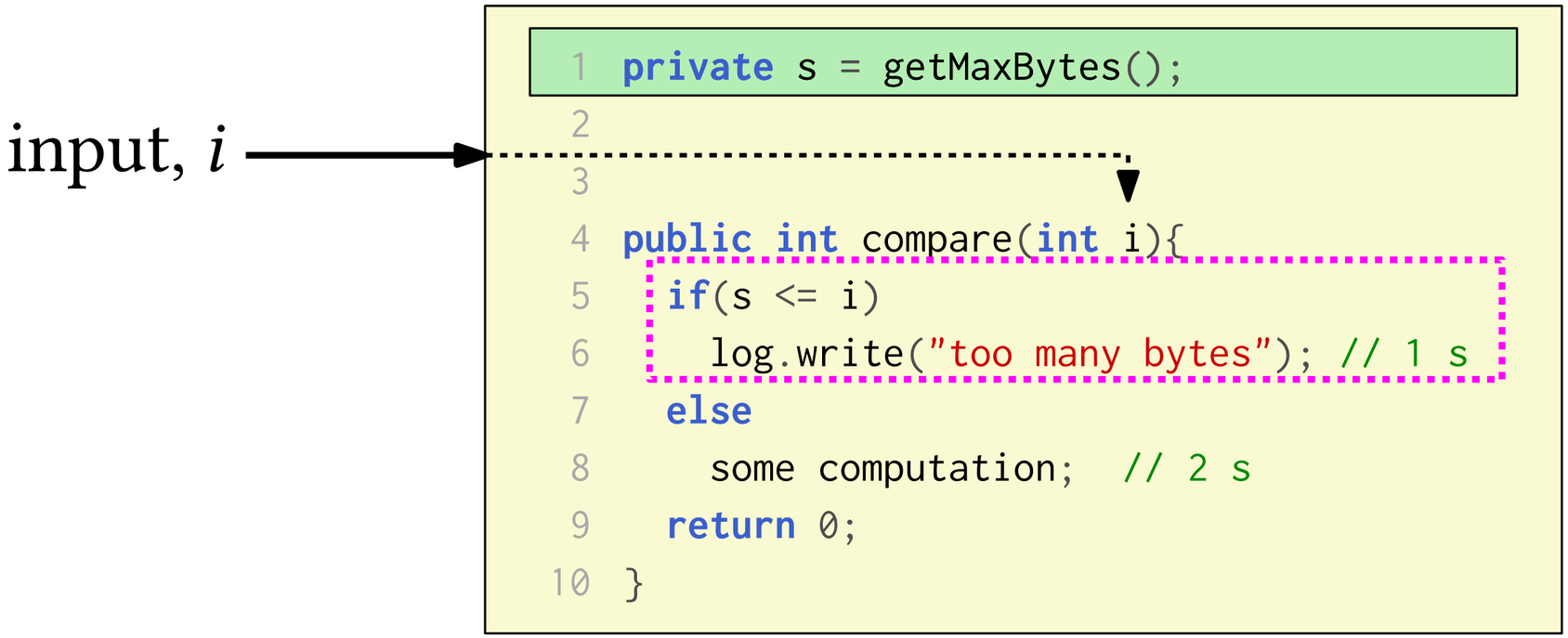

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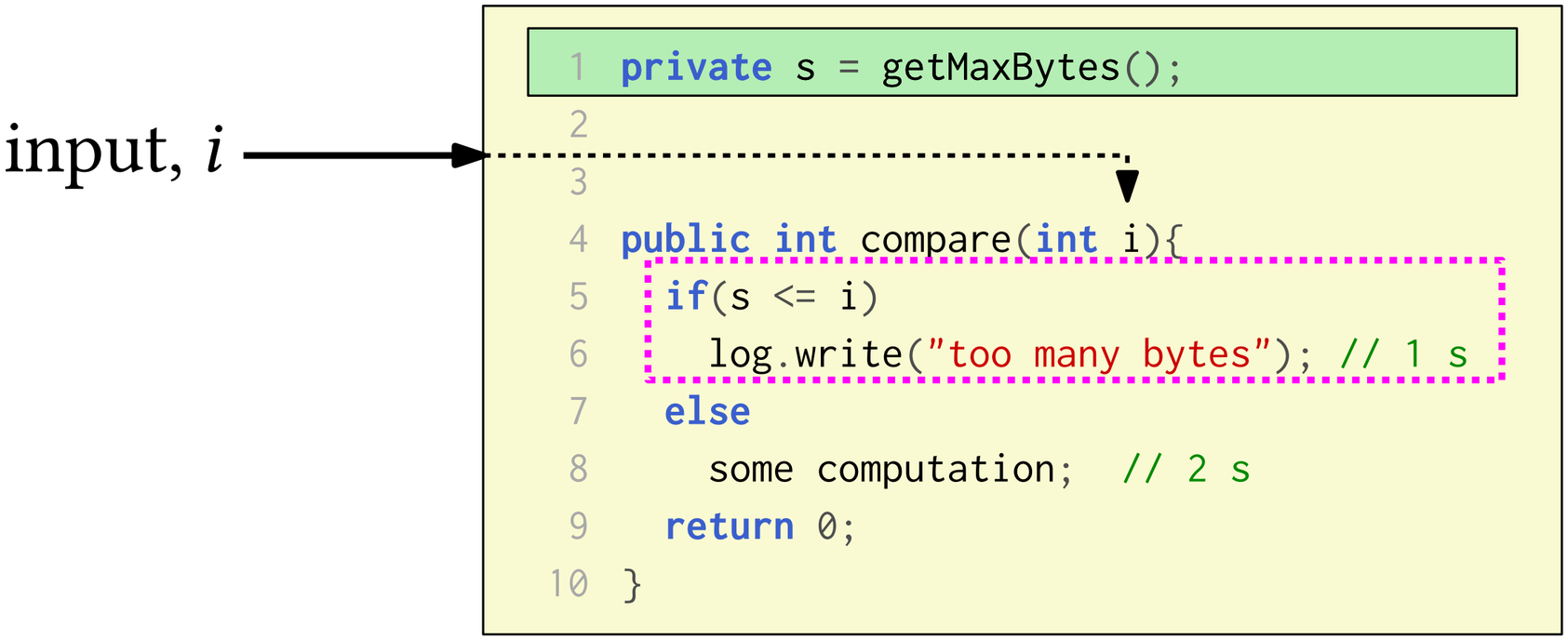

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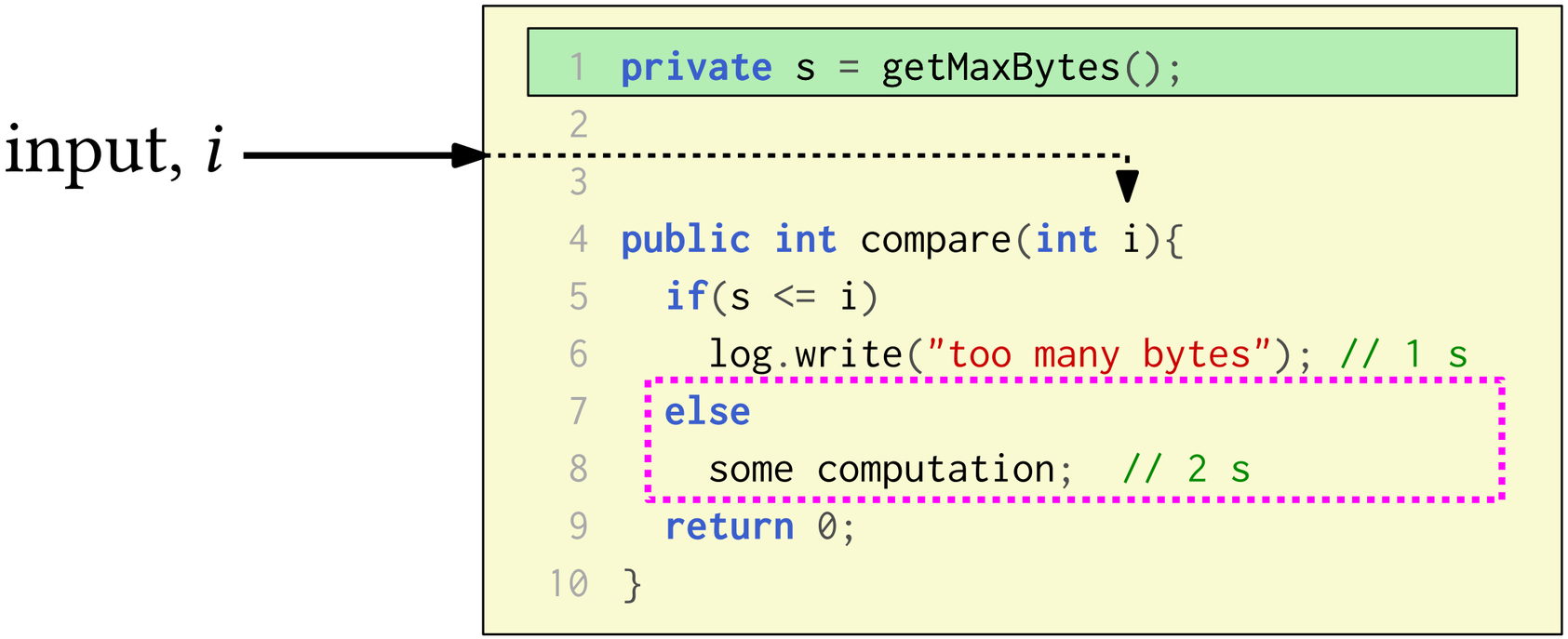

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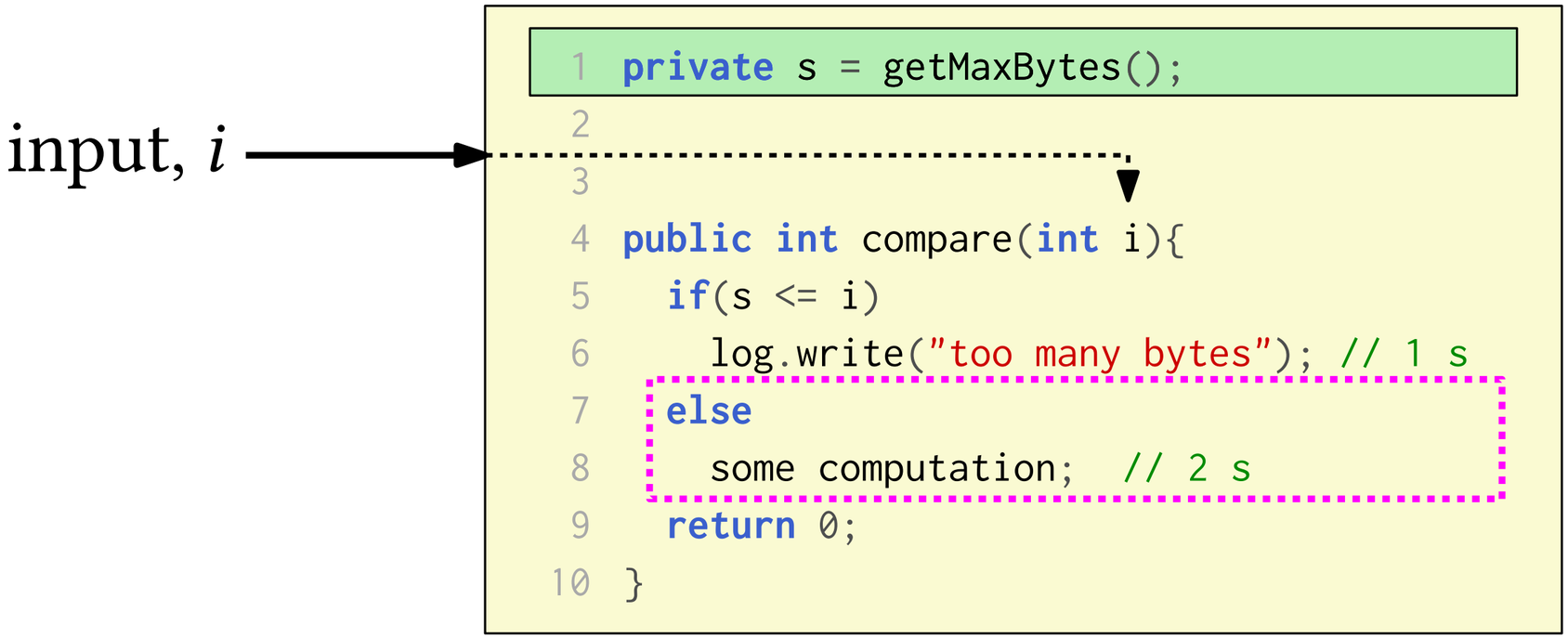

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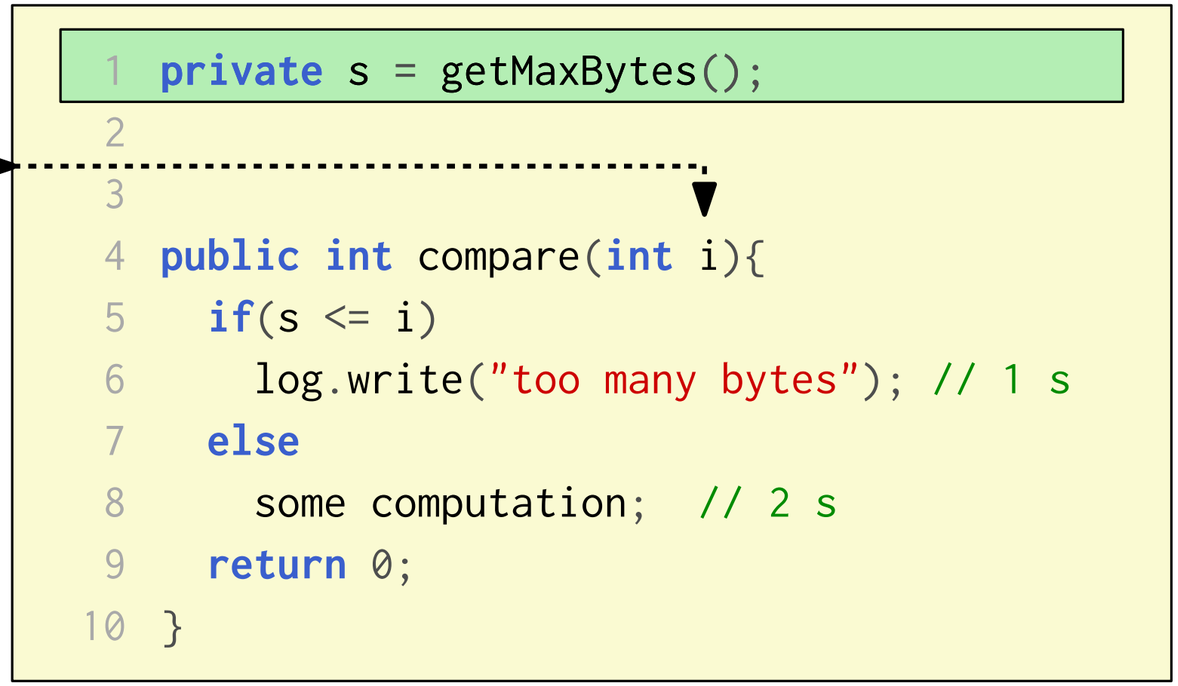

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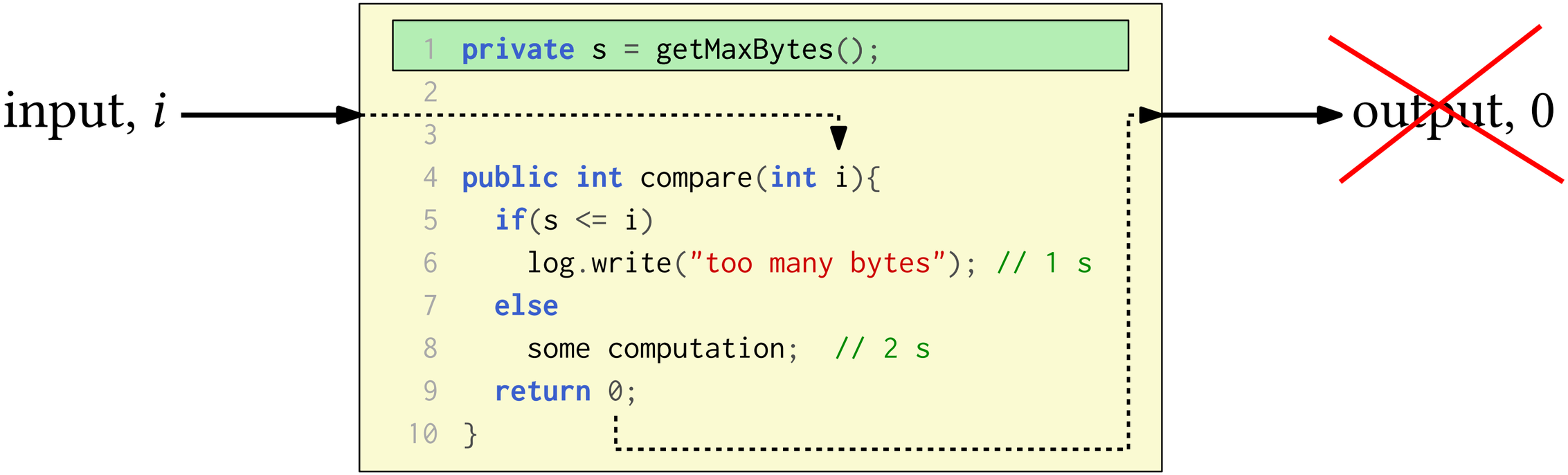

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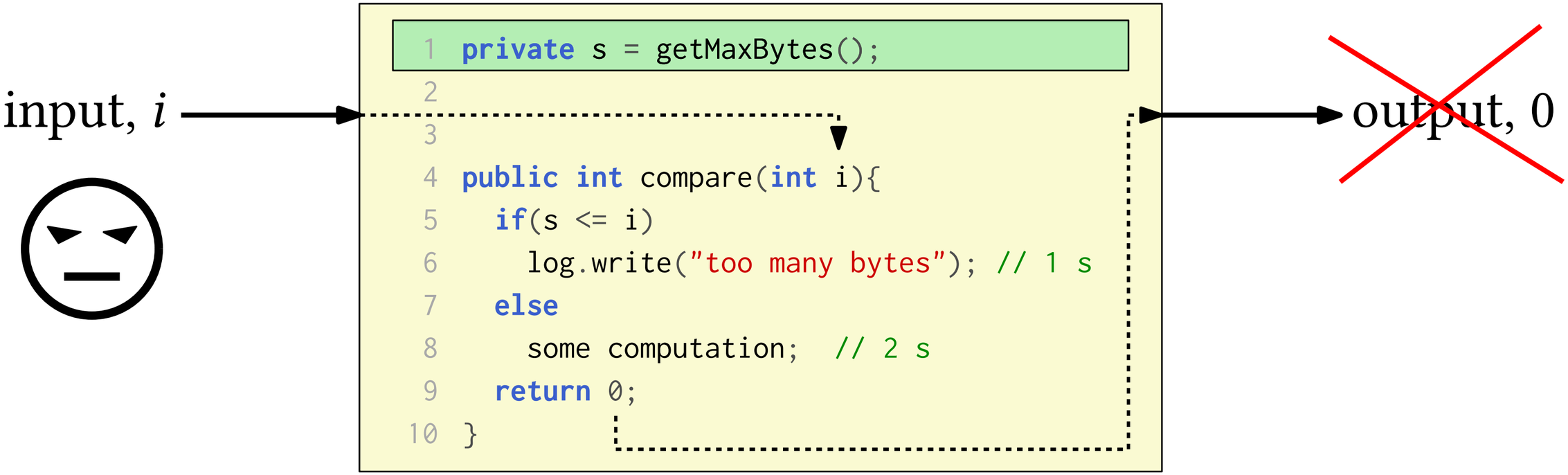

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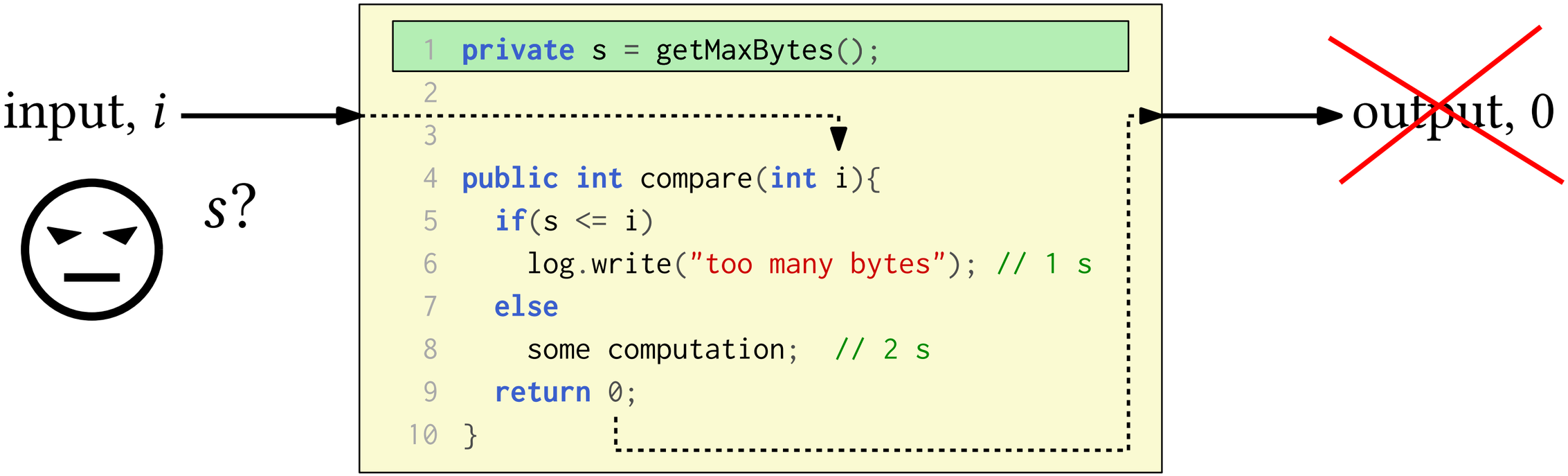

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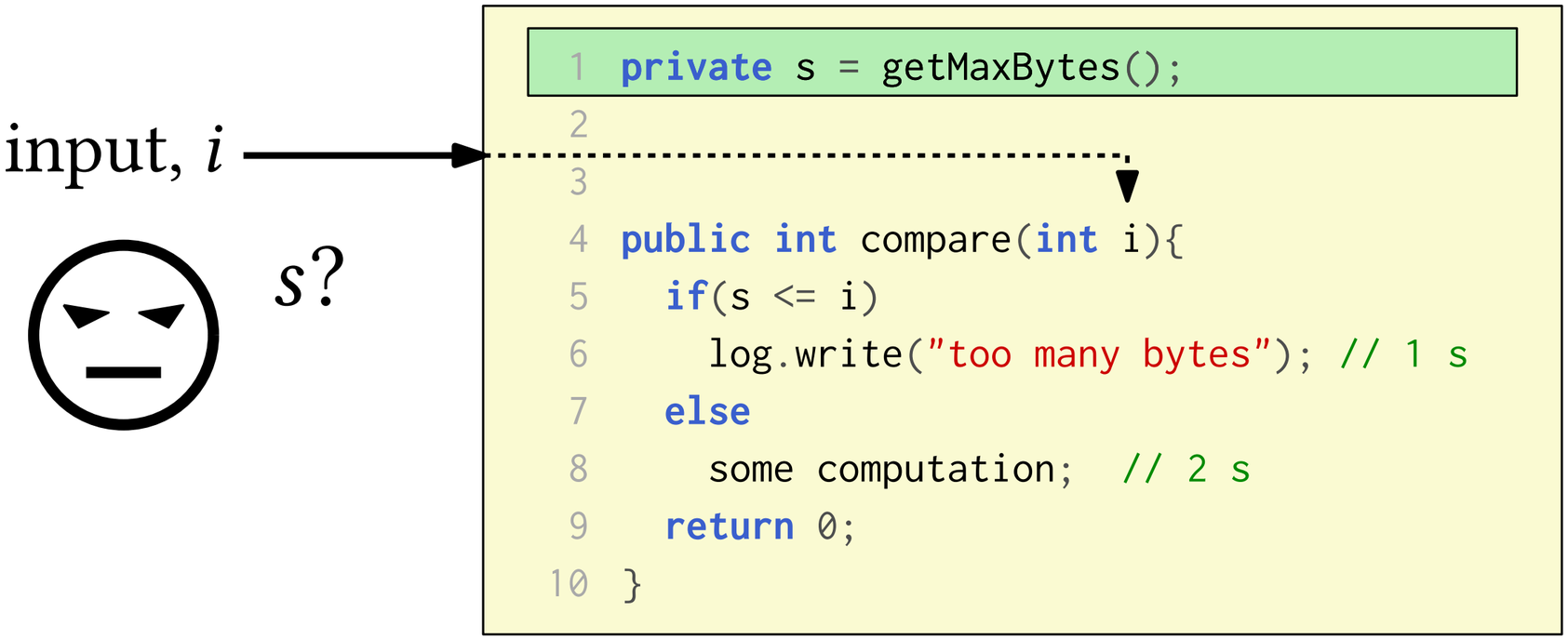

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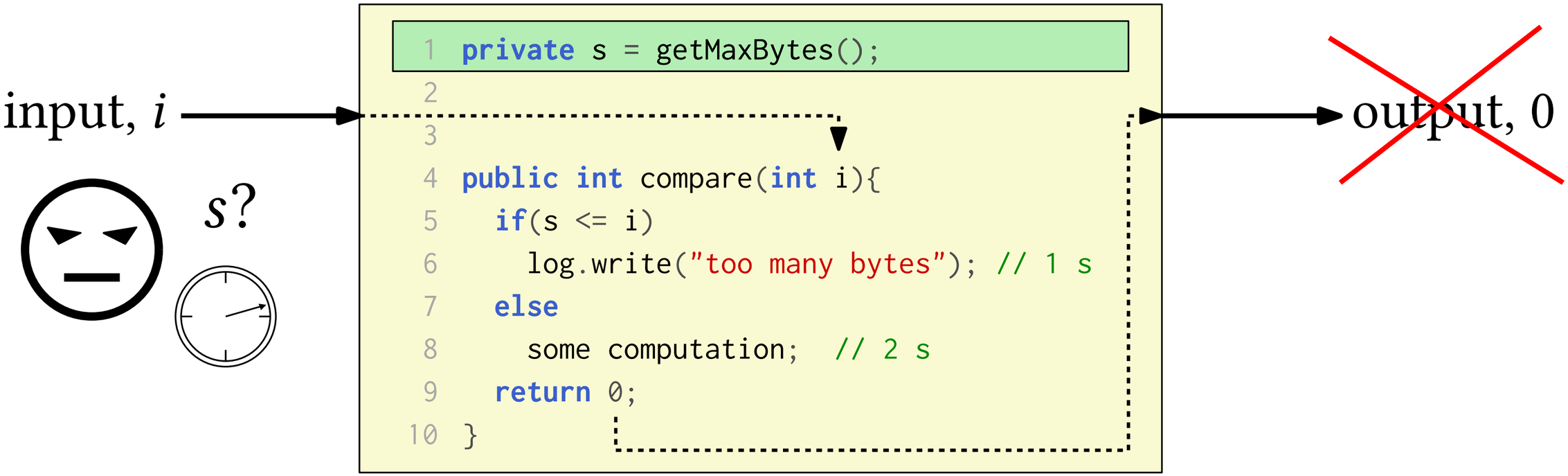

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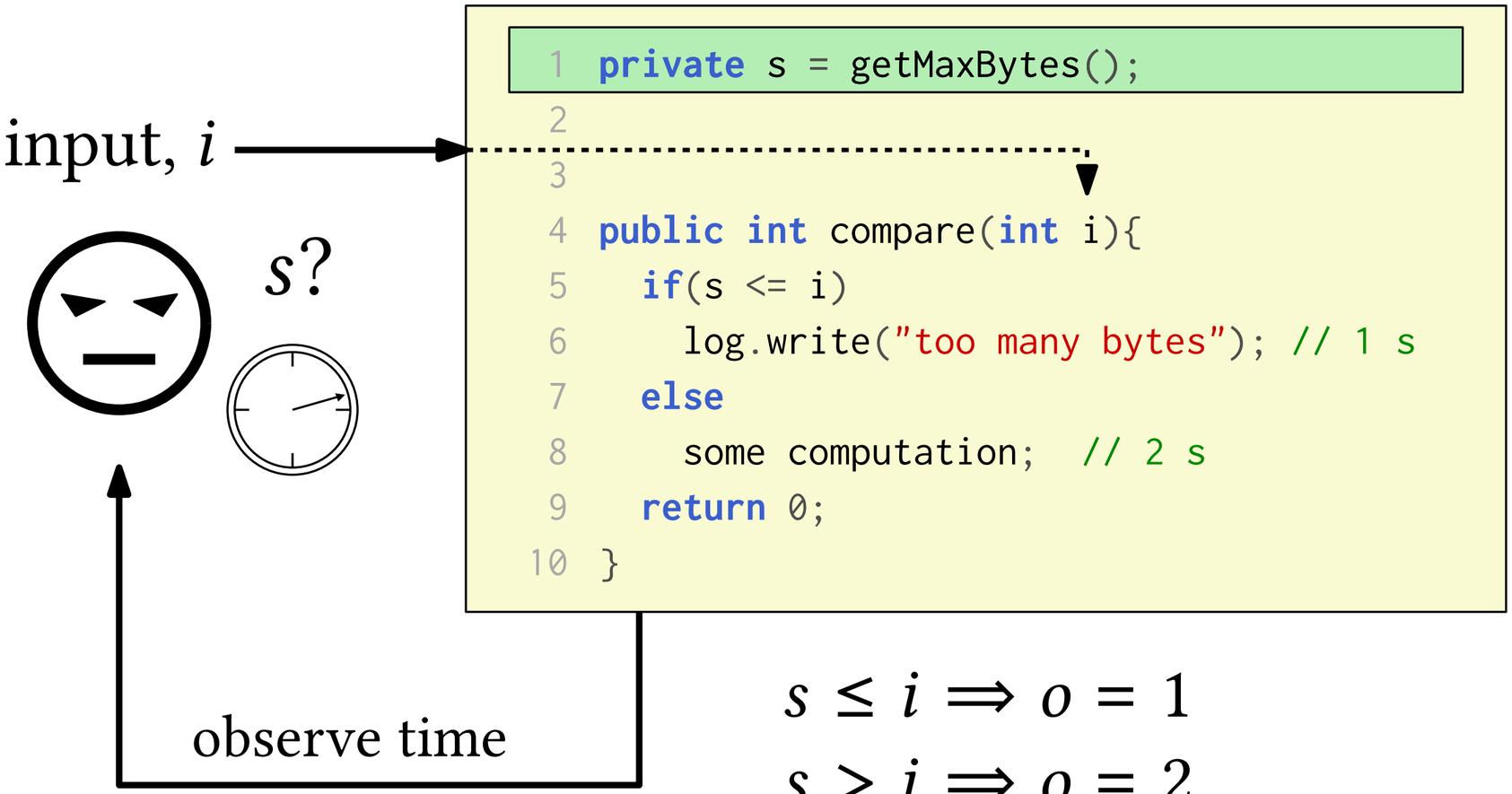

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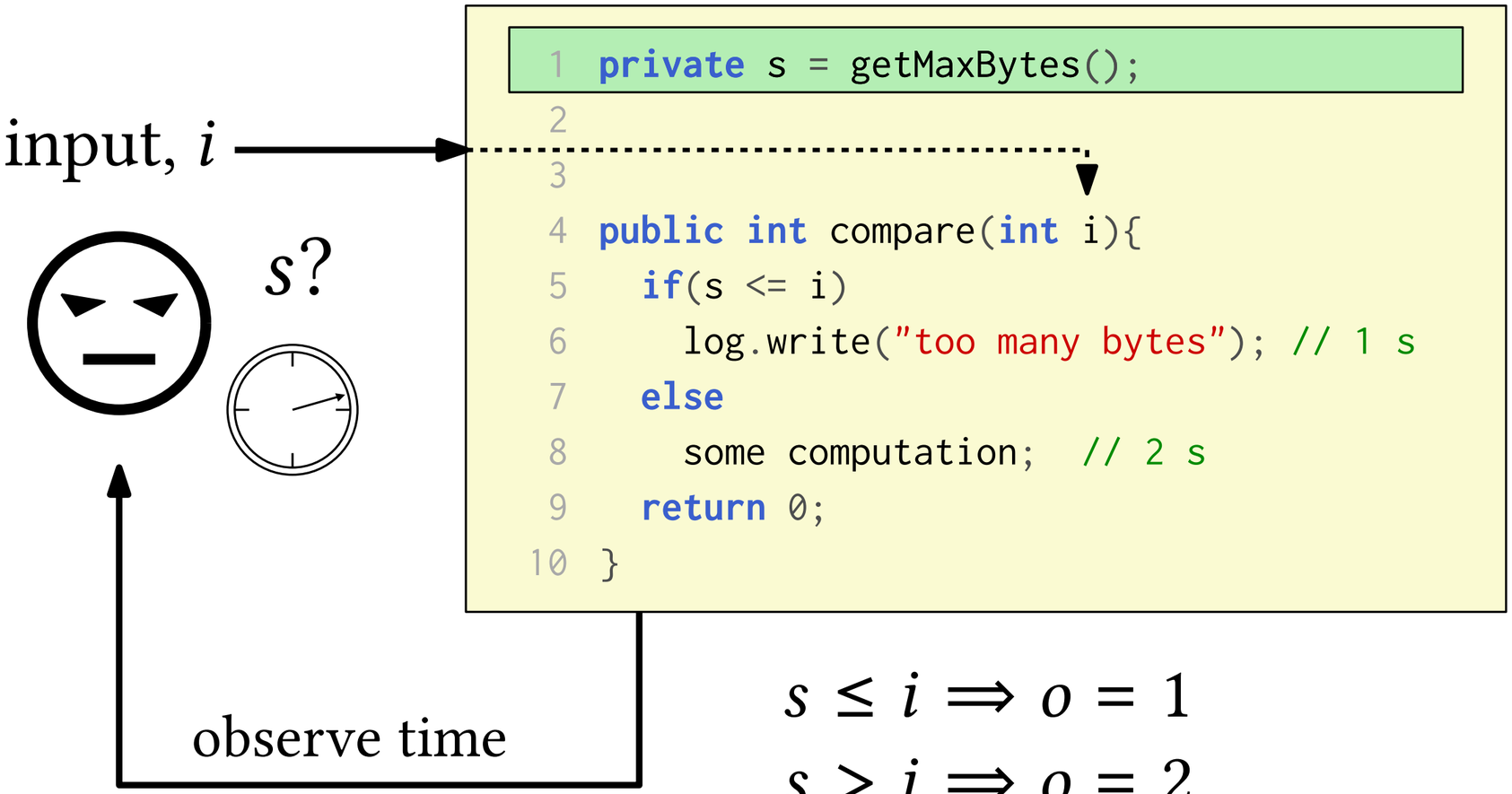

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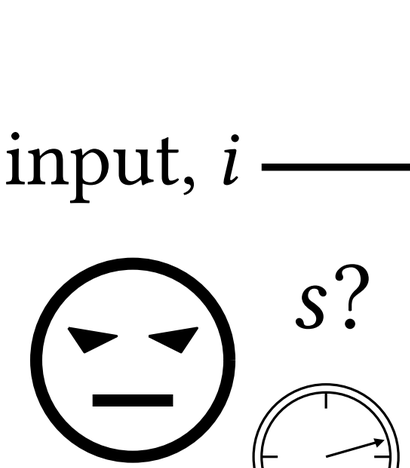


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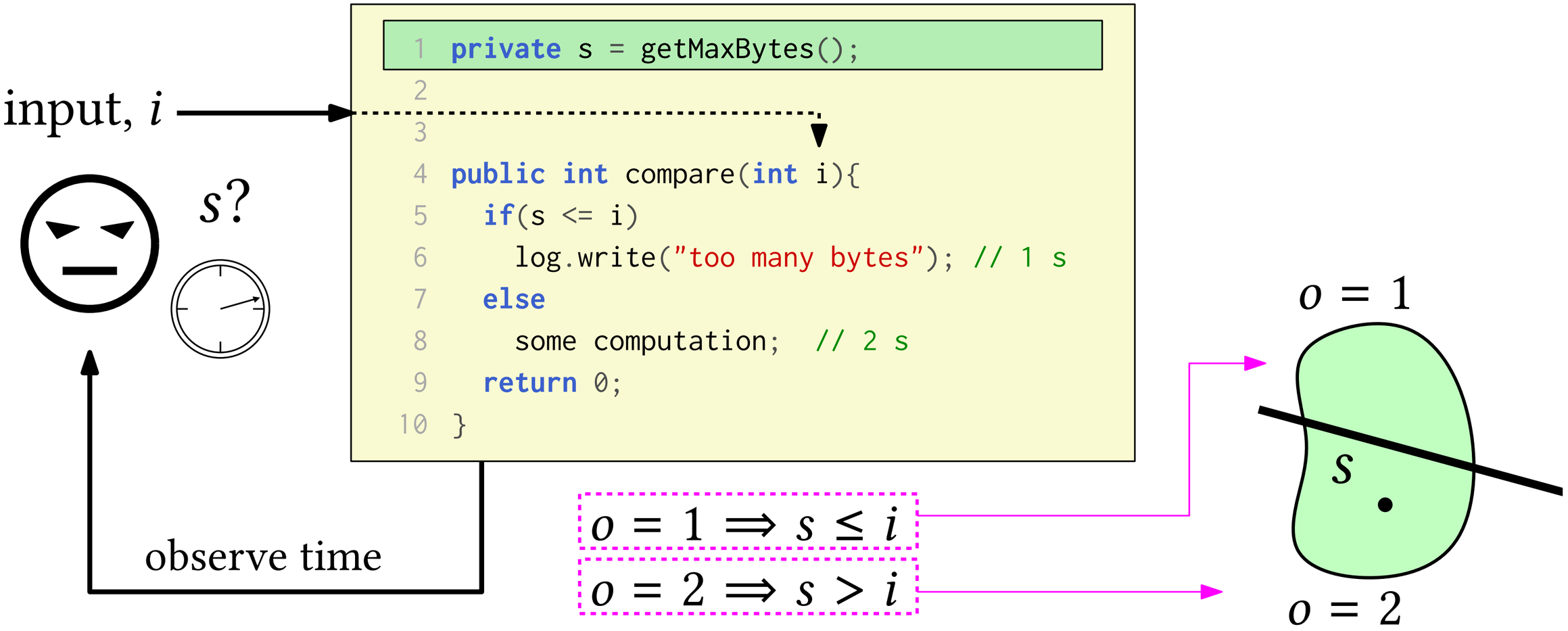

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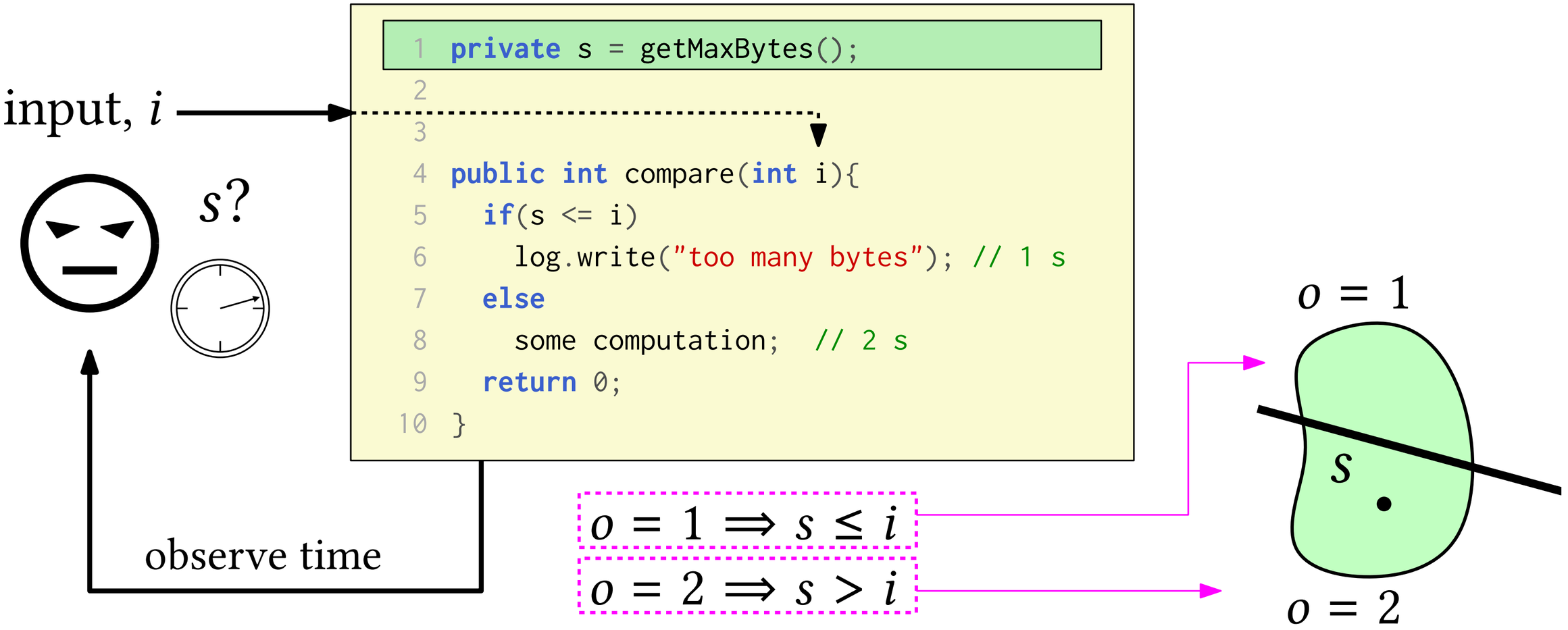

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Goal:

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determine if P is vulnerable to side channel attacks

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How?

Synthesize an attack!

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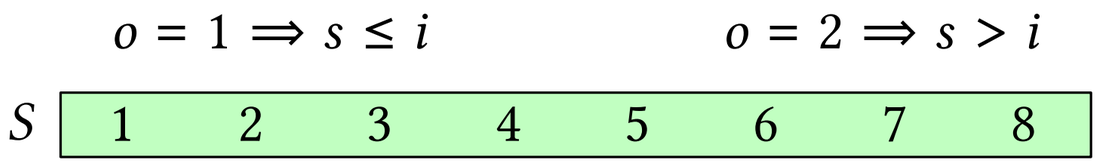

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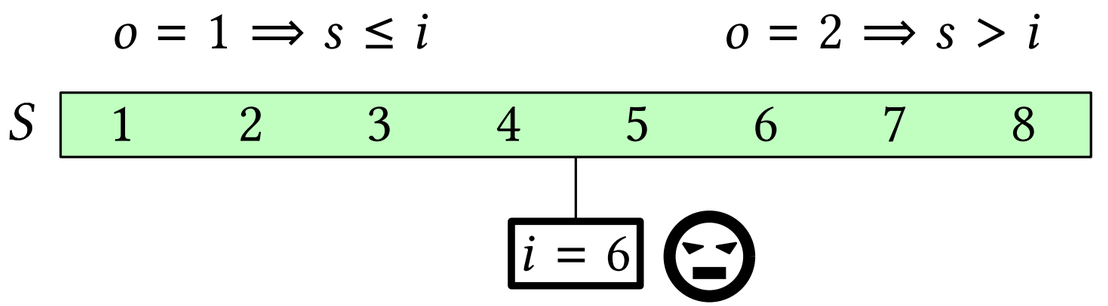

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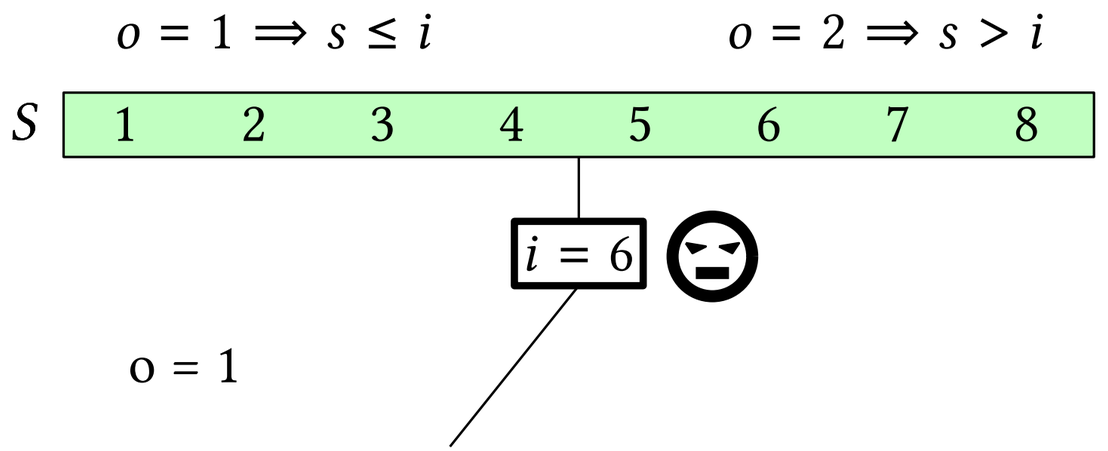
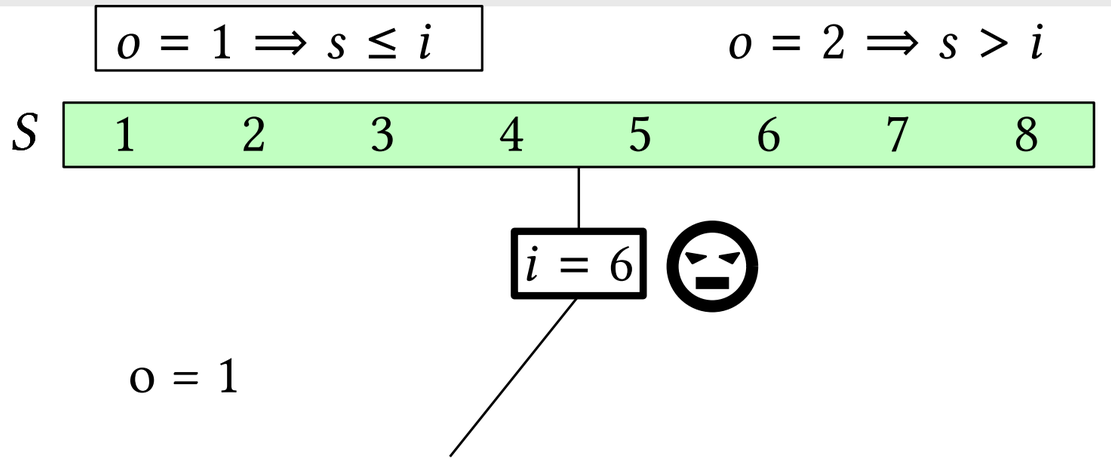
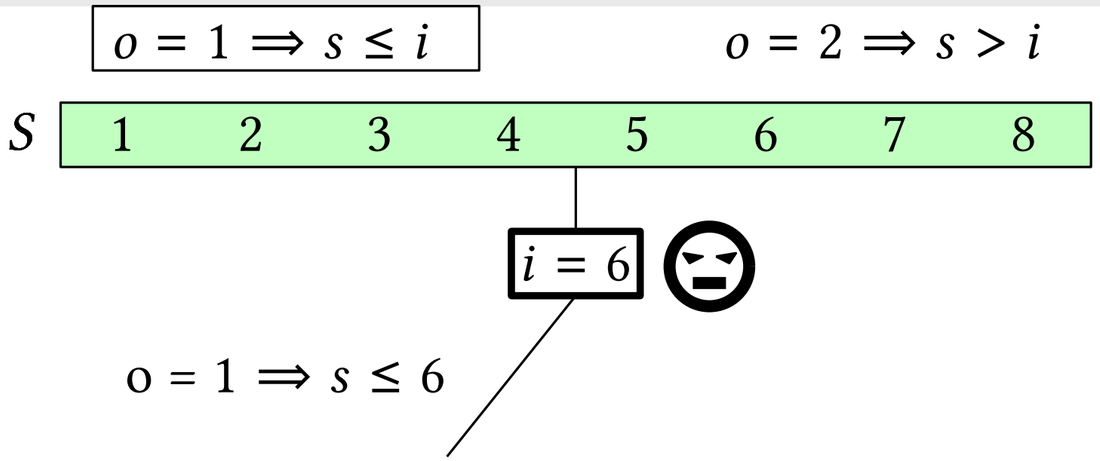


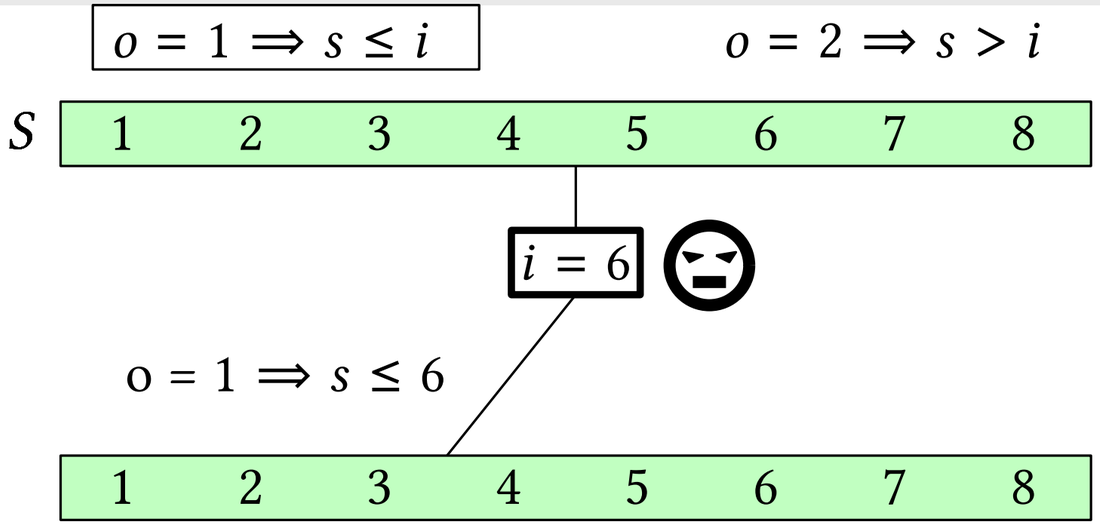
Adaptive Attack Trees



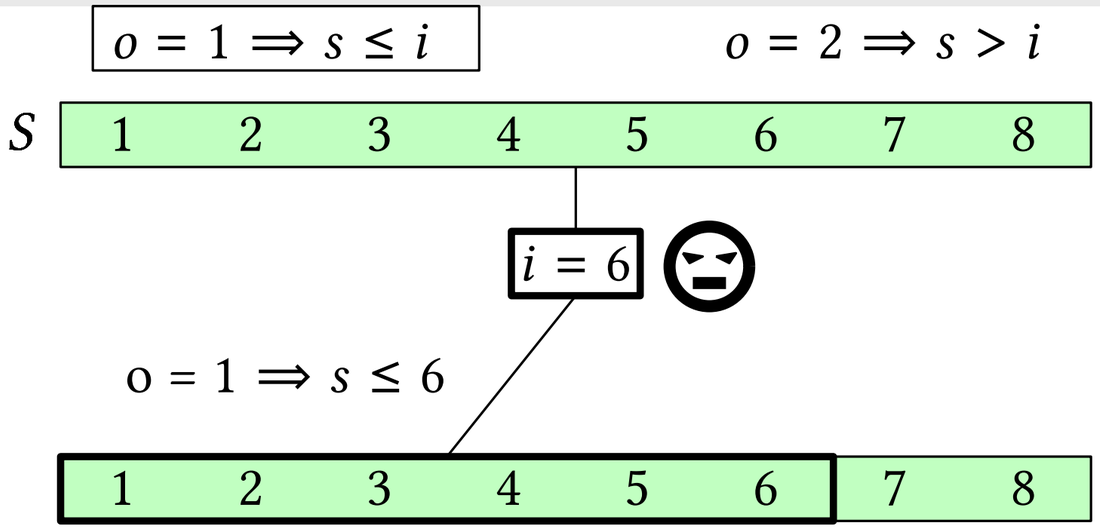
Adaptive Attack Trees



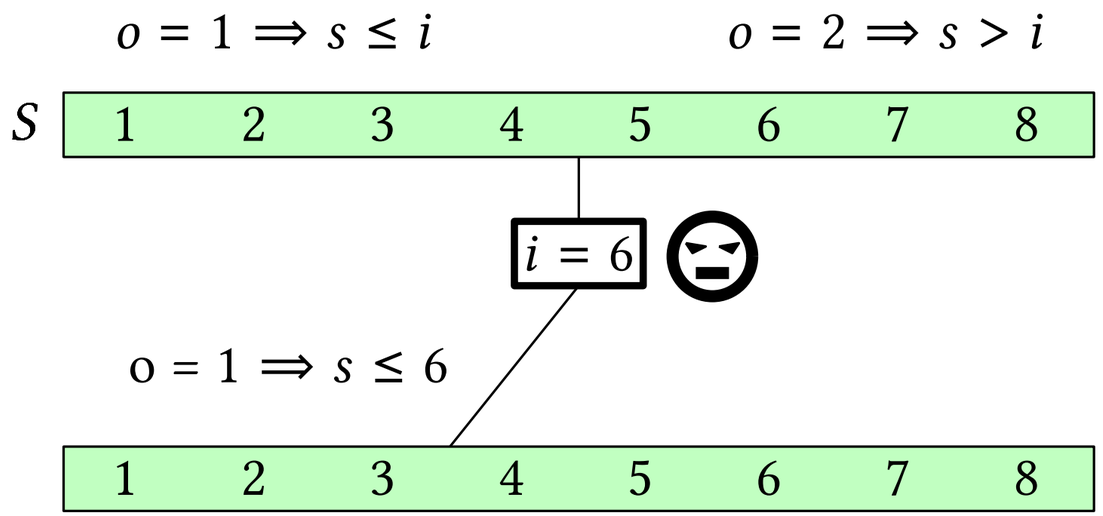
Adaptive Attack Trees



Adaptive Attack Trees



Adaptive Attack Trees



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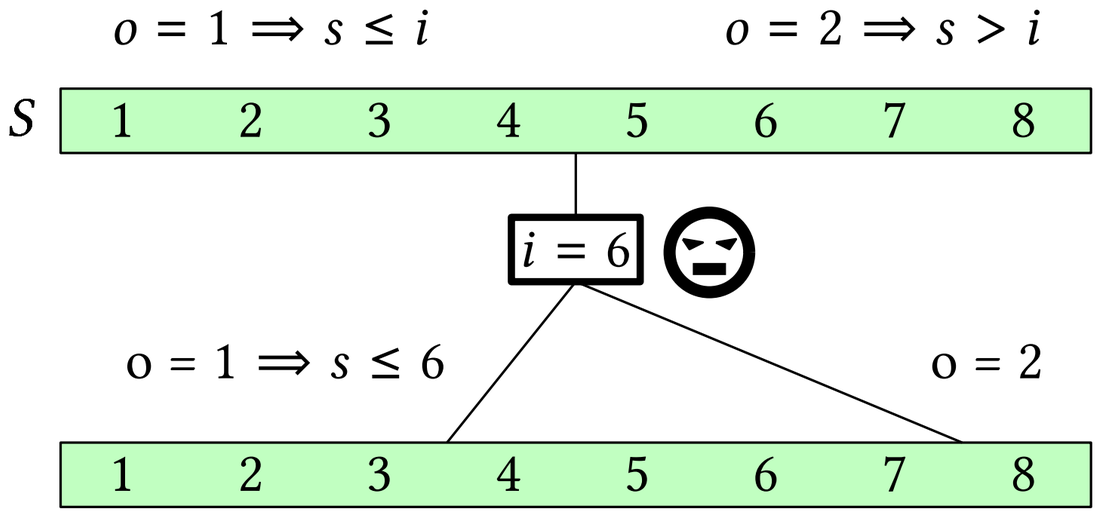
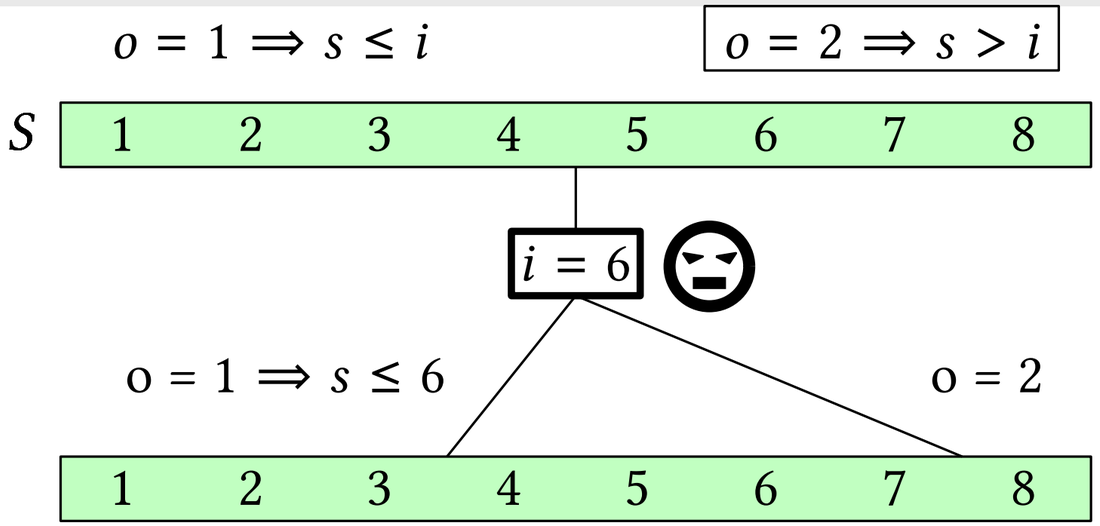
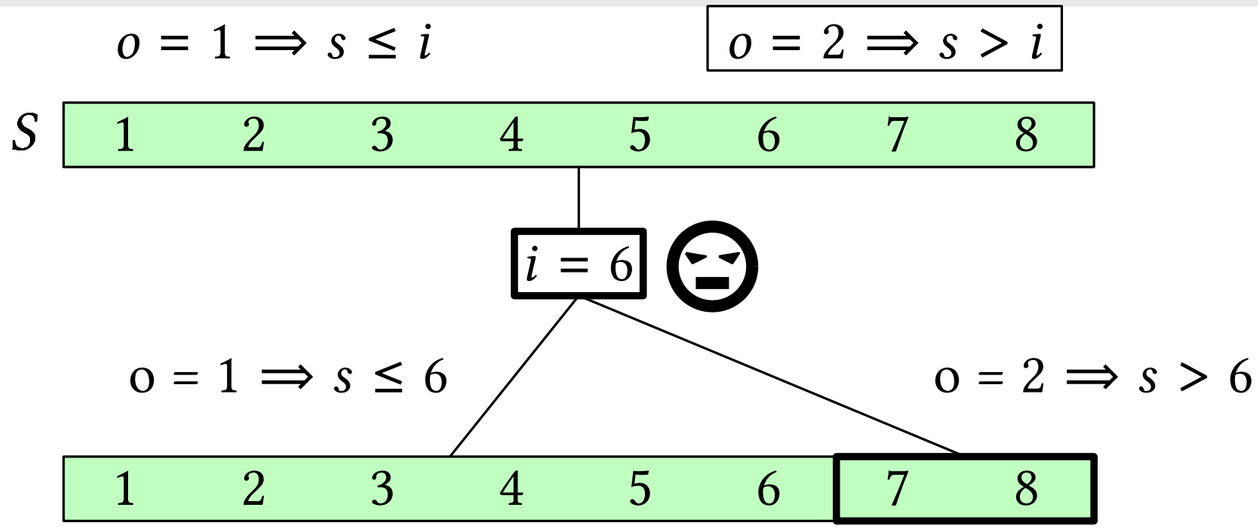


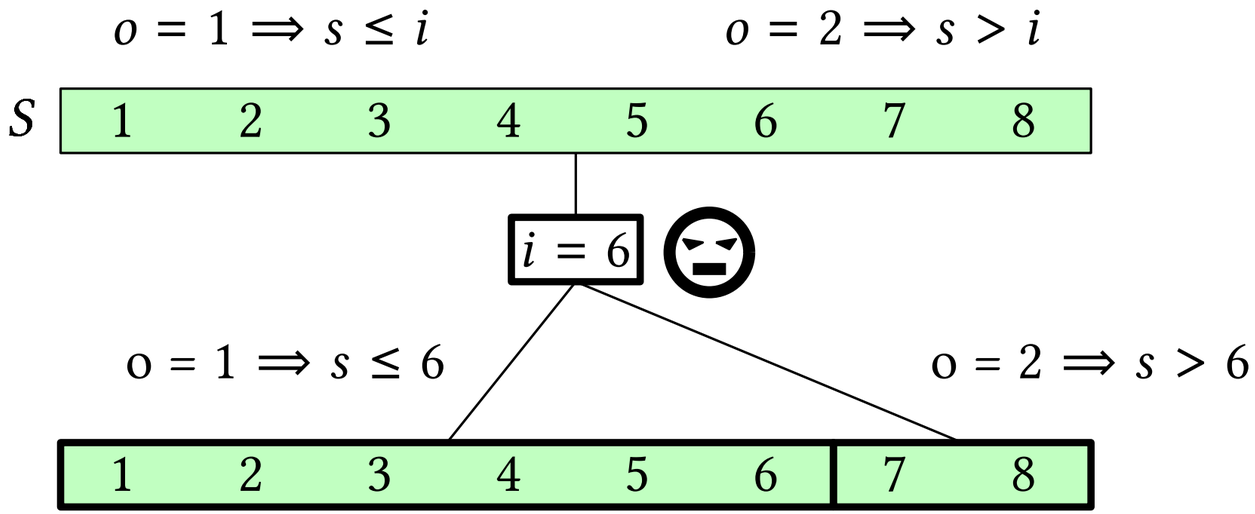
Adaptive Attack Trees



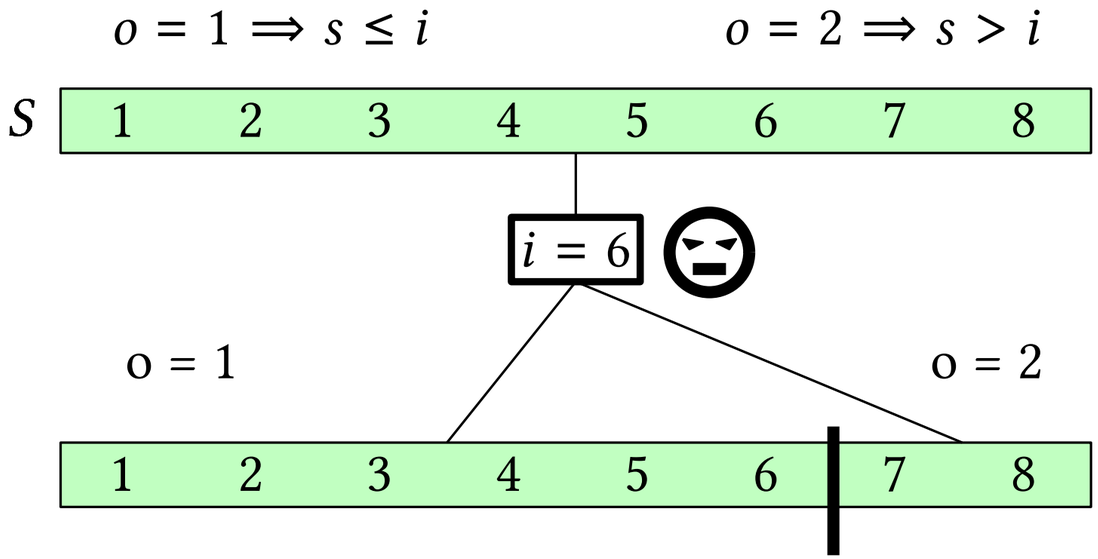
Adaptive Attack Trees



Adaptive Attack Trees

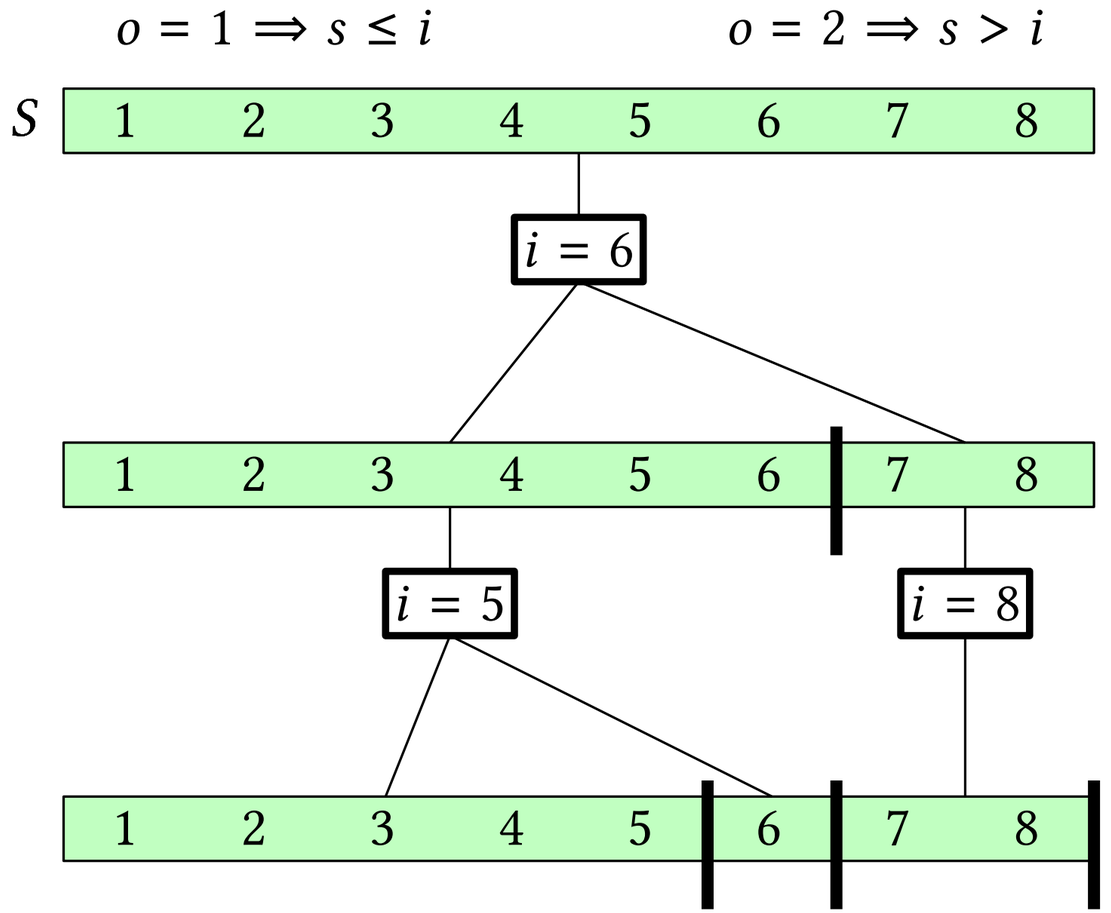


Adaptive Attack Trees

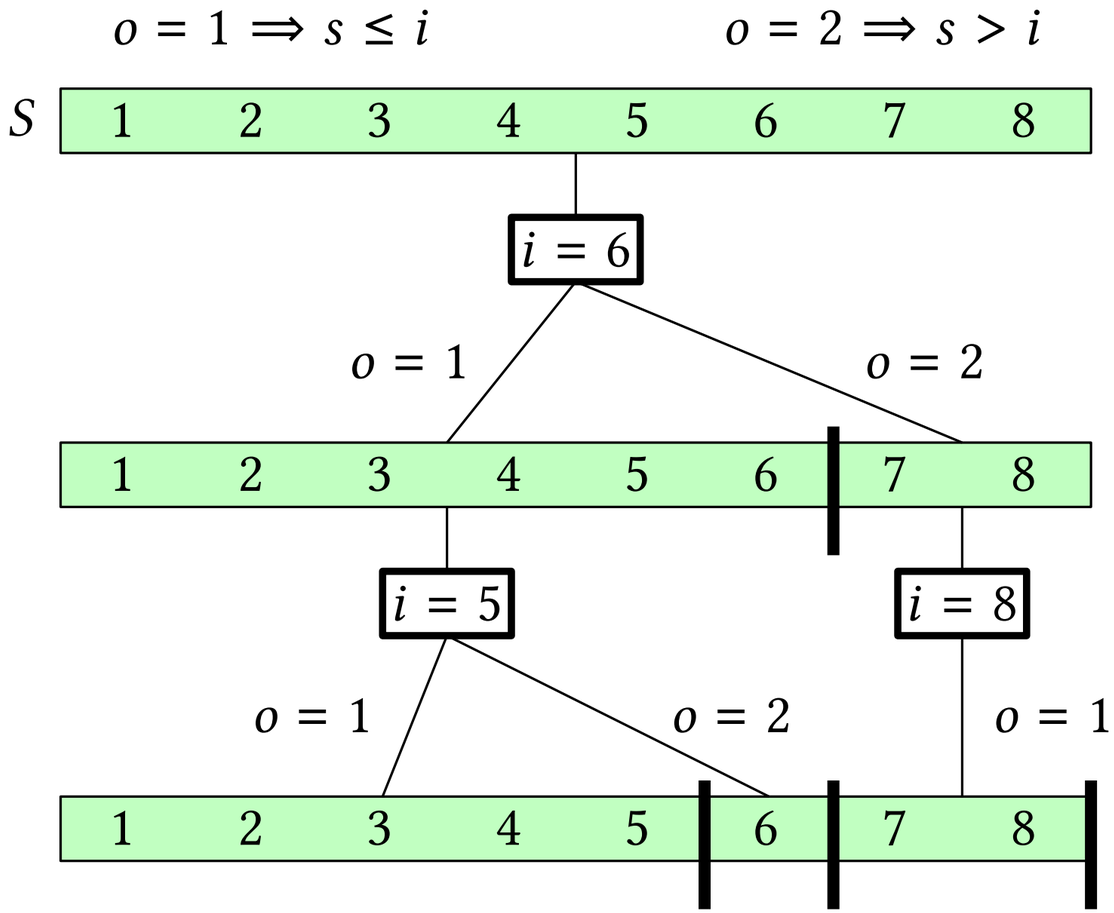


attacker's (i, o) **partitions** S domain

Adaptive Attack Trees

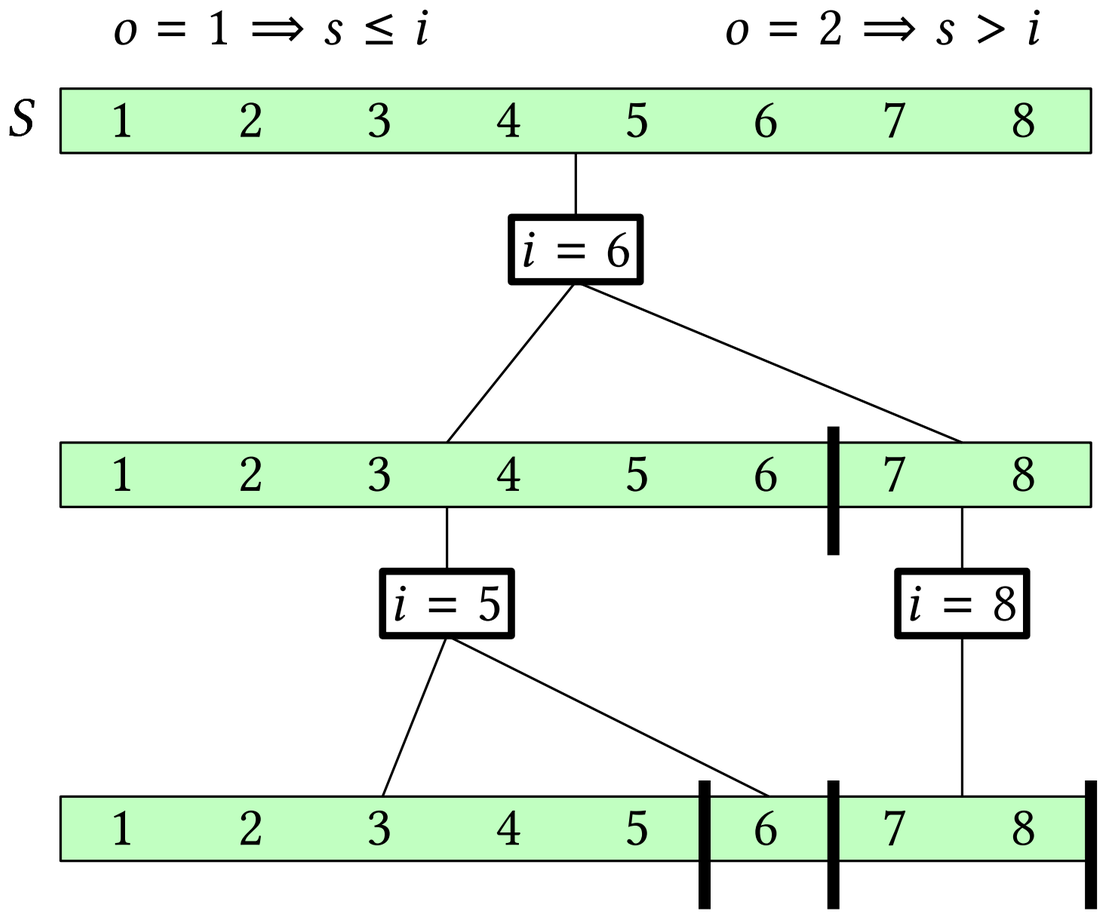


Adaptive Attack Trees

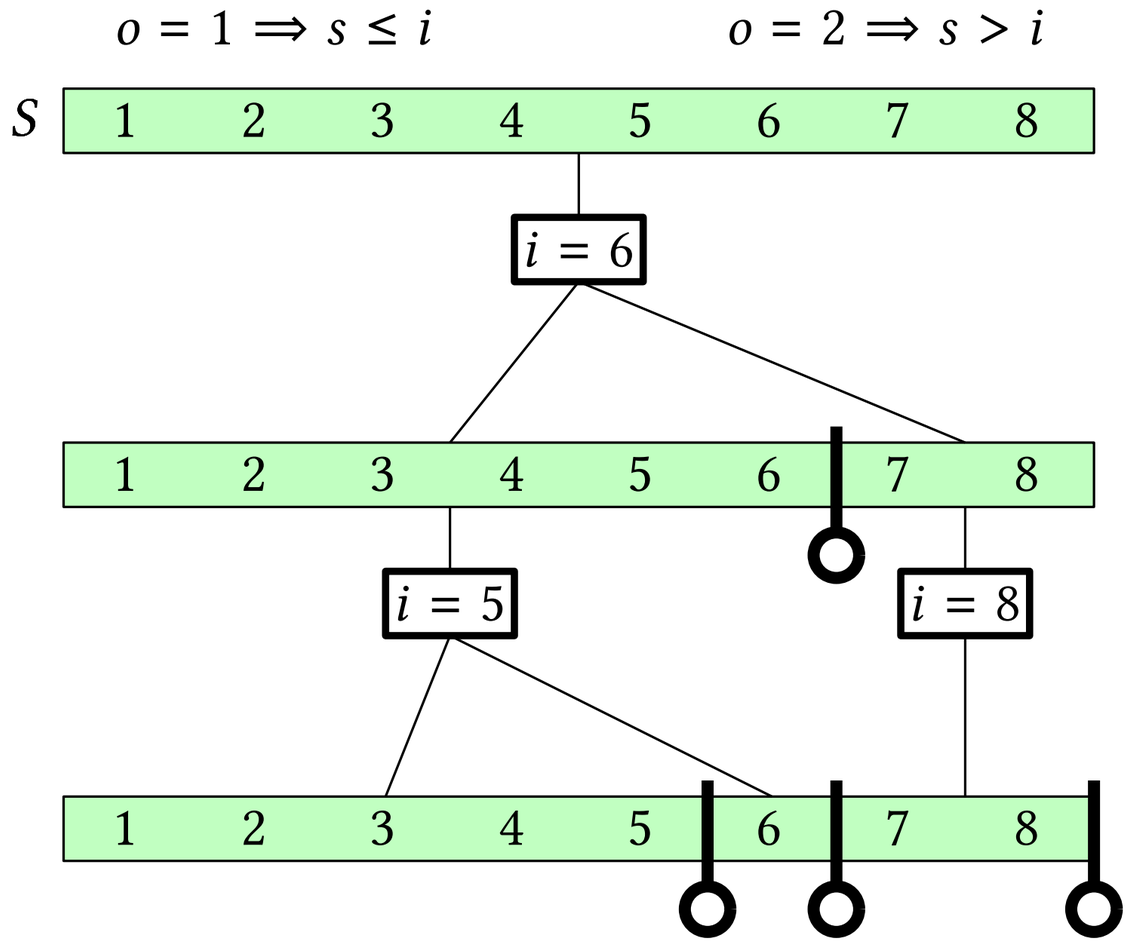


attacker's (i, o) sequences **partition** the S domain

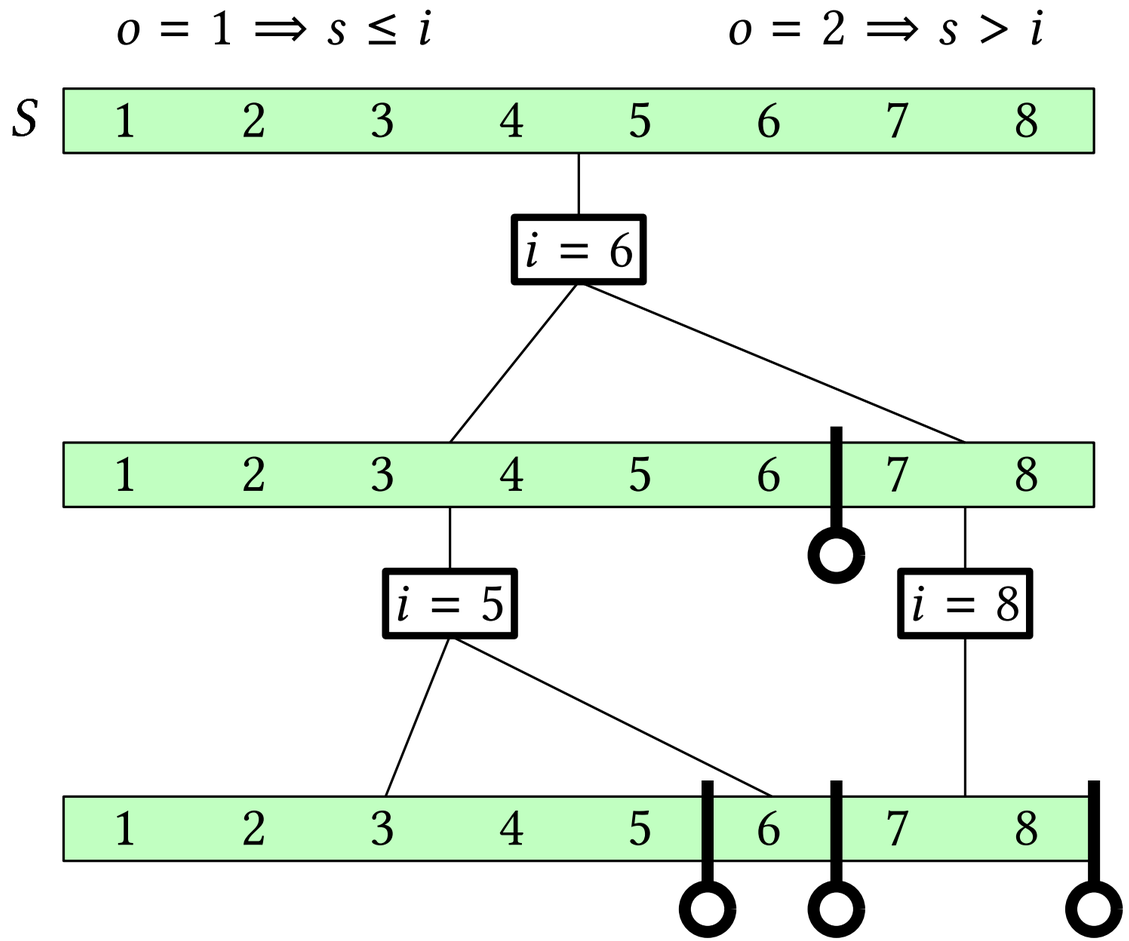
Adaptive Attack Trees



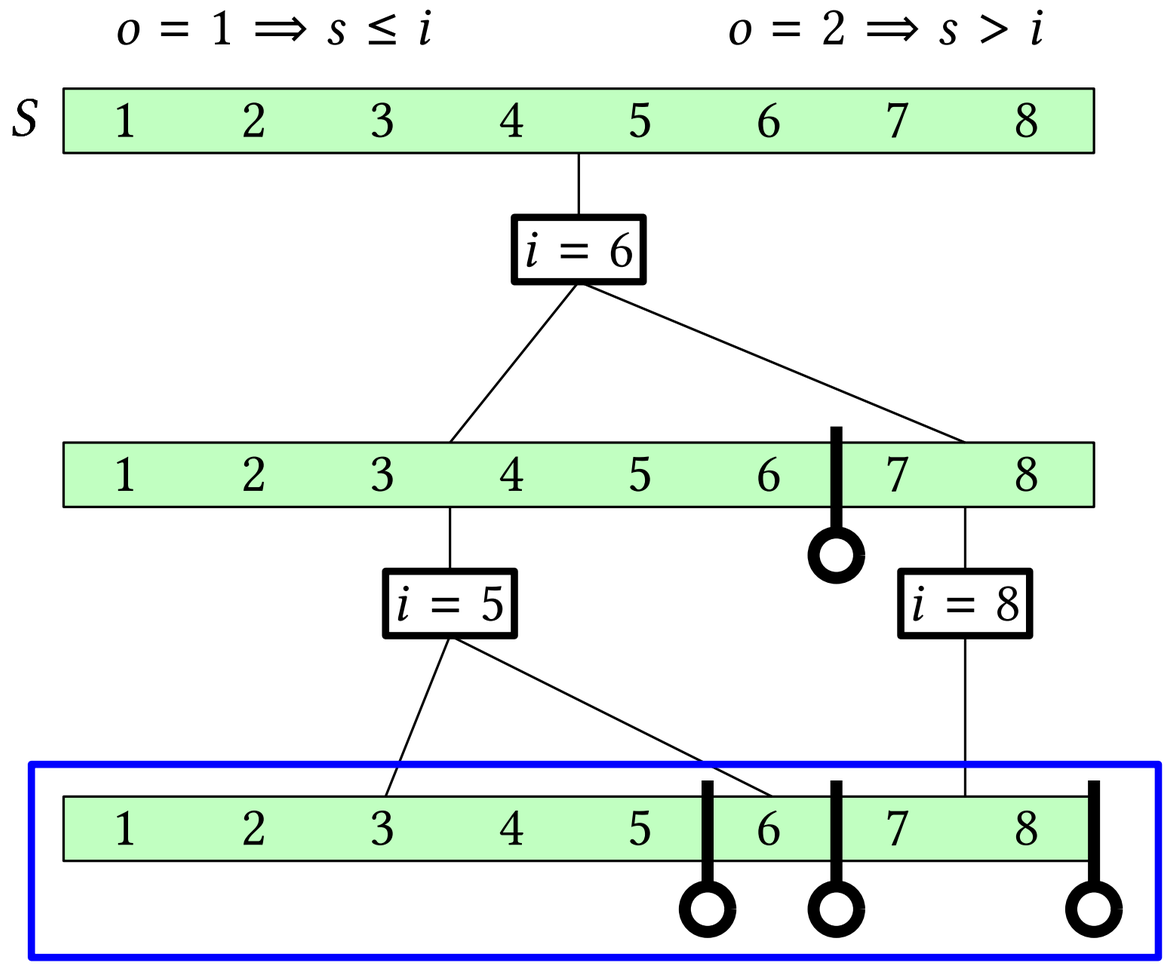
Adaptive Attack Trees



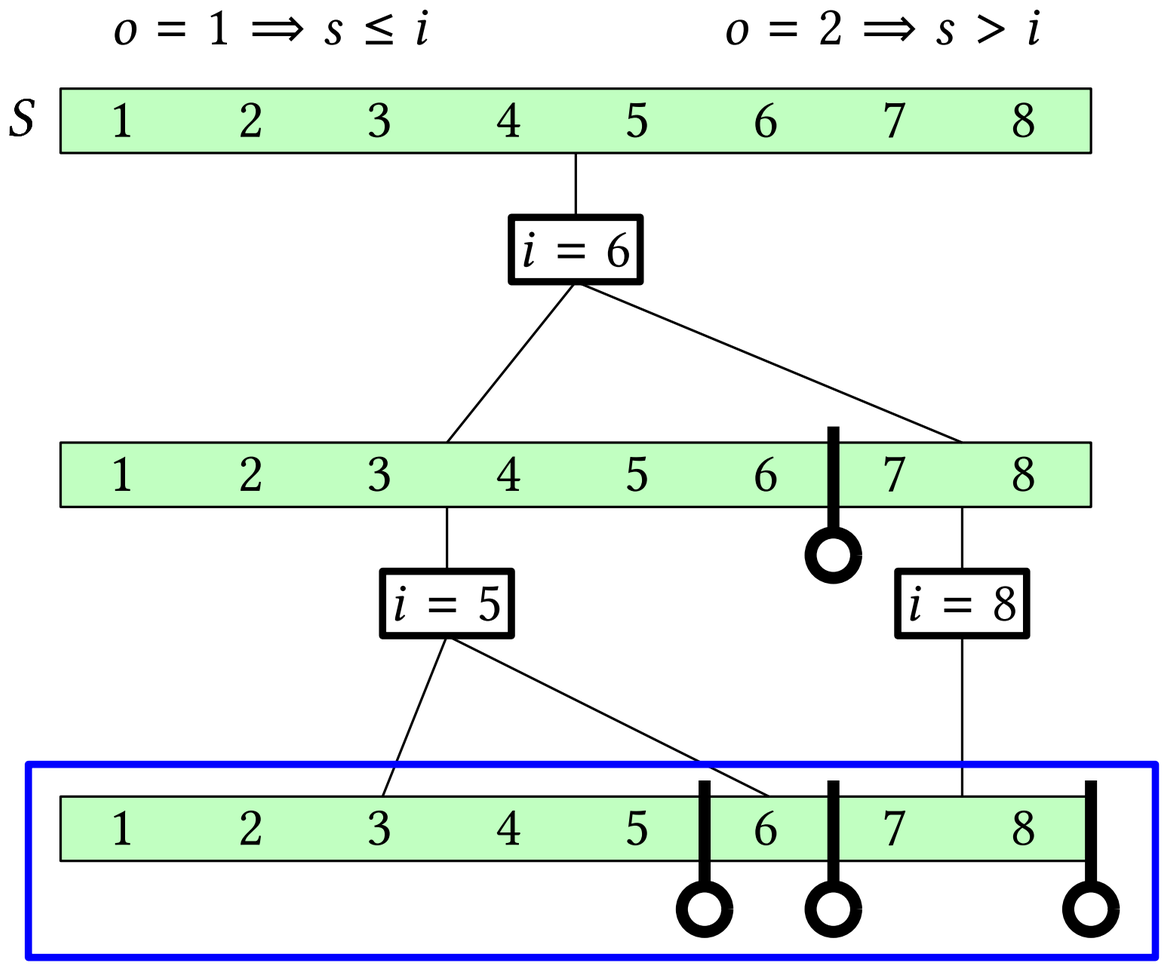
Adaptive Attack Trees



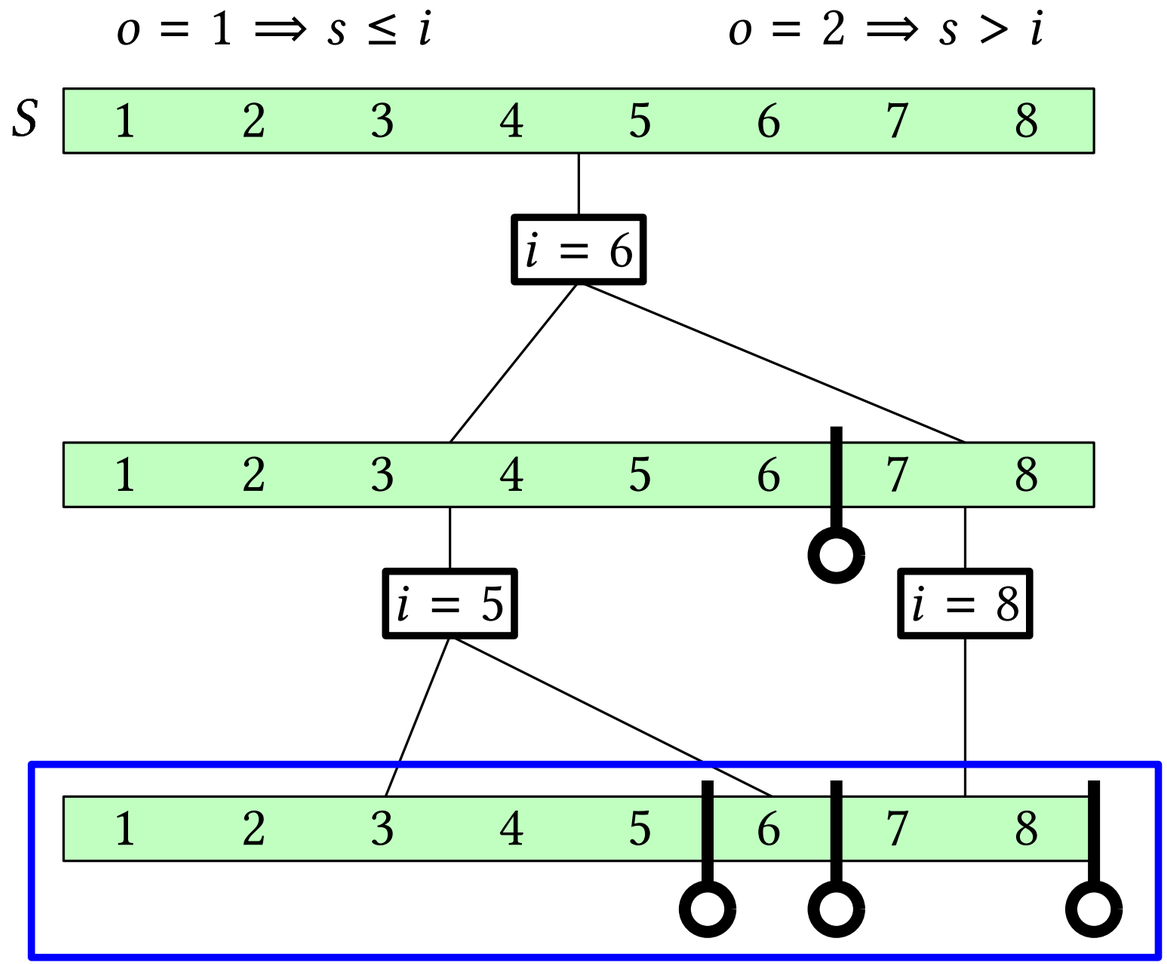
Adaptive Attack Trees



Adaptive Attack Trees



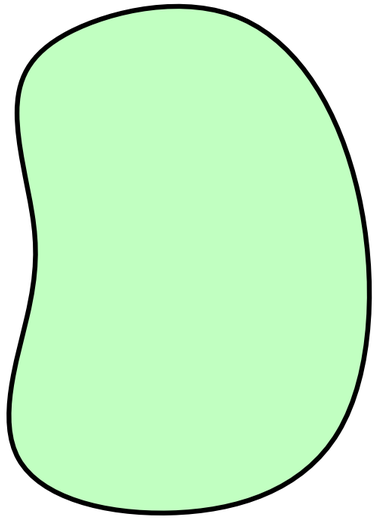
Adaptive Attack Trees



How to choose the best partition?

Entropy: Side Channels and Searching

$i_0 \in I$

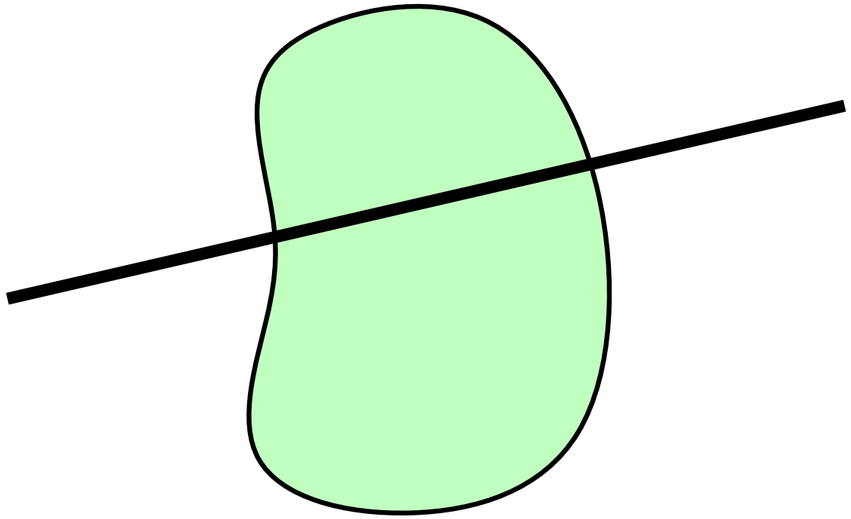


secret $s \in S$

Entropy: Side Channels and Searching

$i_0 \in I$

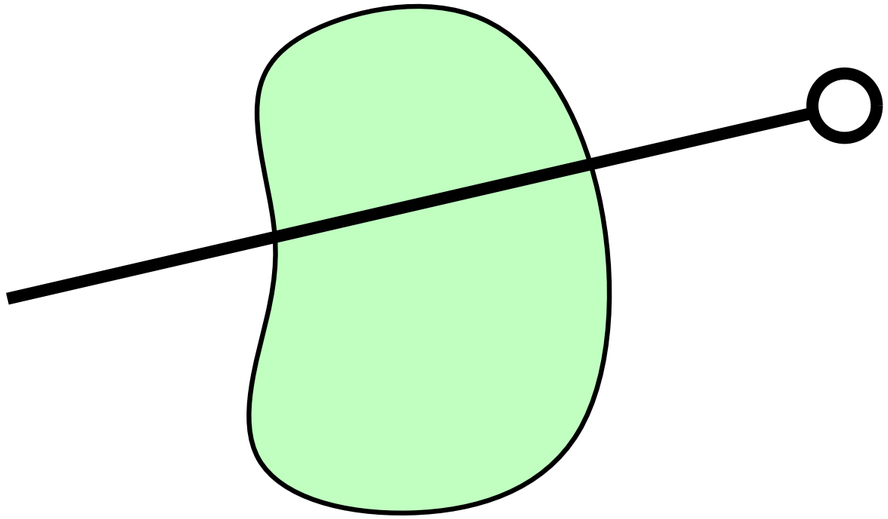
secret $s \in S$



Entropy: Side Channels and Searching

$i_0 \in I$

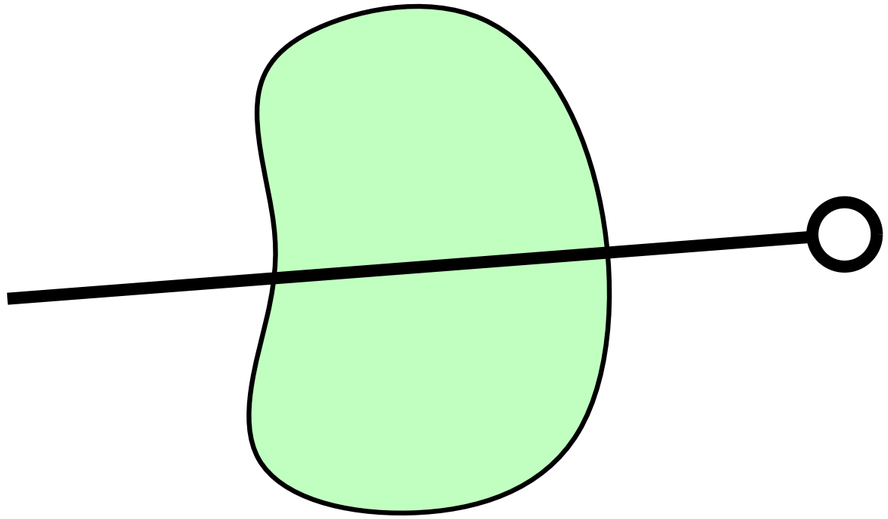
secret $s \in S$



Entropy: Side Channels and Searching

$i_0 \in I$

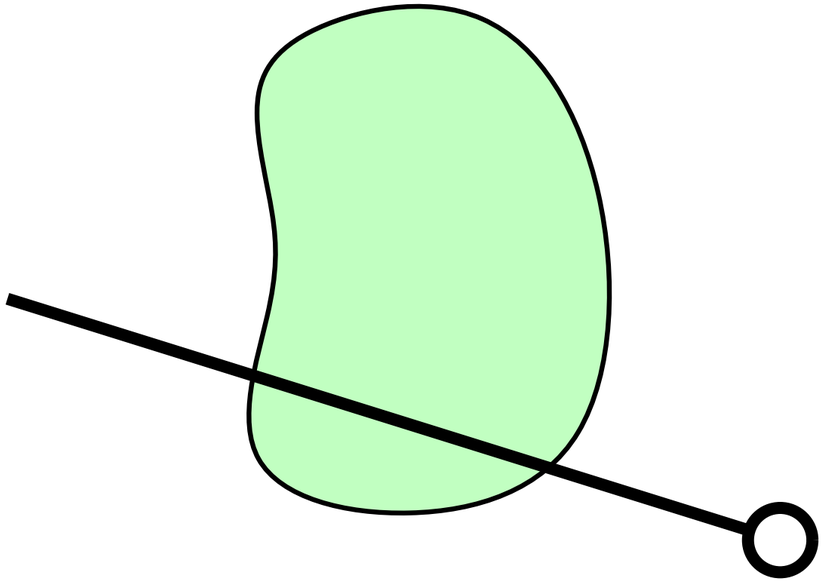
secret $s \in S$



Entropy: Side Channels and Searching

$i_0 \in I$

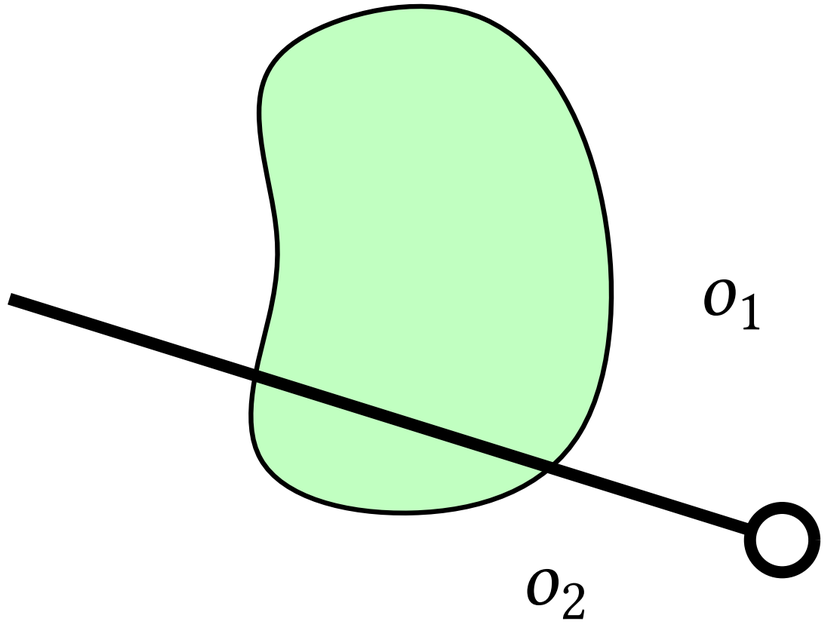
secret $s \in S$



Entropy: Side Channels and Searching

$i_0 \in I$

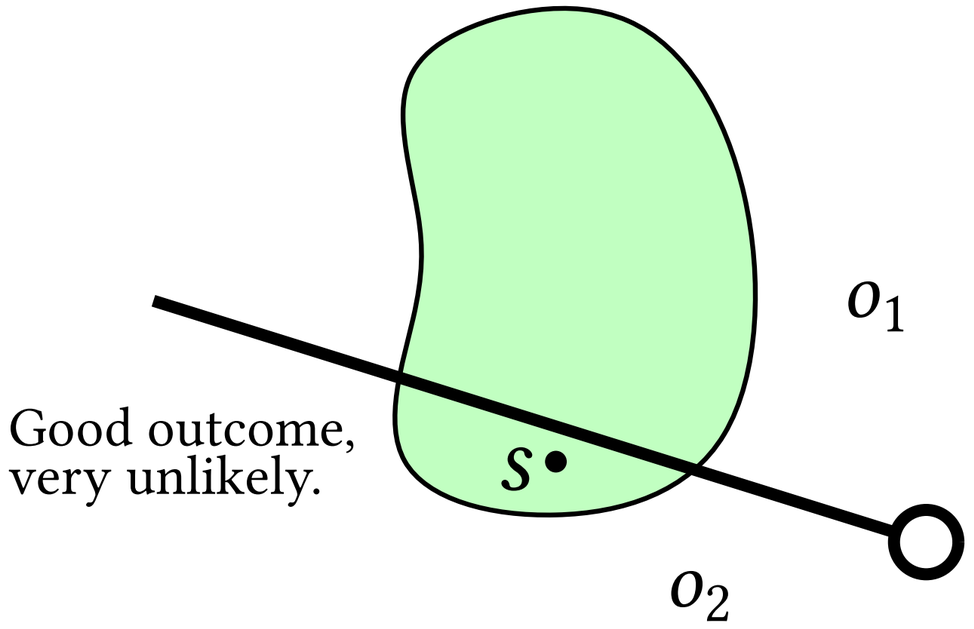
secret $s \in S$



Entropy: Side Channels and Searching

$i_0 \in I$

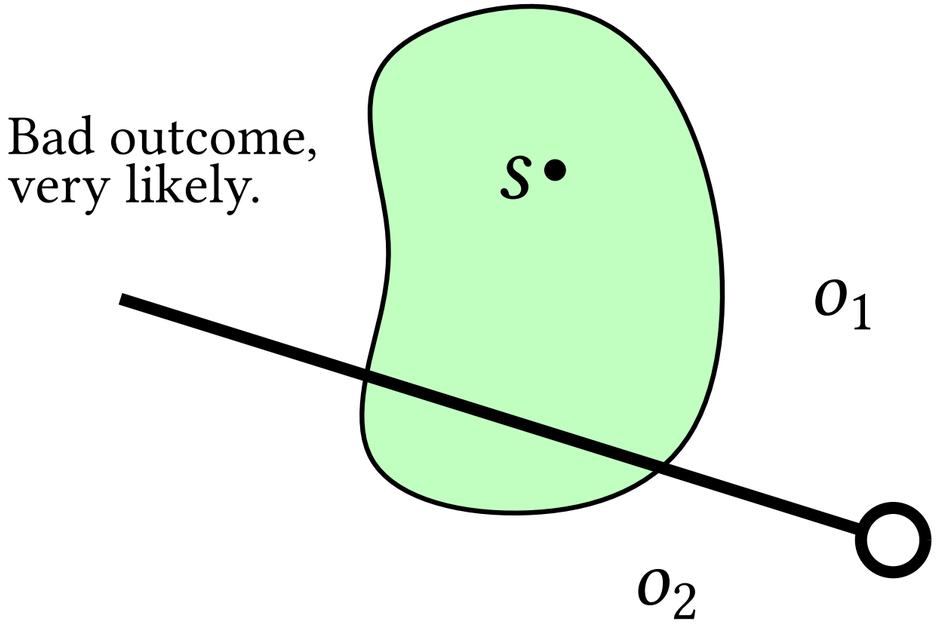
secret $s \in S$



Entropy: Side Channels and Searching

$i_0 \in I$

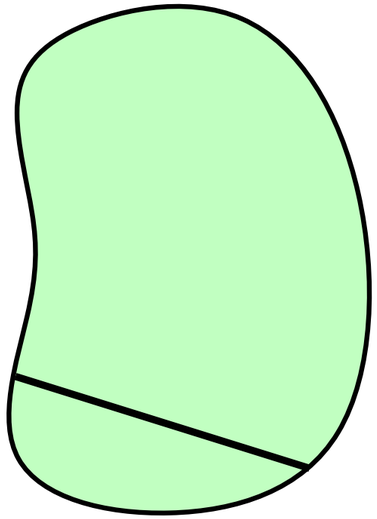
secret $s \in S$



Entropy: Side Channels and Searching

$i_0 \in I$

secret $s \in S$

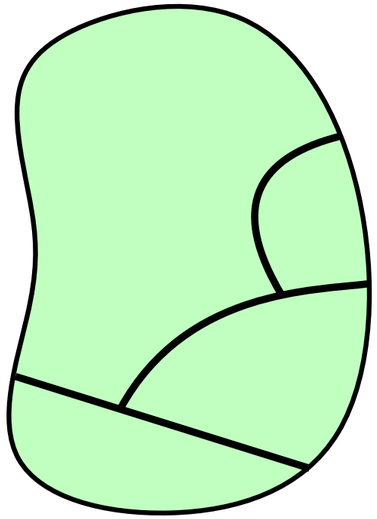


Entropy: Side Channels and Searching

$i_0 \in I$

$i_1 \in I$

$i_2 \in I$



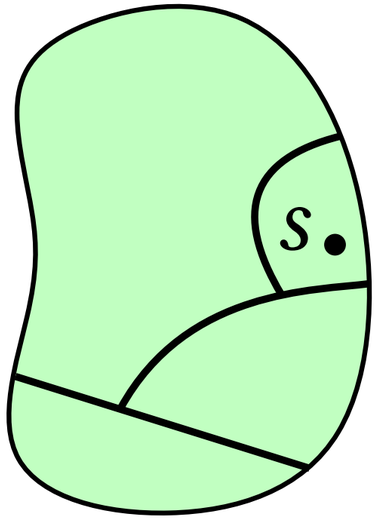
secret $s \in S$

Entropy: Side Channels and Searching

$i_0 \in I$

$i_1 \in I$

$i_2 \in I$



secret $s \in S$

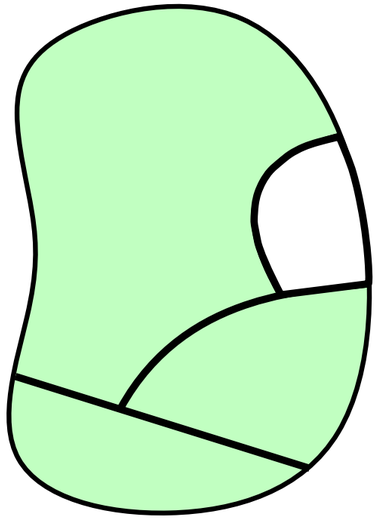
Entropy: Side Channels and Searching

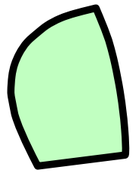
$i_0 \in I$

$i_1 \in I$

$i_2 \in I$

secret $s \in S$



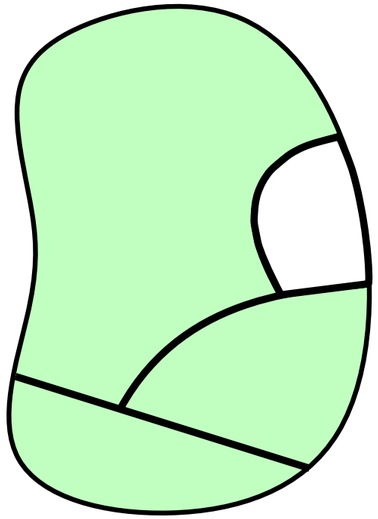
$p(s \in$  $)$

Entropy: Side Channels and Searching

$i_0 \in I$

$i_1 \in I$

$i_2 \in I$



secret $s \in S$

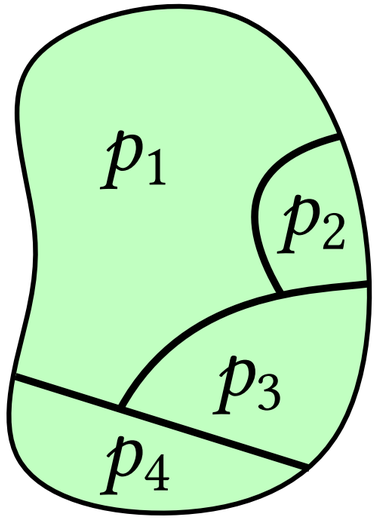
$$p(s \in \text{[shape]}) = \frac{|\text{[shape]}|}{|\text{[shape]}|}$$

Entropy: Side Channels and Searching

$i_0 \in I$

$i_1 \in I$

$i_2 \in I$



secret $s \in S$

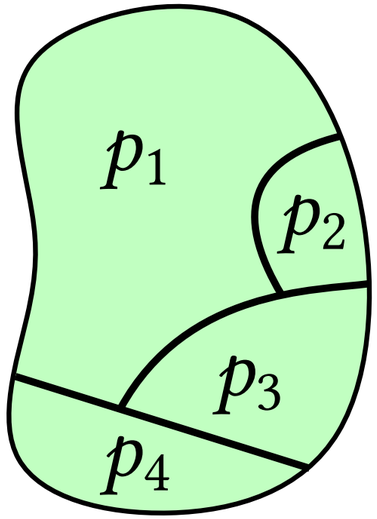
Entropy: Side Channels and Searching

secret $s \in S$

$i_0 \in I$

$i_1 \in I$

$i_2 \in I$



Quantify expected info gain measured in bits.

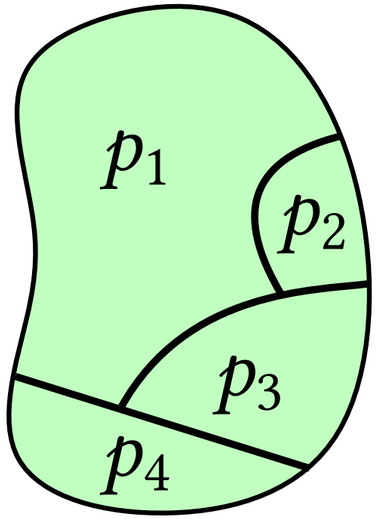
Entropy: Side Channels and Searching

$i_0 \in I$

$i_1 \in I$

$i_2 \in I$

secret $s \in S$



Quantify expected info gain measured in bits.

$$\frac{1}{p_j}$$

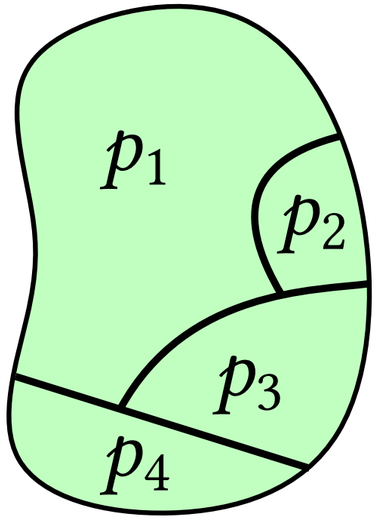
Entropy: Side Channels and Searching

$i_0 \in I$

$i_1 \in I$

$i_2 \in I$

secret $s \in S$



Quantify expected info gain measured in bits.

$$\log_2 \frac{1}{p_j}$$

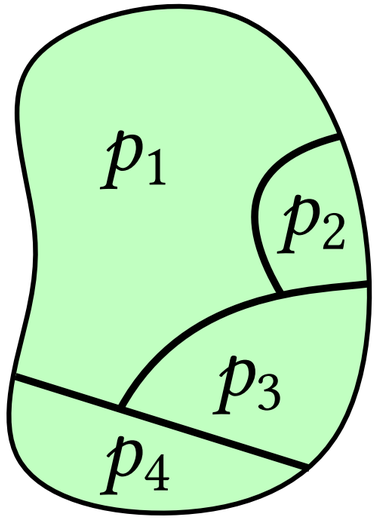
Entropy: Side Channels and Searching

$i_0 \in I$

$i_1 \in I$

$i_2 \in I$

secret $s \in S$



Quantify expected info gain measured in bits.

$$\sum_{j=1}^{n} p_j \log_2 \frac{1}{p_j}$$

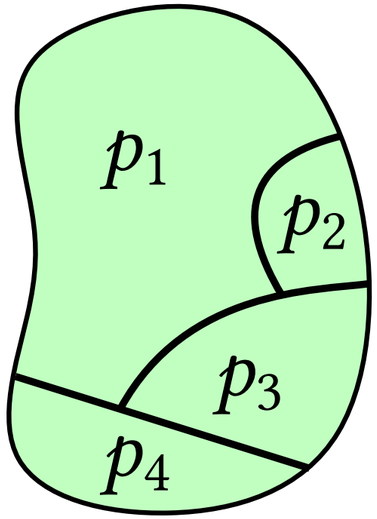
Entropy: Side Channels and Searching

secret $s \in S$

$i_0 \in I$

$i_1 \in I$

$i_2 \in I$



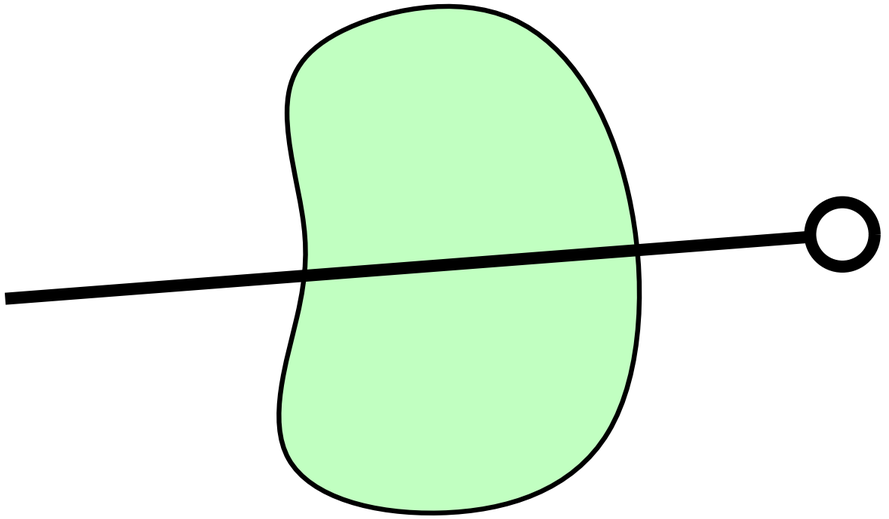
Quantify expected info gain measured in bits.

$$\mathcal{H} = \sum_{j=1}^{n} p_j \log_2 \frac{1}{p_j}$$

Entropy: Side Channels and Searching

$i_0 \in I$

secret $s \in S$



Quantify expected info gain measured in bits.

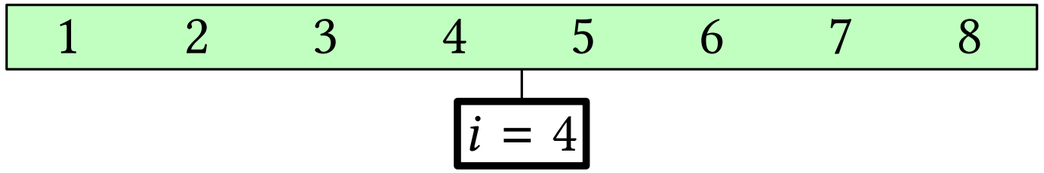
$$\mathcal{H} = \sum_{j=1}^{n} p_j \log_2 \frac{1}{p_j}$$

$o = 1 \Rightarrow s \leq i$

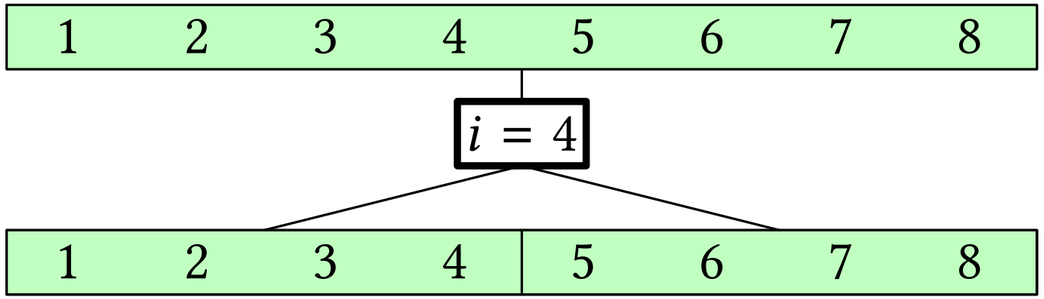
$o = 2 \Rightarrow s > i$

$o = 1 \Rightarrow s \leq i$ $o = 2 \Rightarrow s > i$

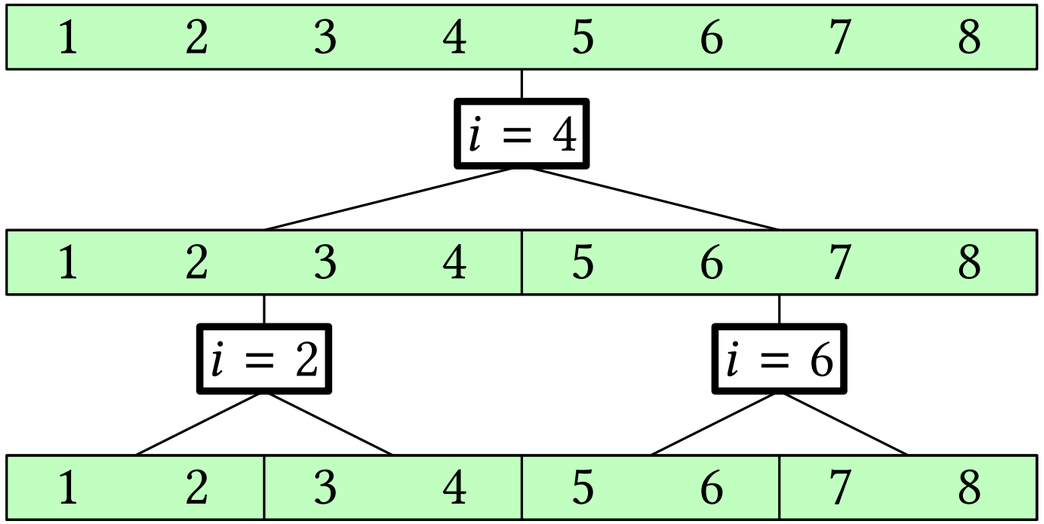
$o = 1 \Rightarrow s \leq i$ $o = 2 \Rightarrow s > i$



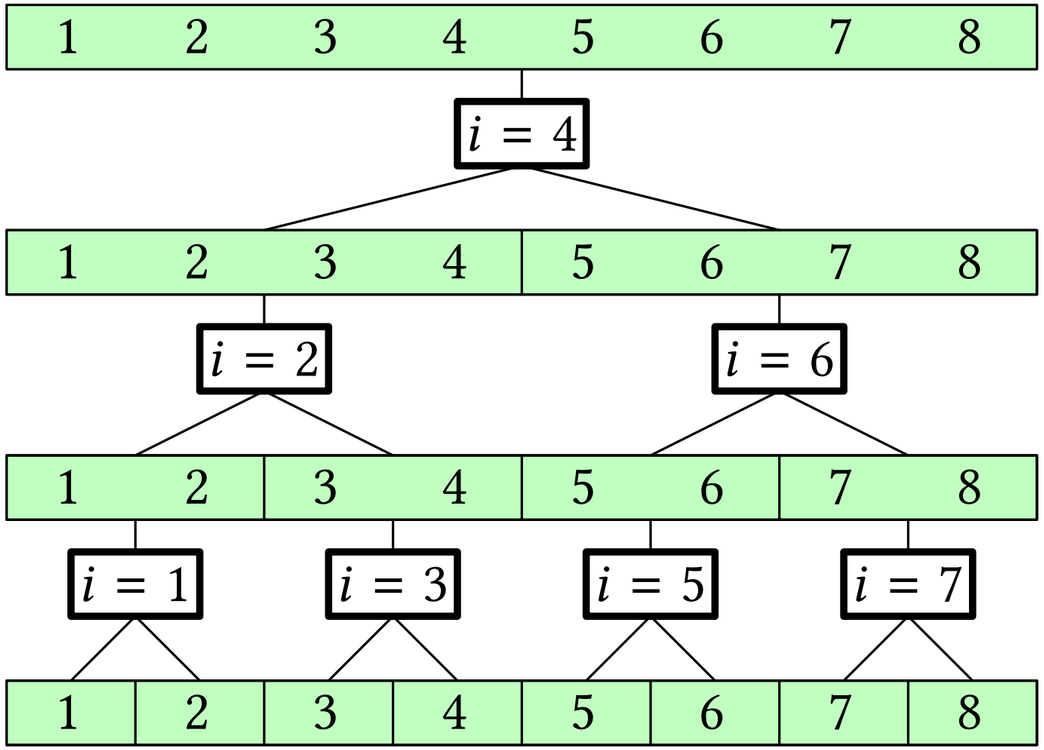
$o = 1 \Rightarrow s \leq i$ $o = 2 \Rightarrow s > i$



$o = 1 \Rightarrow s \leq i$ $o = 2 \Rightarrow s > i$



$o = 1 \Rightarrow s \leq i$ $o = 2 \Rightarrow s > i$



Entropy: Side Channels and Searching

$$\max \mathcal{H} \implies \text{Binary Search}$$

Entropy: Side Channels and Searching

$$\max \mathcal{H} \Rightarrow \text{Binary Search}$$

$$o = 1 \Rightarrow s \leq i \qquad o = 2 \Rightarrow s > i$$

Entropy: Side Channels and Searching

$$\max \mathcal{H} \Rightarrow \text{Binary Search}$$

$$o = 1 \Rightarrow s \leq i \qquad o = 2 \Rightarrow s > i$$

$$\max \mathcal{H} \Rightarrow \text{Optimal Search}$$

any program constraints

Entropy: Side Channels and Searching

$$\max \mathcal{H} \Rightarrow \text{Binary Search}$$

$$o = 1 \Rightarrow s \leq i \qquad o = 2 \Rightarrow s > i$$

$$\max \mathcal{H} \Rightarrow \text{Optimal Search}$$

any program constraints

How to maximize $\mathcal{H}$?

Overall Approach [CSF 2017]

$P(s, i)$

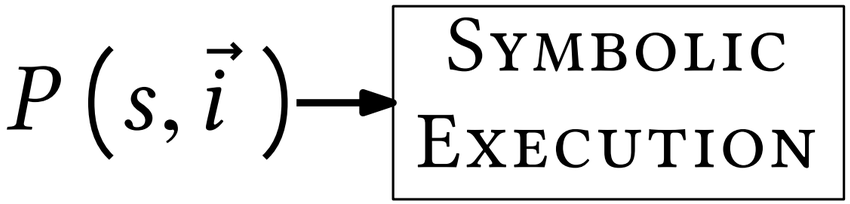
Overall Approach [CSF 2017]

$$P\left(s, \vec{i}\right)$$

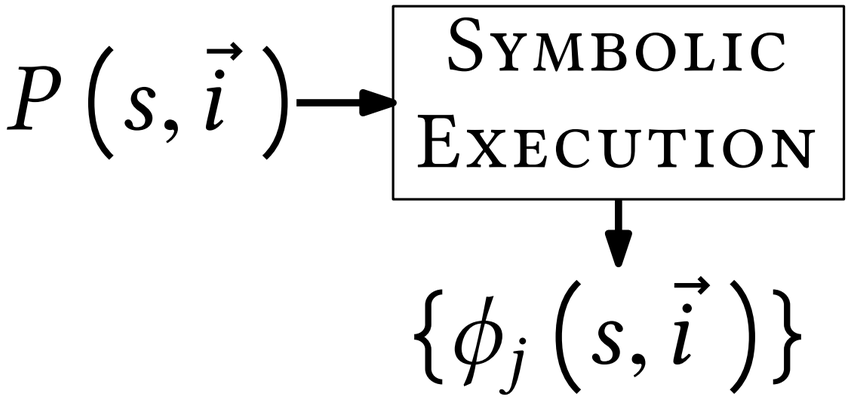
Overall Approach [CSF 2017]

$$P\left(s, \vec{i}\right)$$

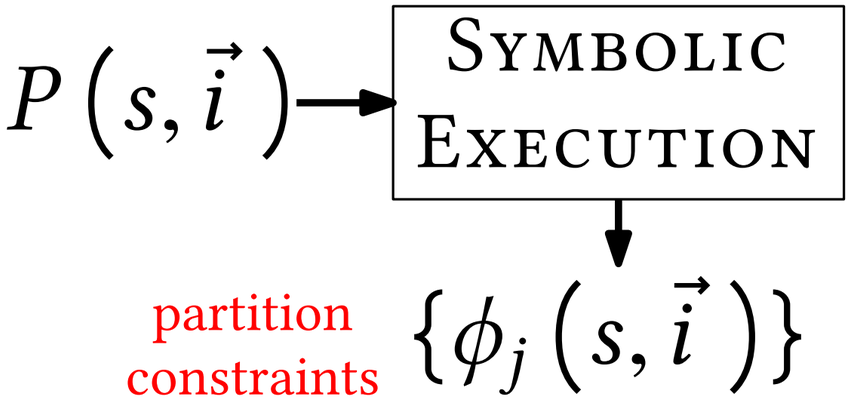
Overall Approach [CSF 2017]



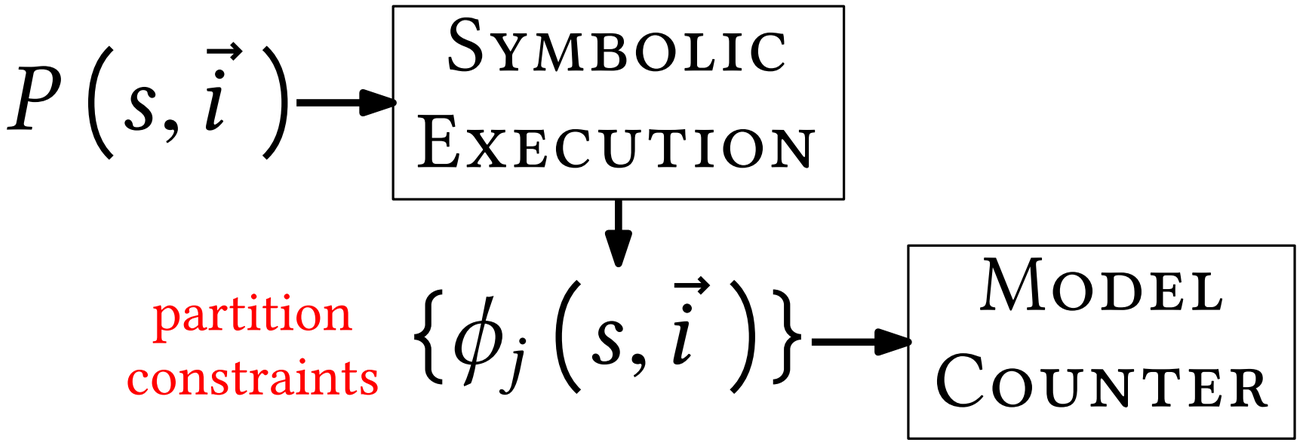
Overall Approach [CSF 2017]



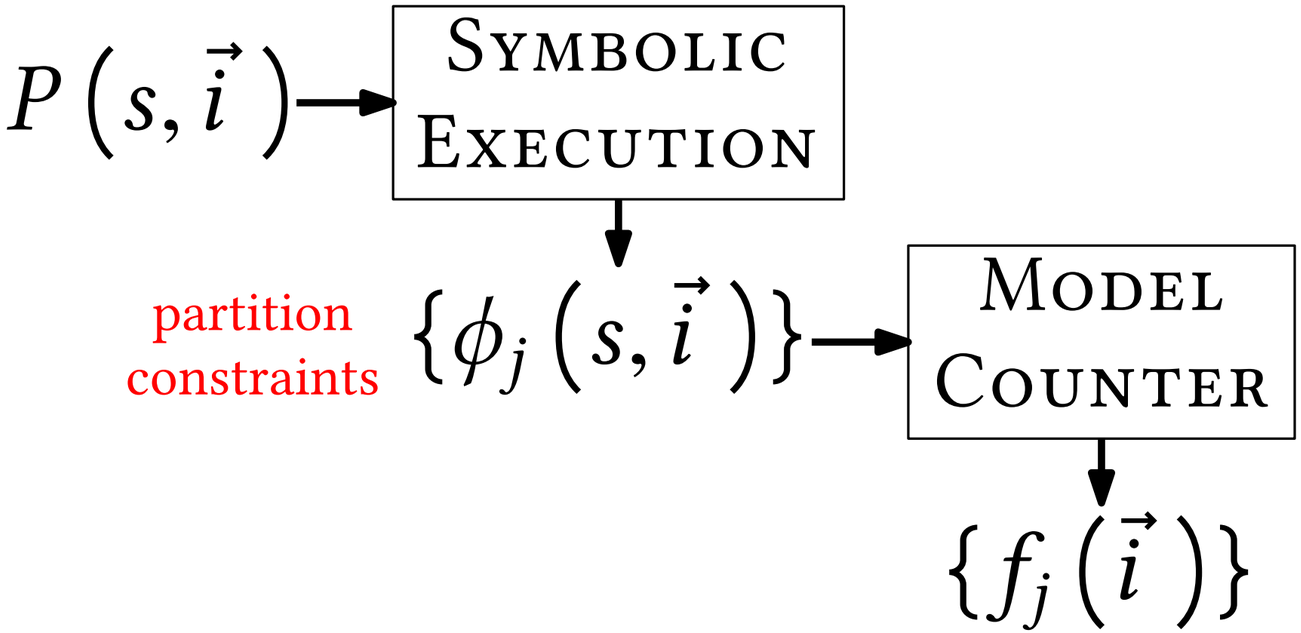
Overall Approach [CSF 2017]



Overall Approach [CSF 2017]



Overall Approach [CSF 2017]



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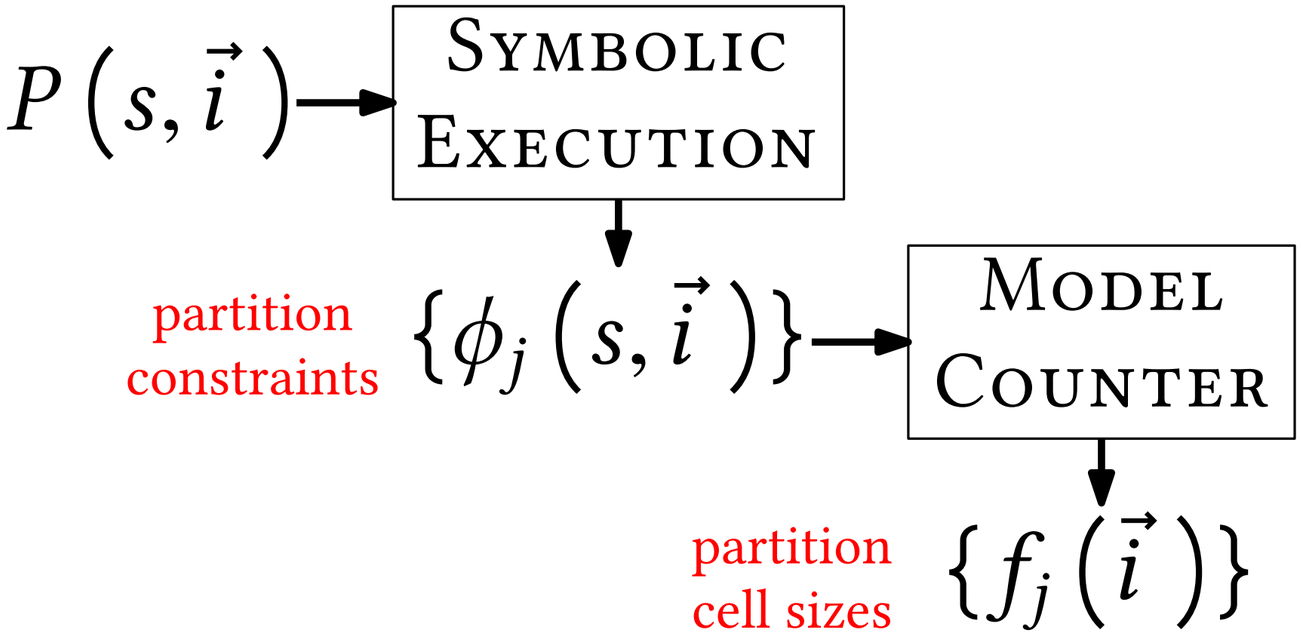

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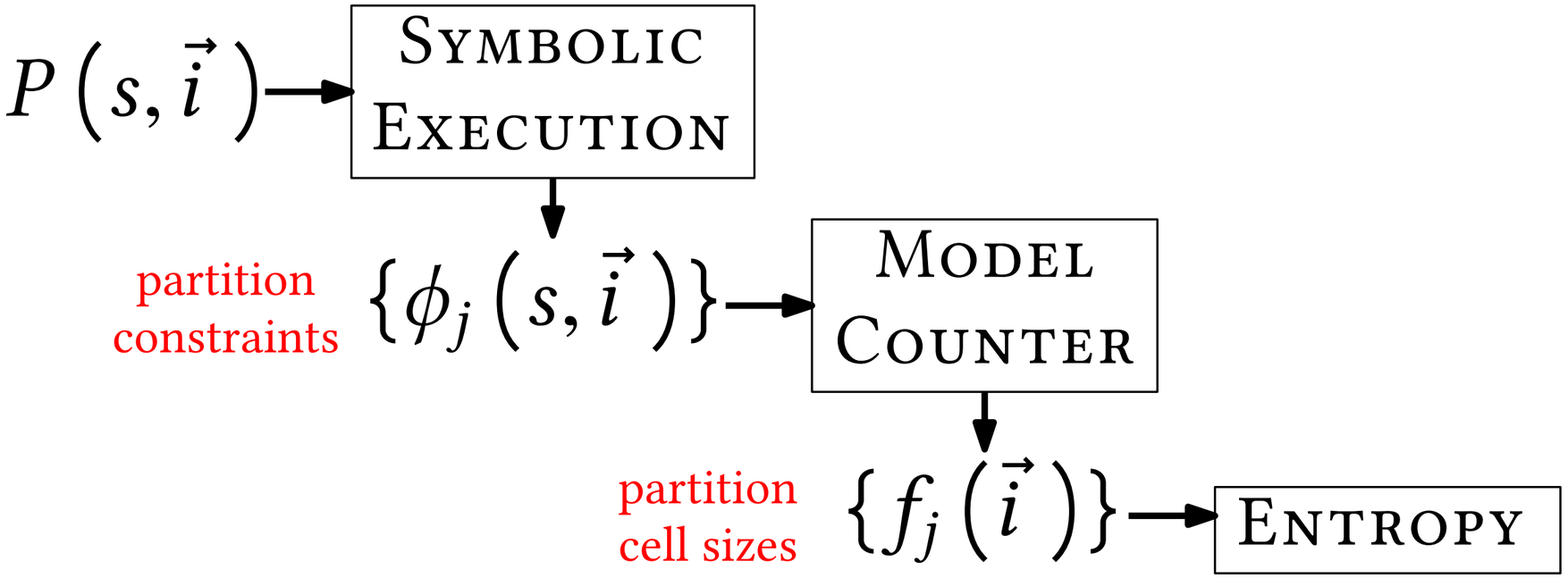

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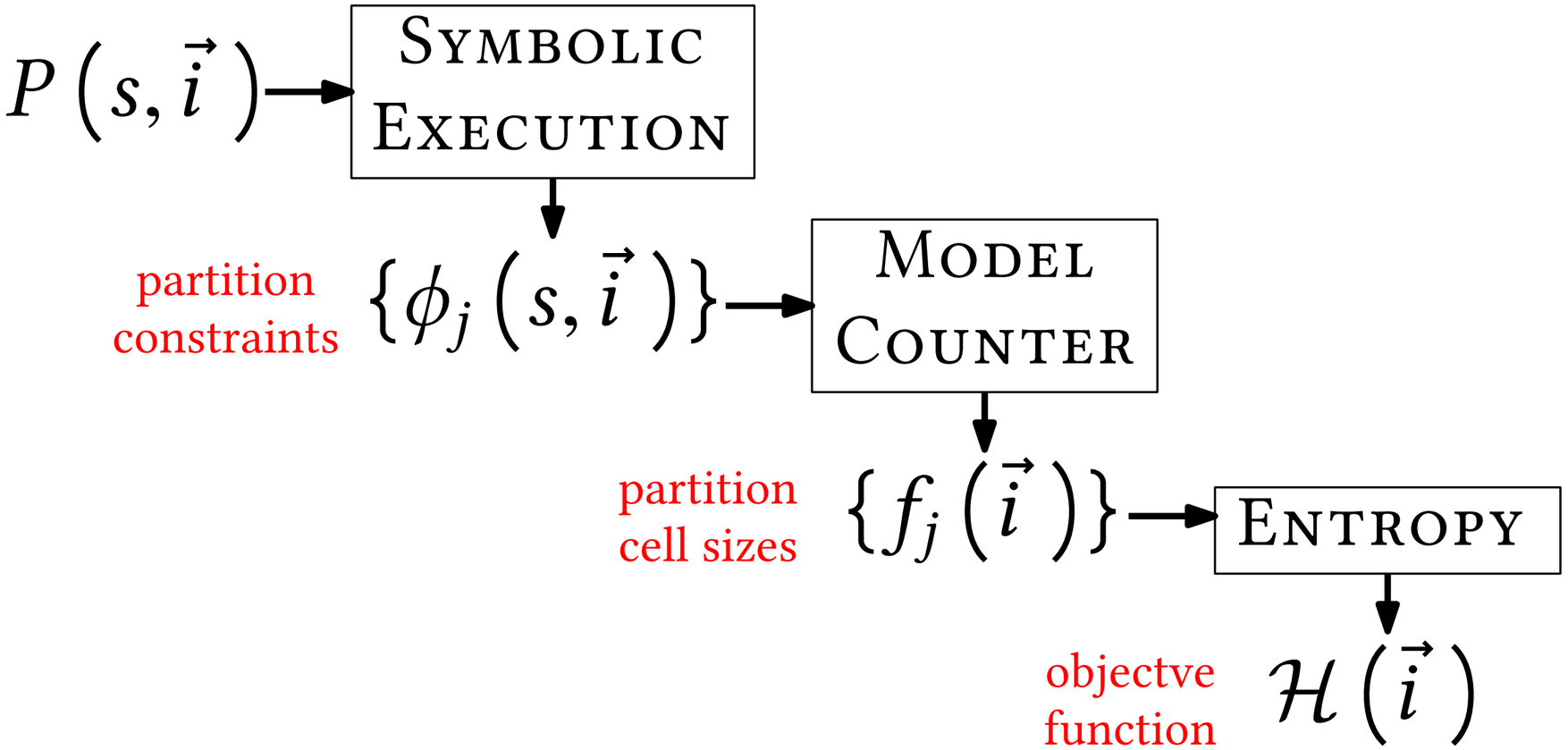

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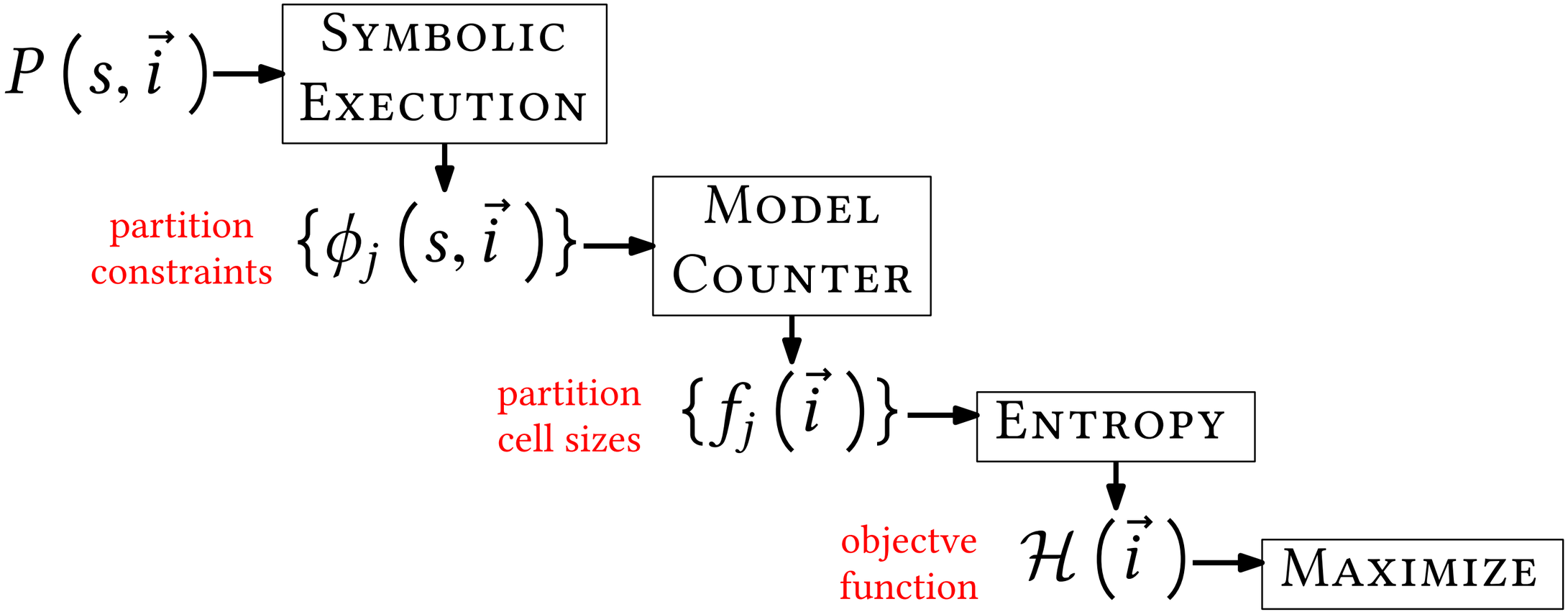

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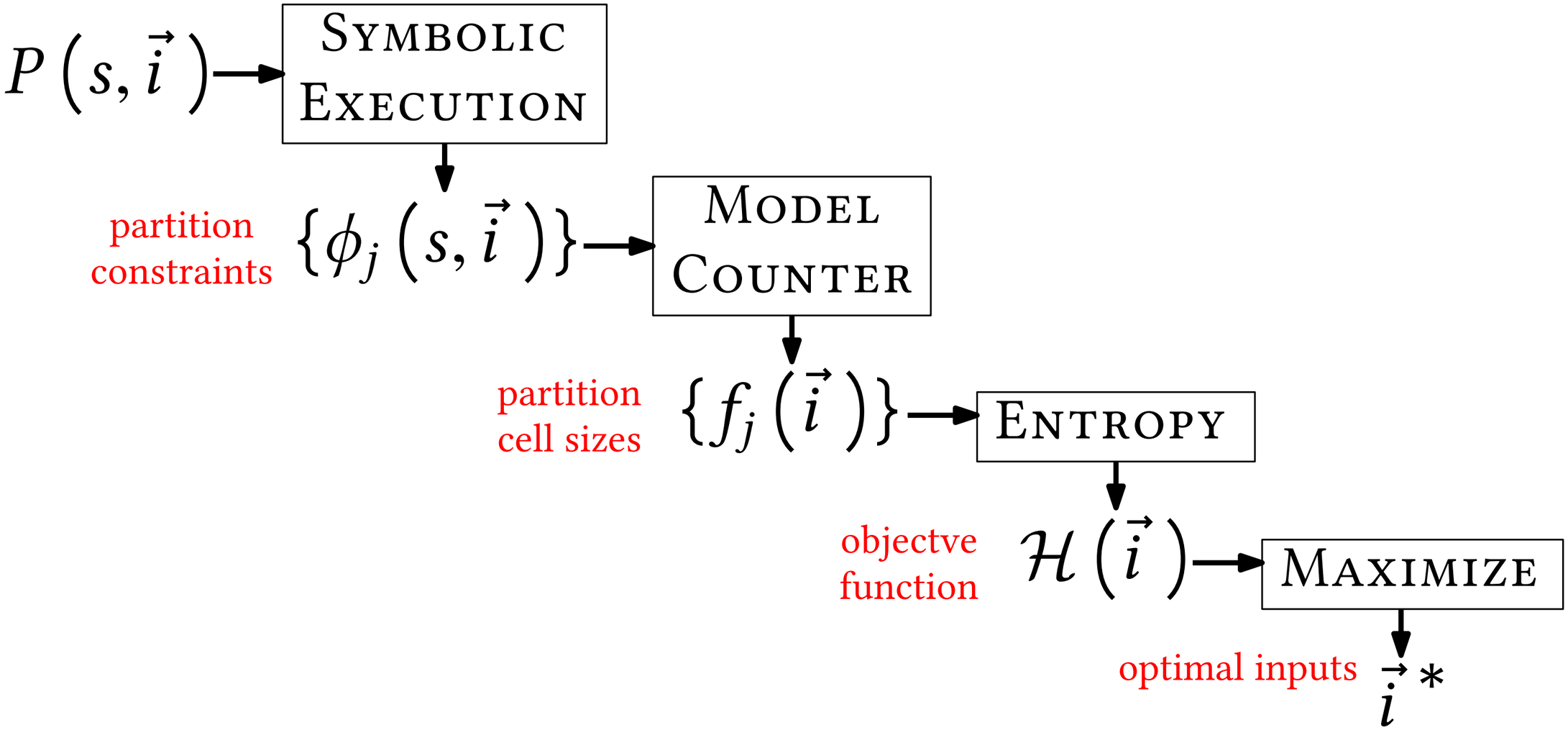

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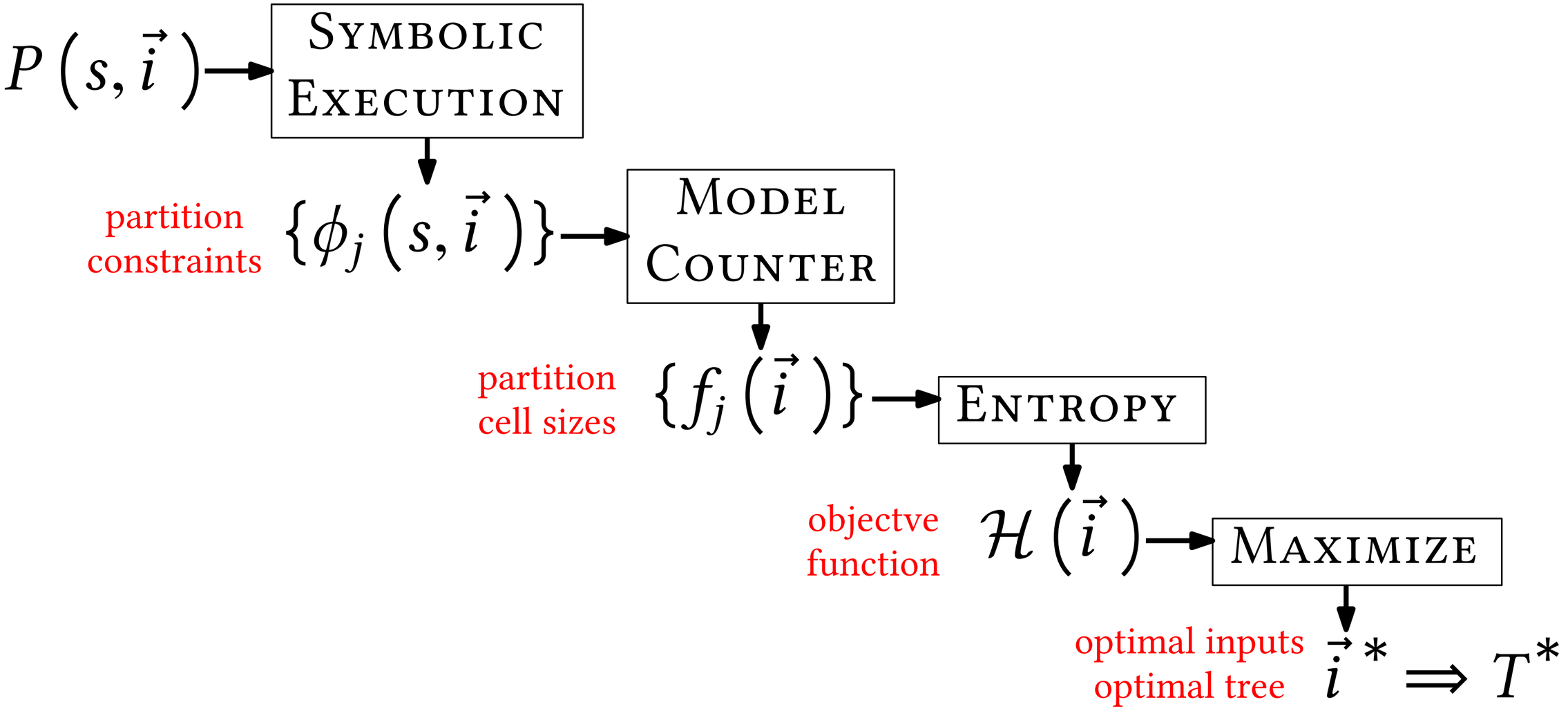

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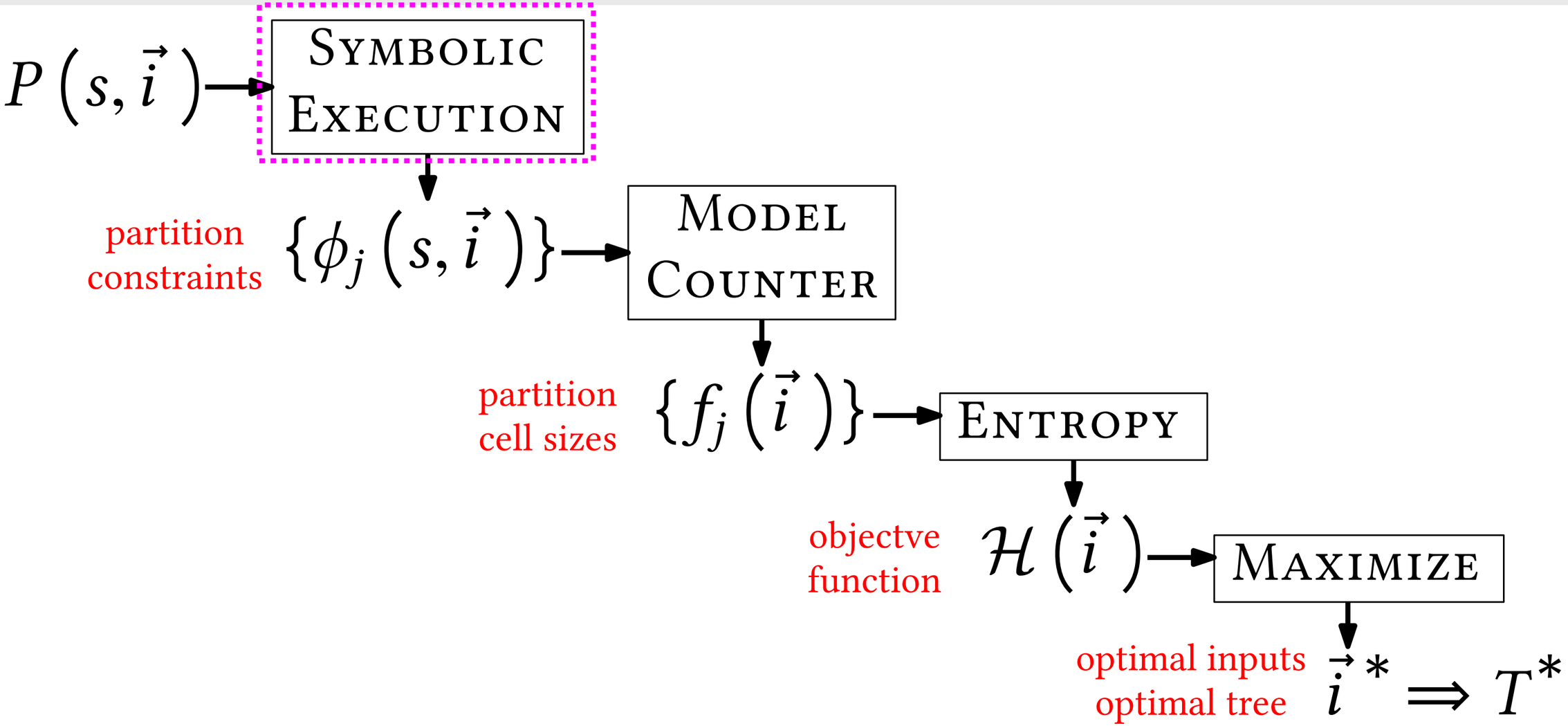

Symbolic Execution

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- Execute program on **symbolic** rather than concrete inputs.

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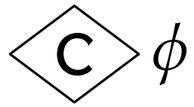

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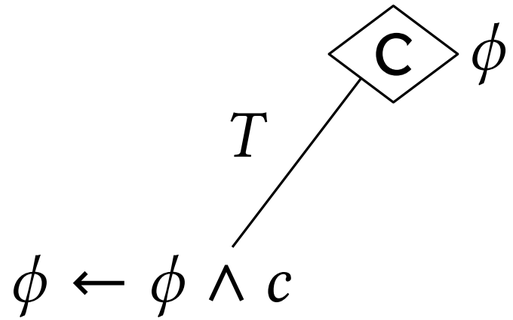

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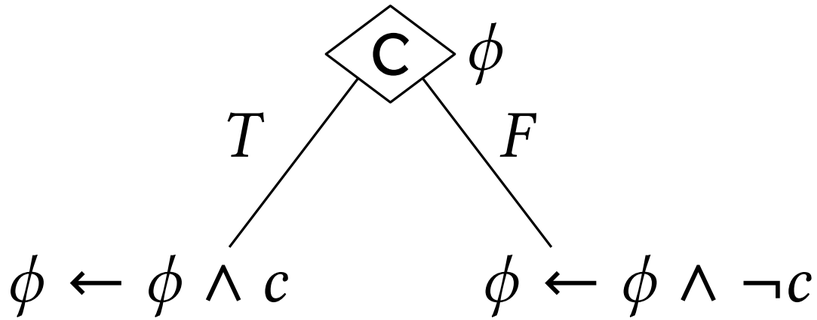

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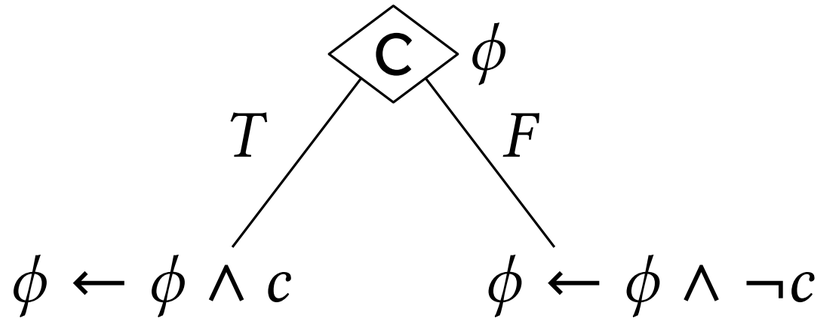

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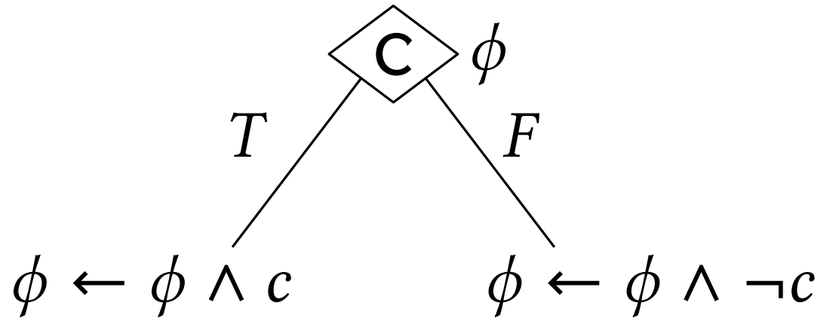

- Check satisfiability of ϕ using constraint solvers (like Z3).
- Maintain **cost model** for every path constraint.

Symbolic Attack Tree via Symbolic Execution

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$$o = 1 \Longrightarrow s \leq i \qquad o = 2 \Longrightarrow s > i$$

Symbolic Attack Tree via Symbolic Execution

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$\boxed{i = i_0}$ 

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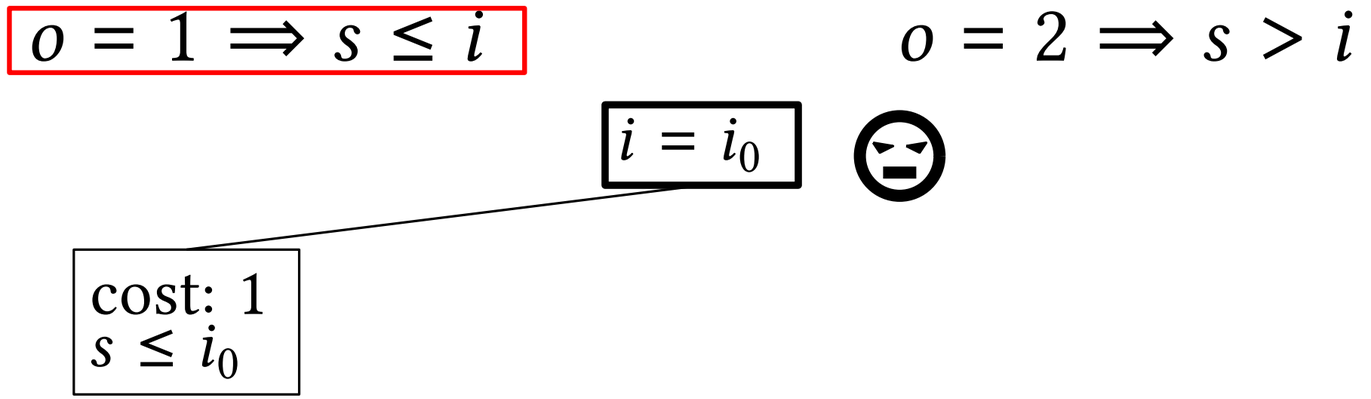

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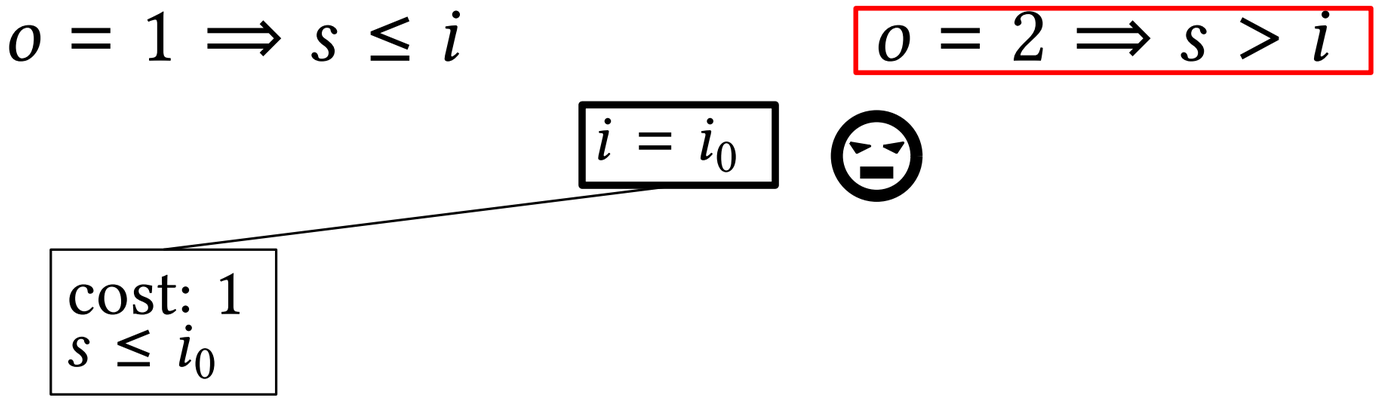

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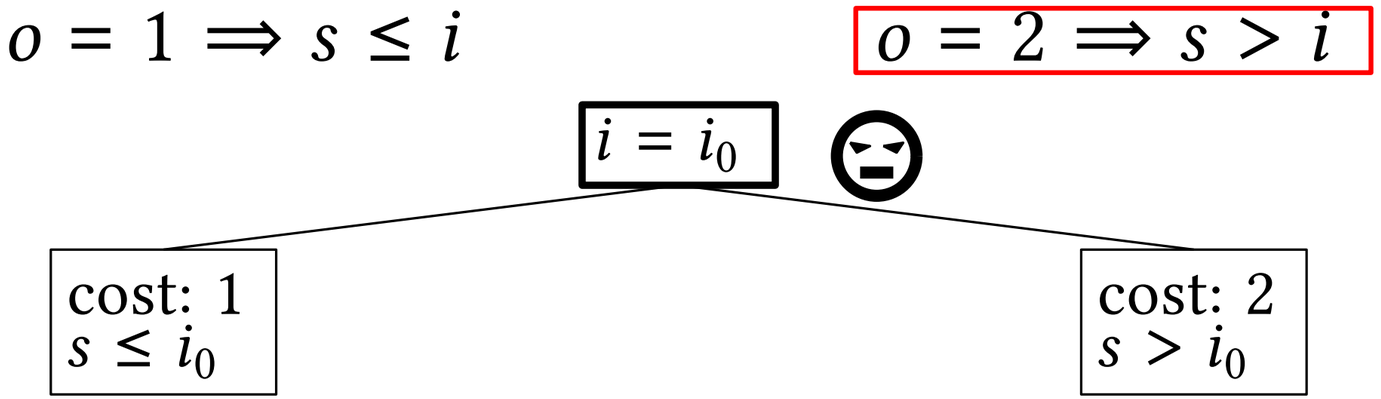

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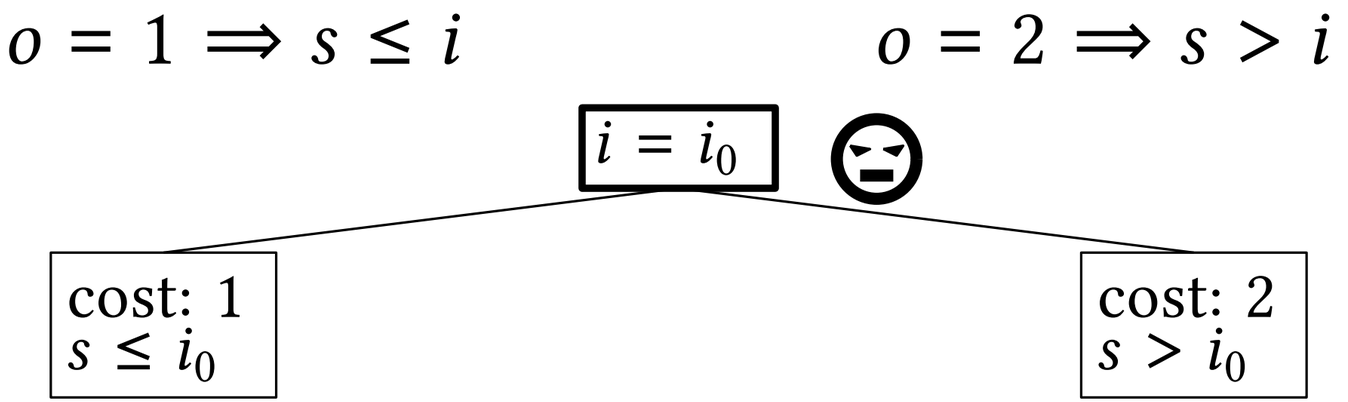

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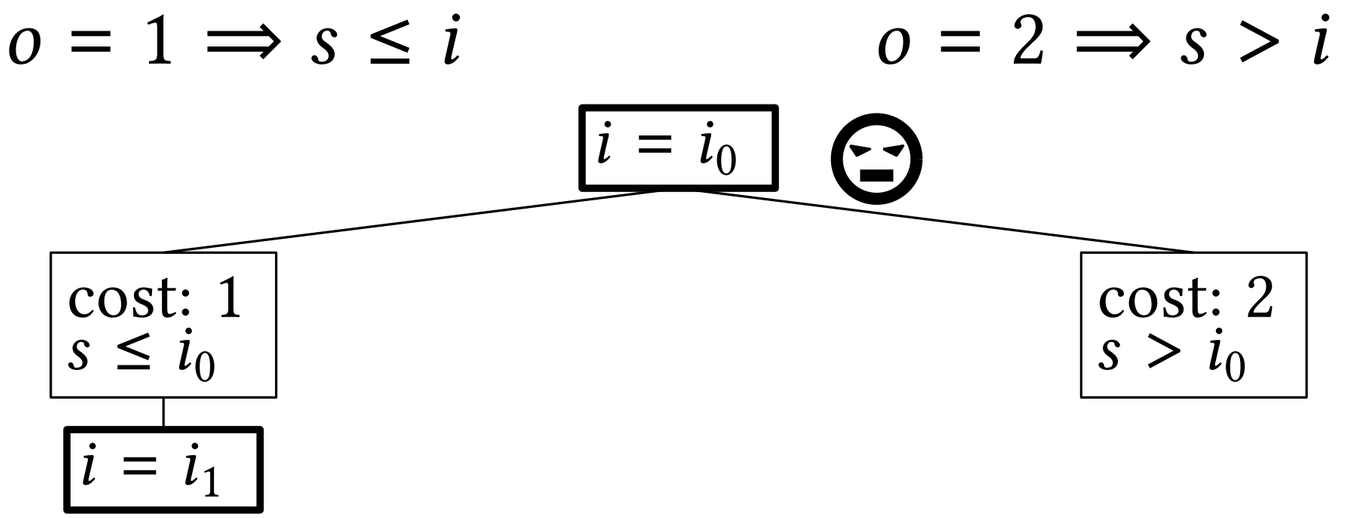

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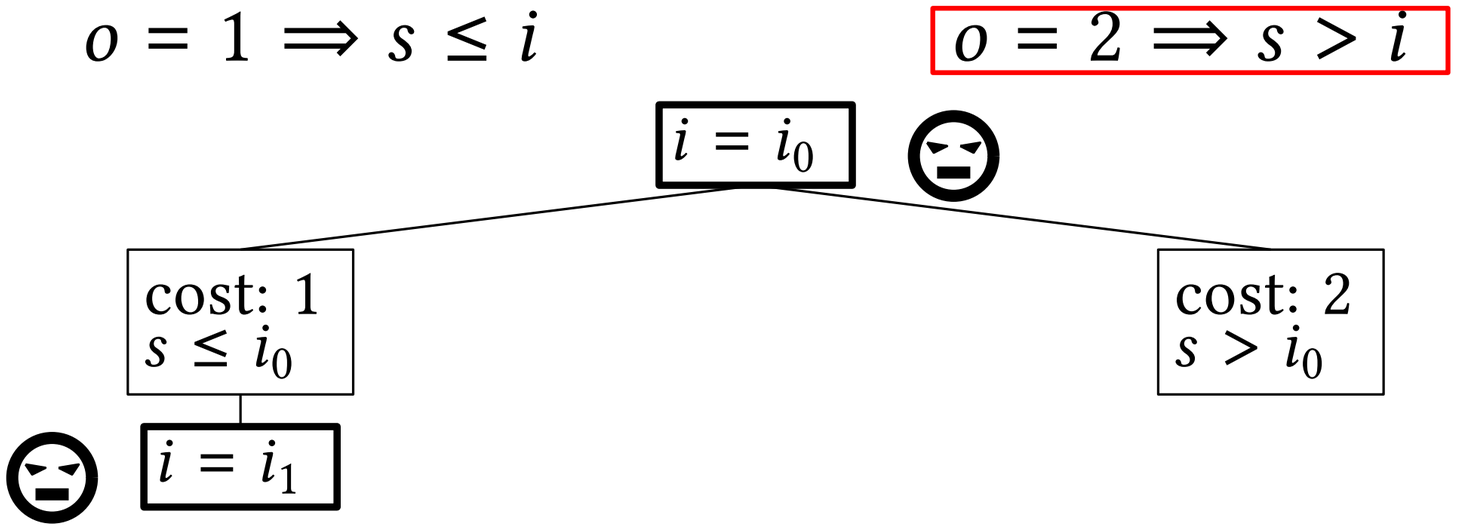

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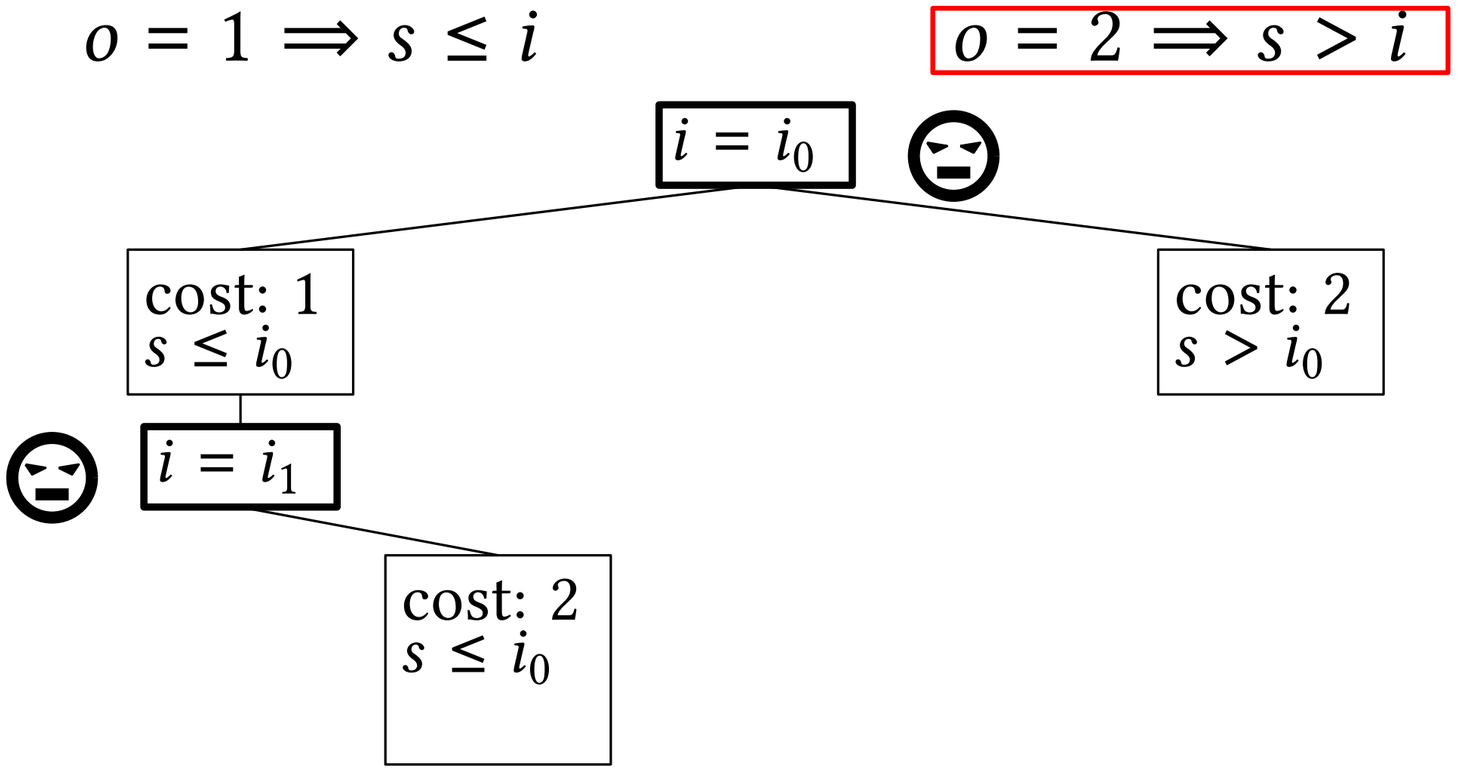

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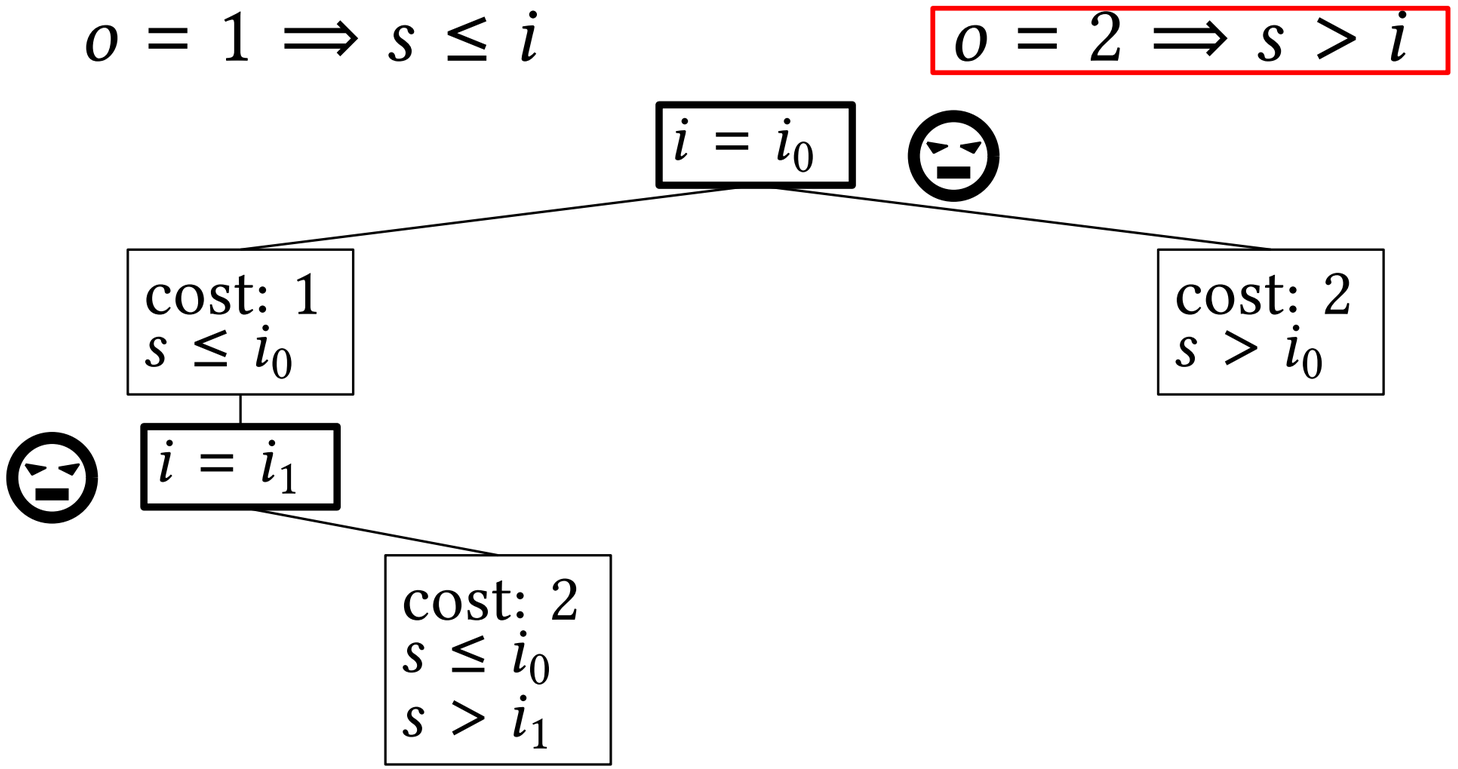

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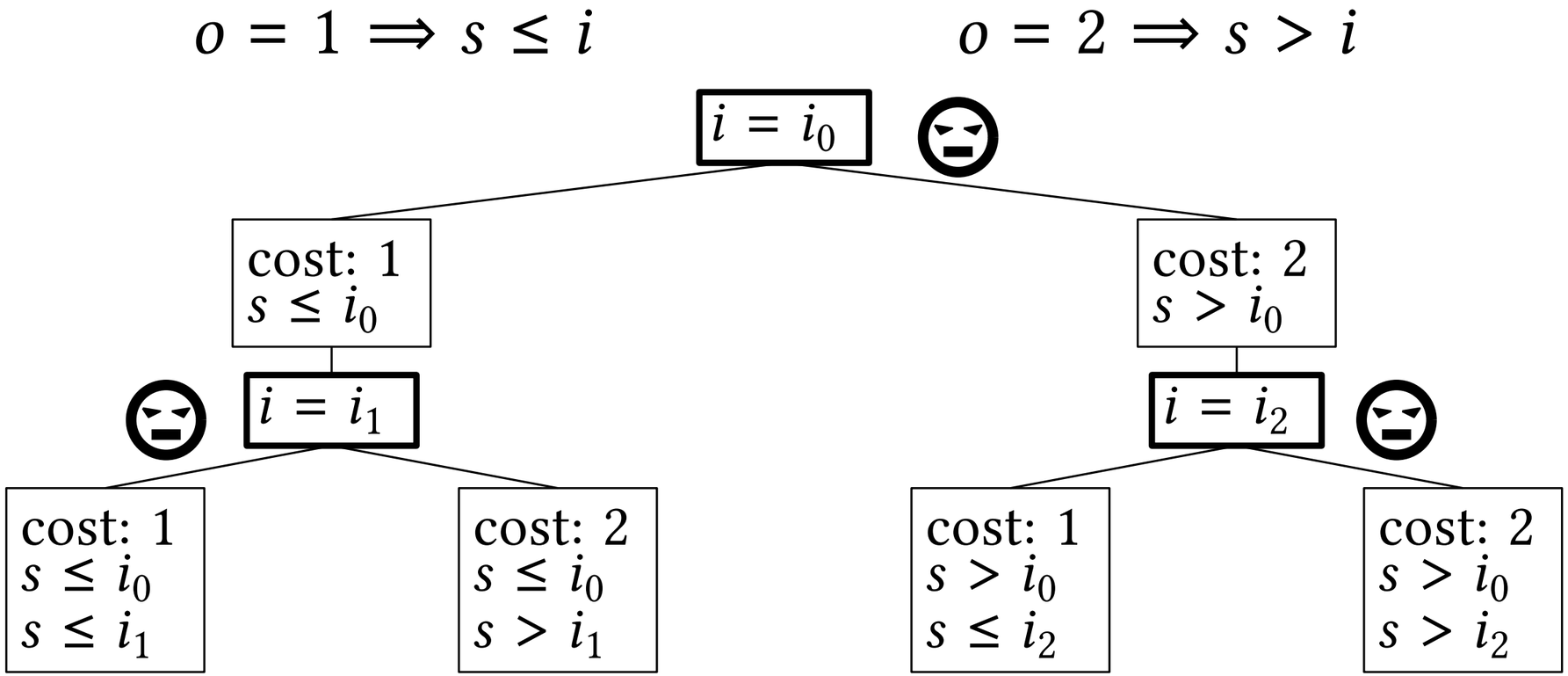

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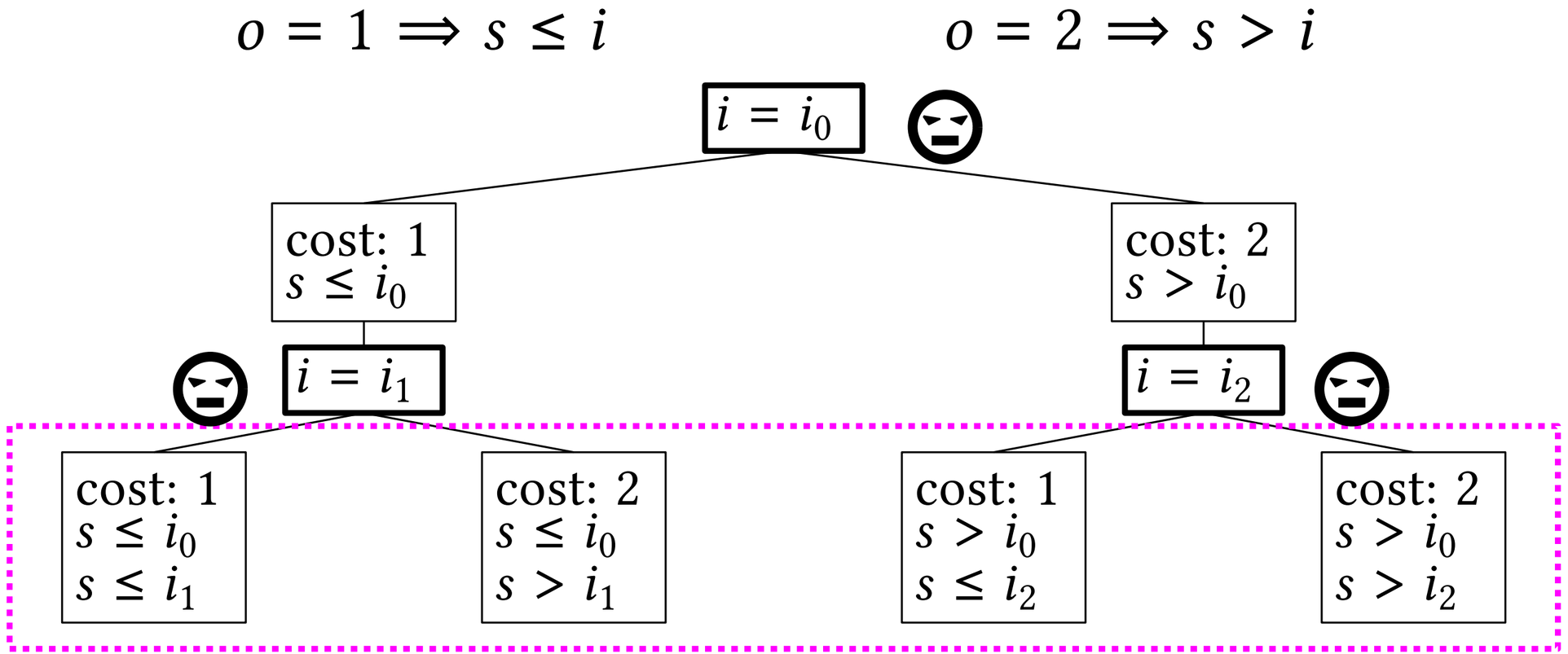

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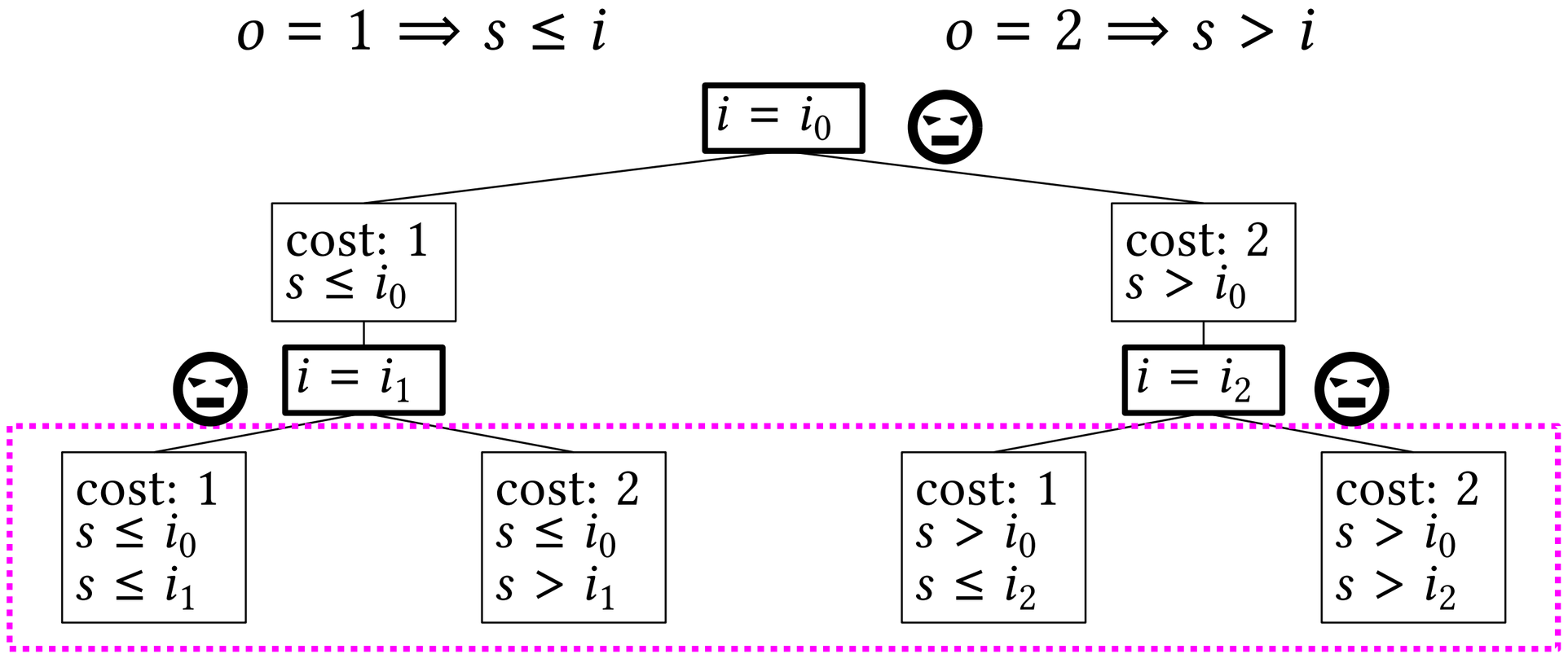
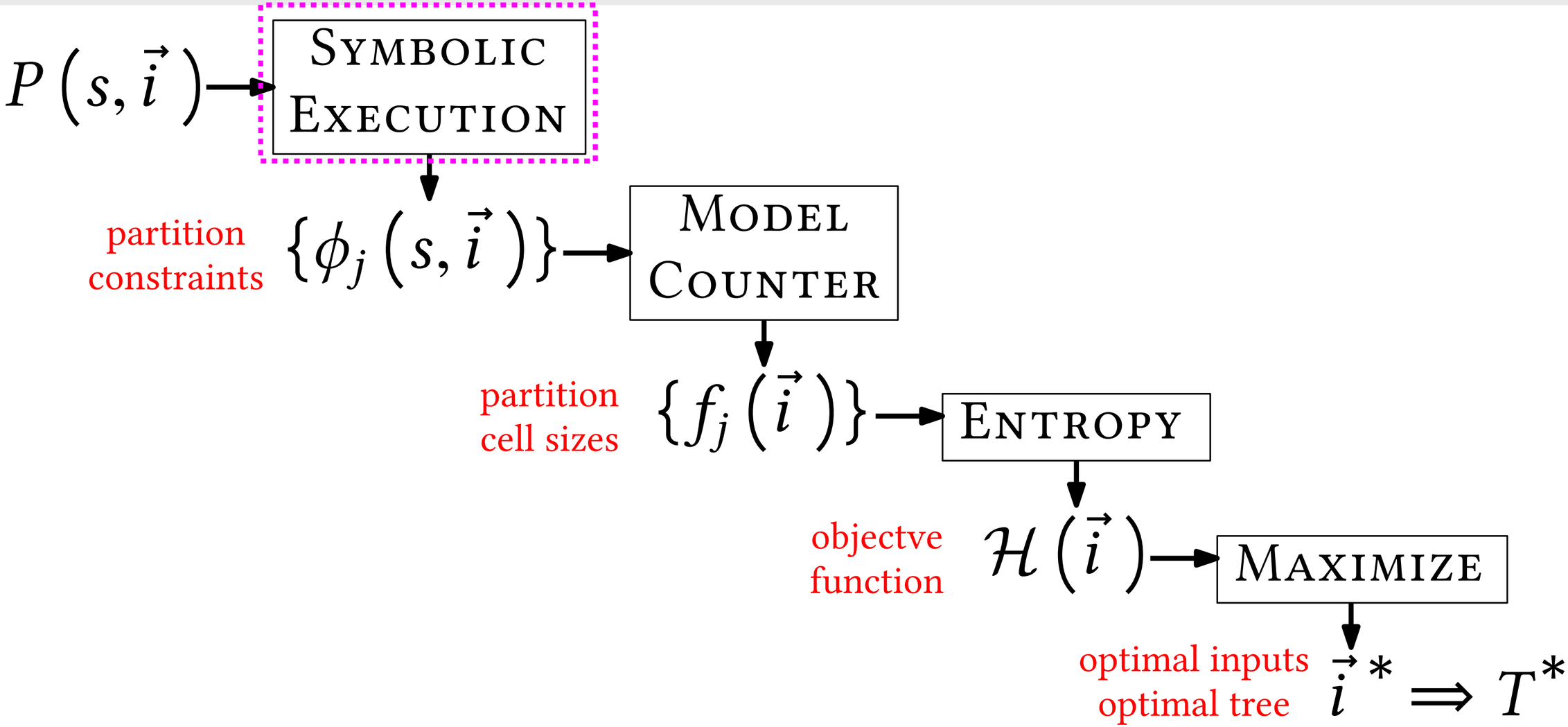


Set of leaf constraints define a **symbolic partition**.

Overall Approach



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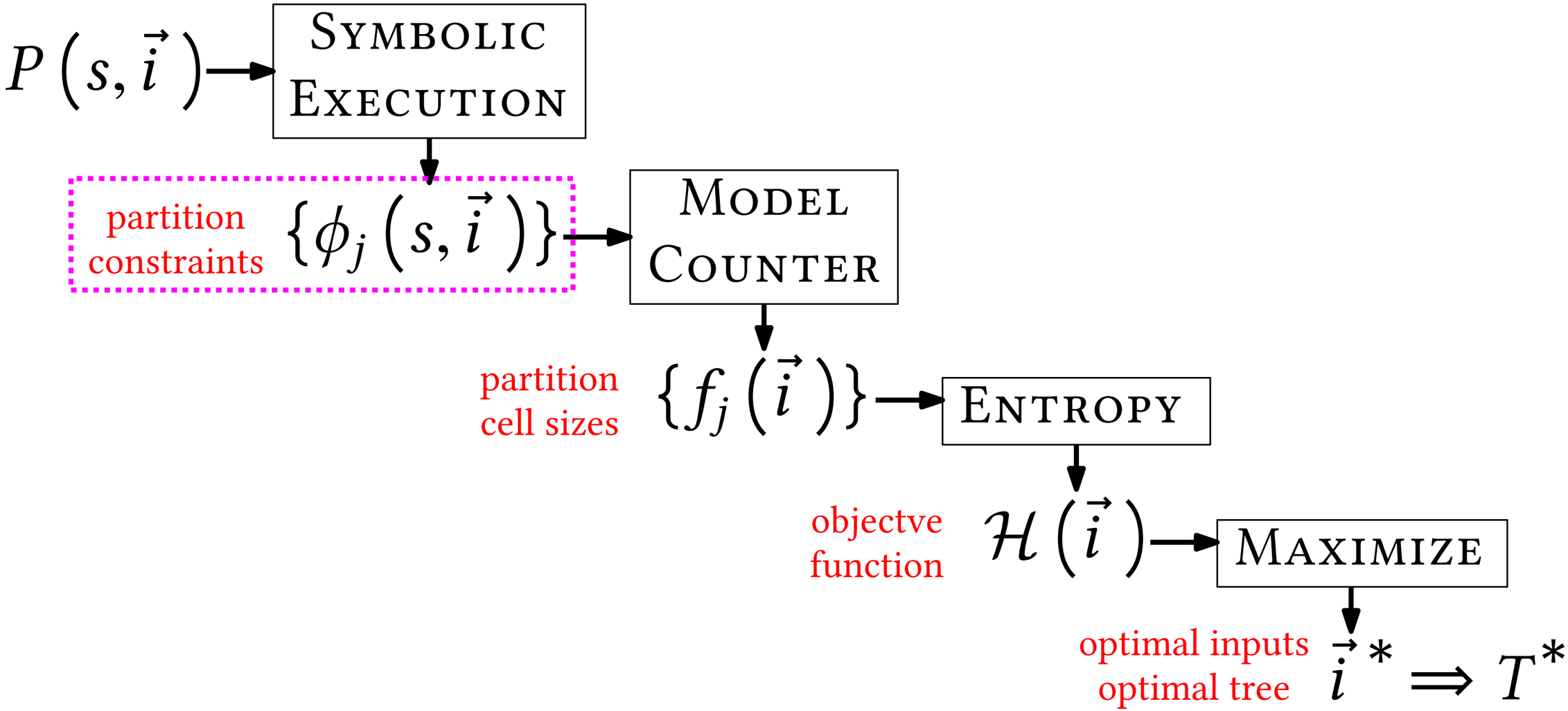

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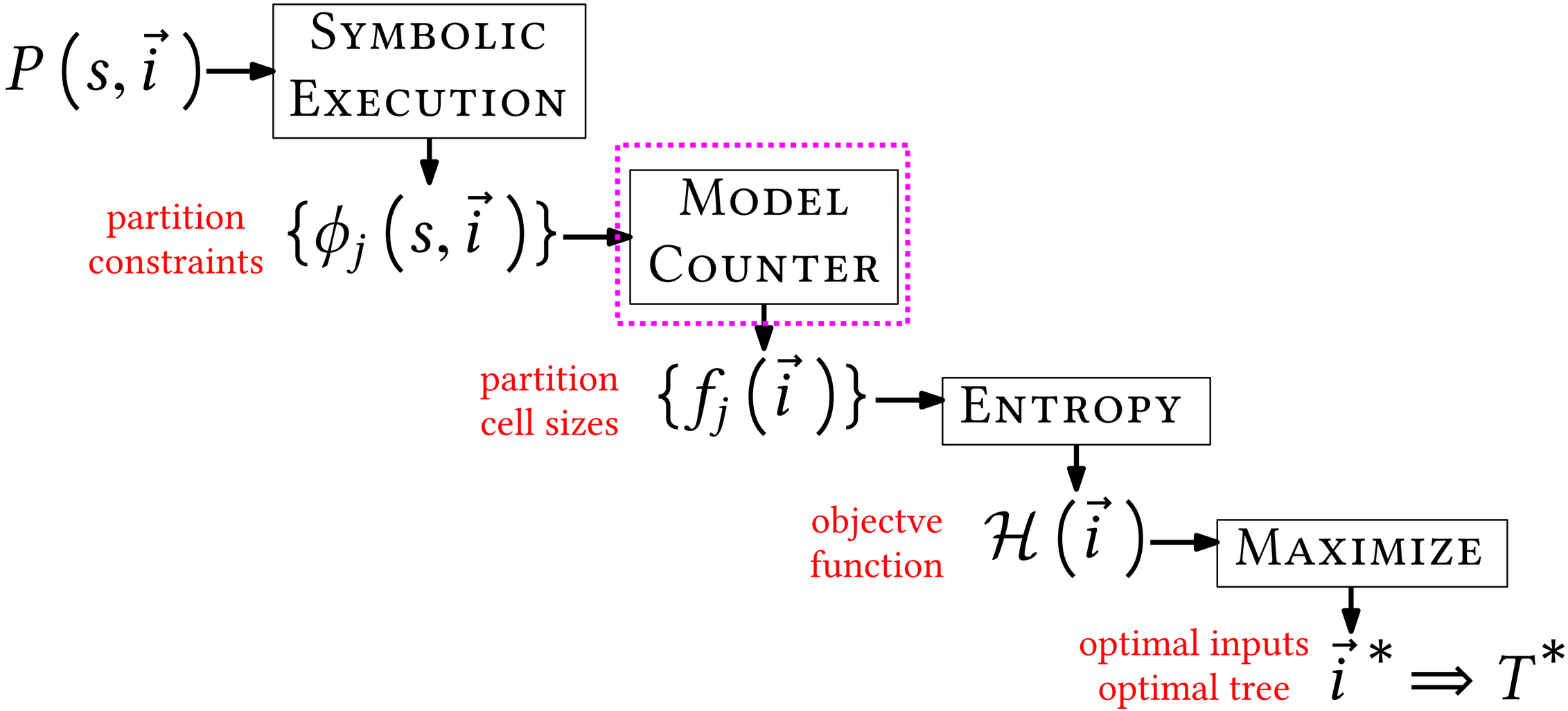

Partition Cell Sizes via Symbolic Model Counting

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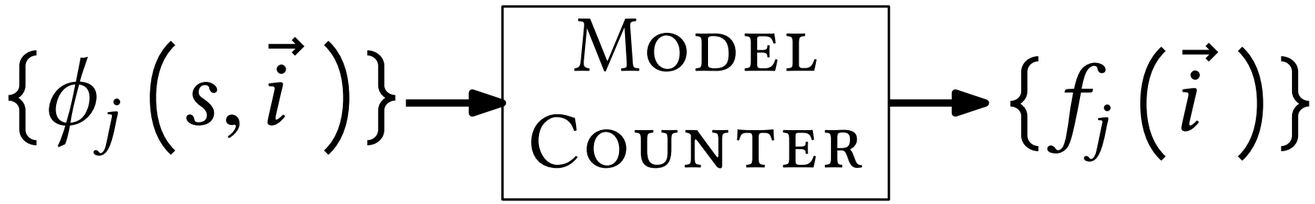

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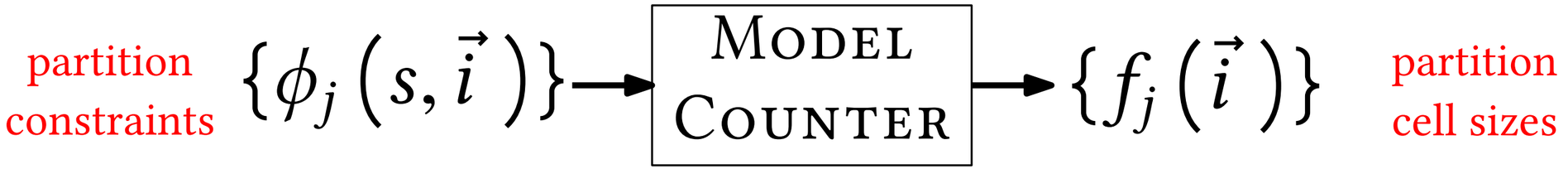

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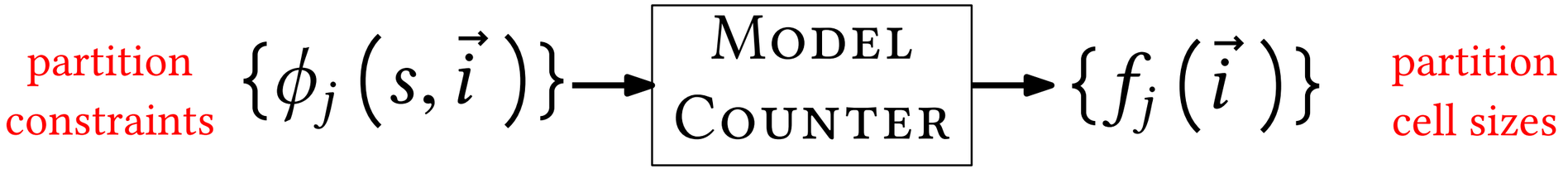

$f_j(\vec{i})$: size of partition cell j

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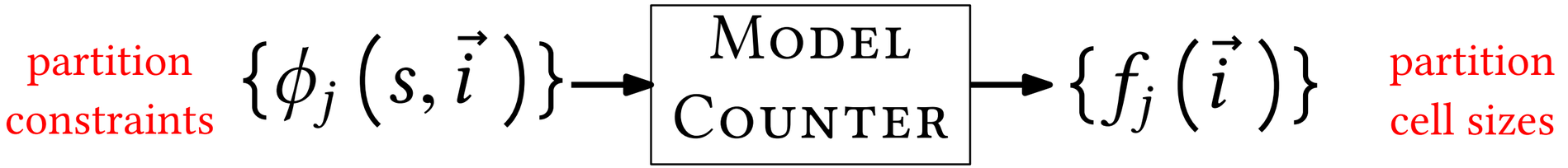

$$f_j(\vec{i}) : \text{size of partition cell } j$$

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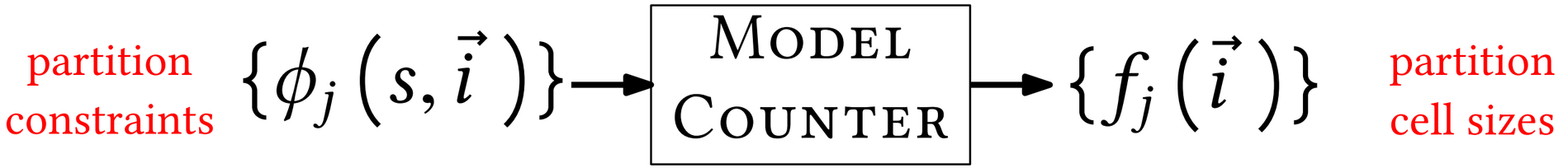

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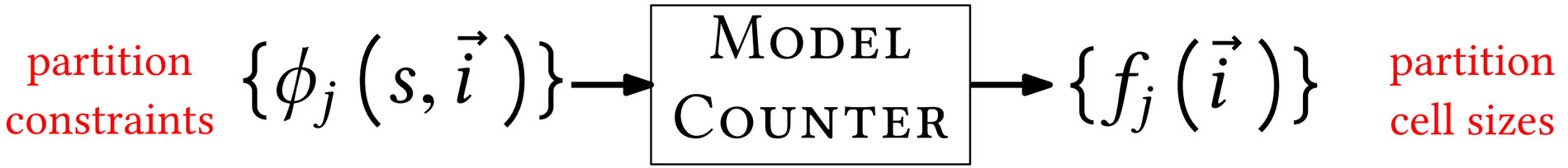

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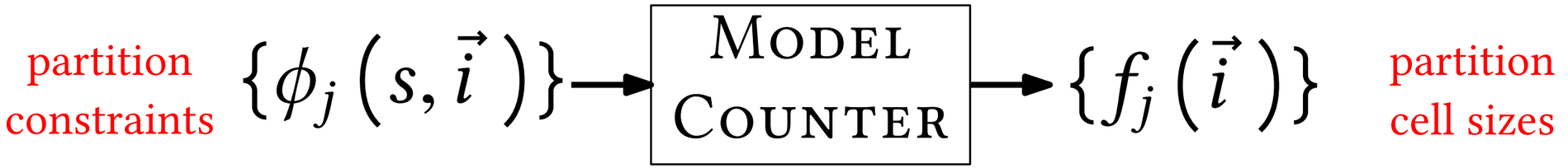

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SMC: Strings
LattE: Linear Integer Arithmetic

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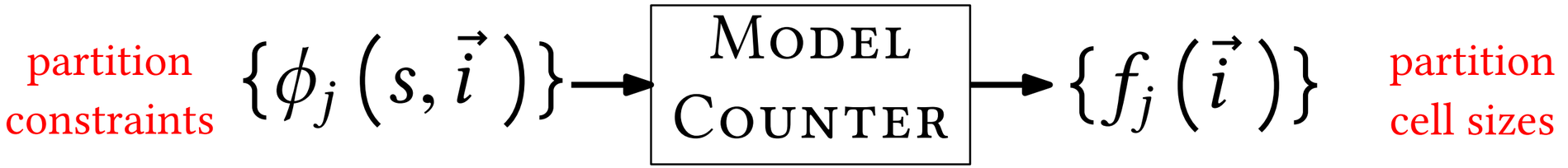

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$\text{Barvinok}\left(\phi_j\left(s, \vec{i}\right), \vec{i}\right)$: piecewise polynomial function $f_j\left(\vec{i}\right)$

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$$f\left(i_0, i_1\right) = \begin{cases} i_0 - i_1 & \text{if } 1 \leq i_1 \leq i_0 \leq 8 \\ i_0 & \text{if } i_1 < 1 \leq i_0 \leq 8 \\ 8 - i_1 & \text{if } 1 \leq i_1 \leq 8 \leq i_0 \\ 8 & \text{if } i_1 \leq 1 < 8 \leq i_0 \\ 0 & \text{otherwise} \end{cases}$$

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$$f\left(6, 2\right) = 4$$

Partition Cell Sizes via Symbolic Model Counting

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$f\left(6, 2\right) = 4$ $\qquad$ $f\left(5, -1\right) = 5$

Partition Cell Sizes via Symbolic Model Counting

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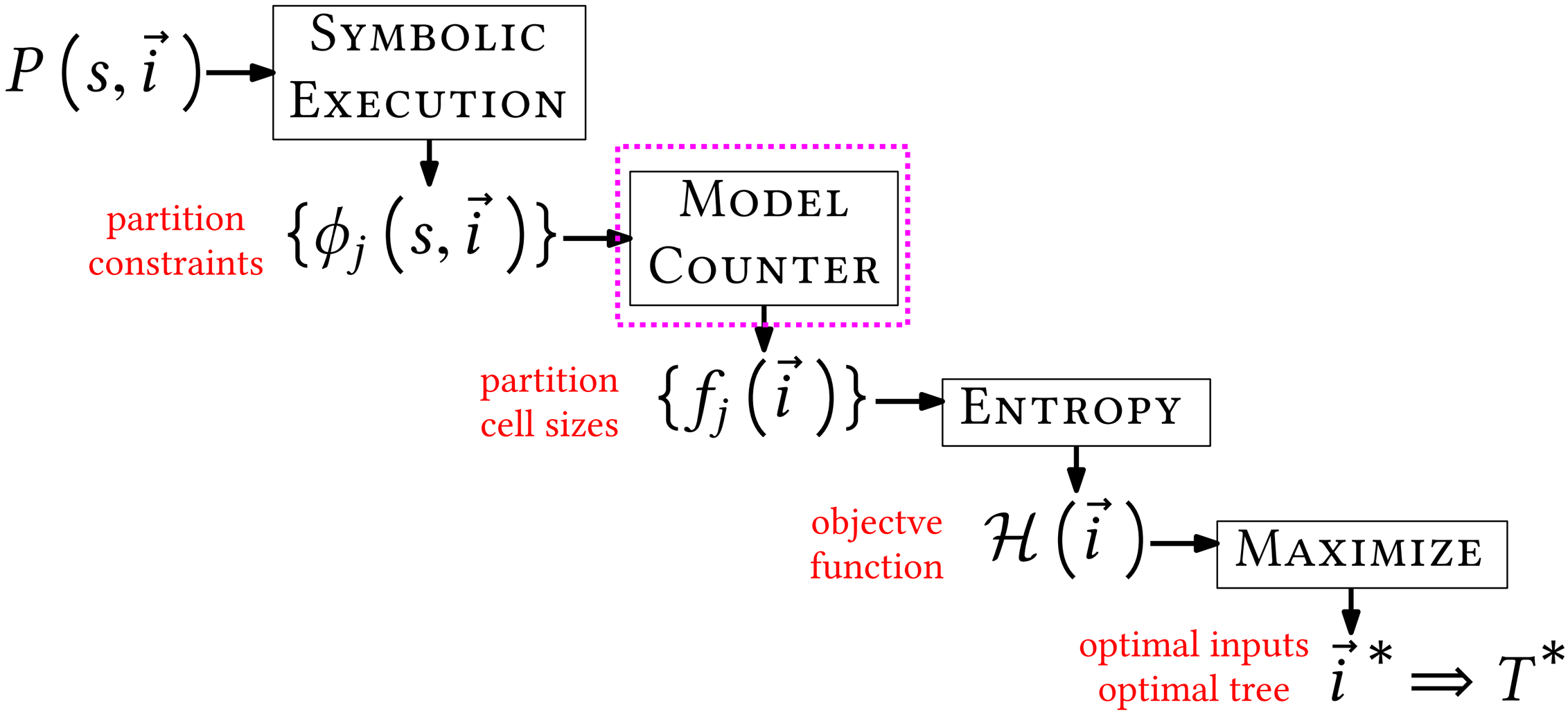
$f\left(6, 2\right) = 4$ $\quad$ $f\left(5, -1\right) = 5$ $\quad$ $f\left(3, 7\right) = 0$


$P\left(s, \vec{i}\right)$
Symbolic Execution
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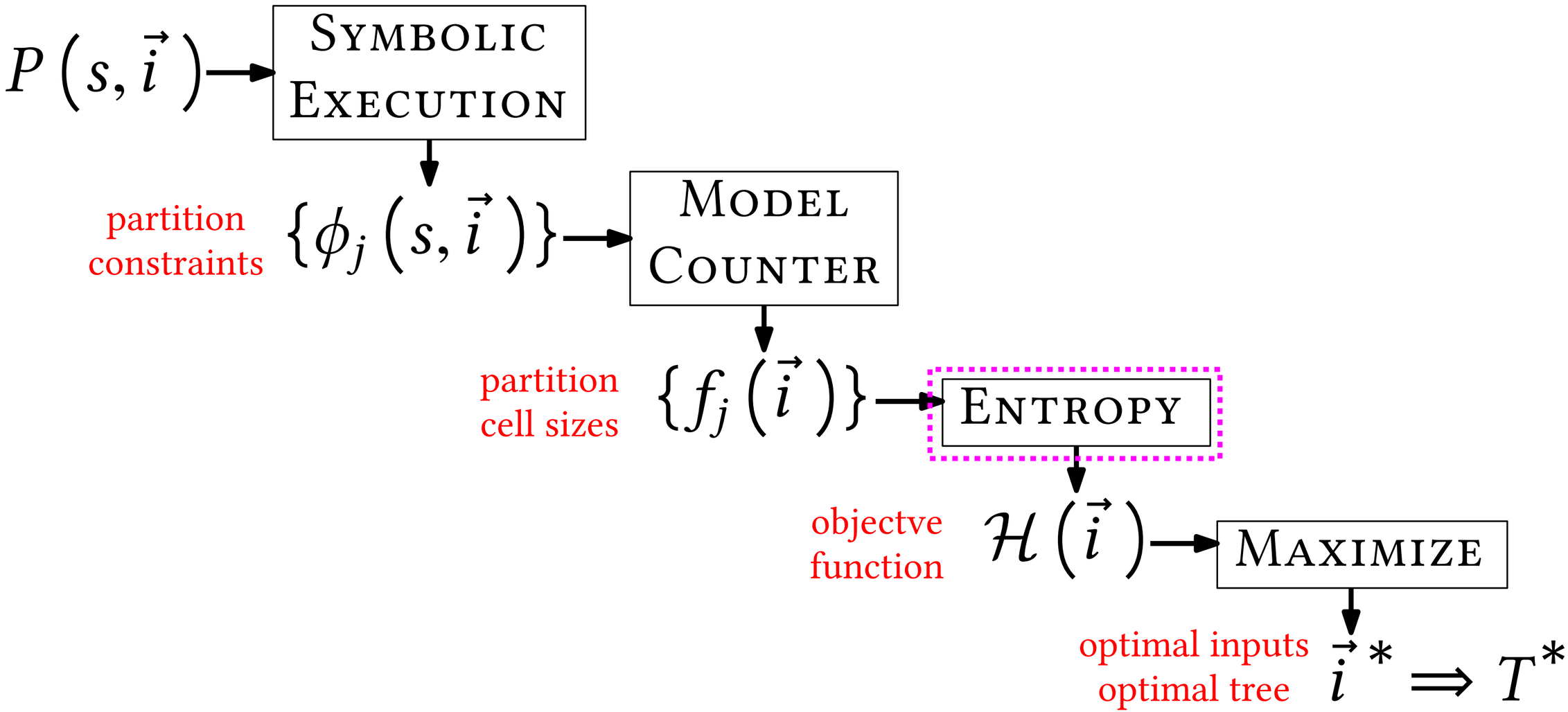
Model Counter
partition cell sizes
$\{f_j\left(\vec{i}\right)\}$
Entropy
objectve function
$\mathcal{H}\left(\vec{i}\right)$
Maximize
optimal inputs
optimal tree
$\vec{i}^{\,*} \Longrightarrow T^*$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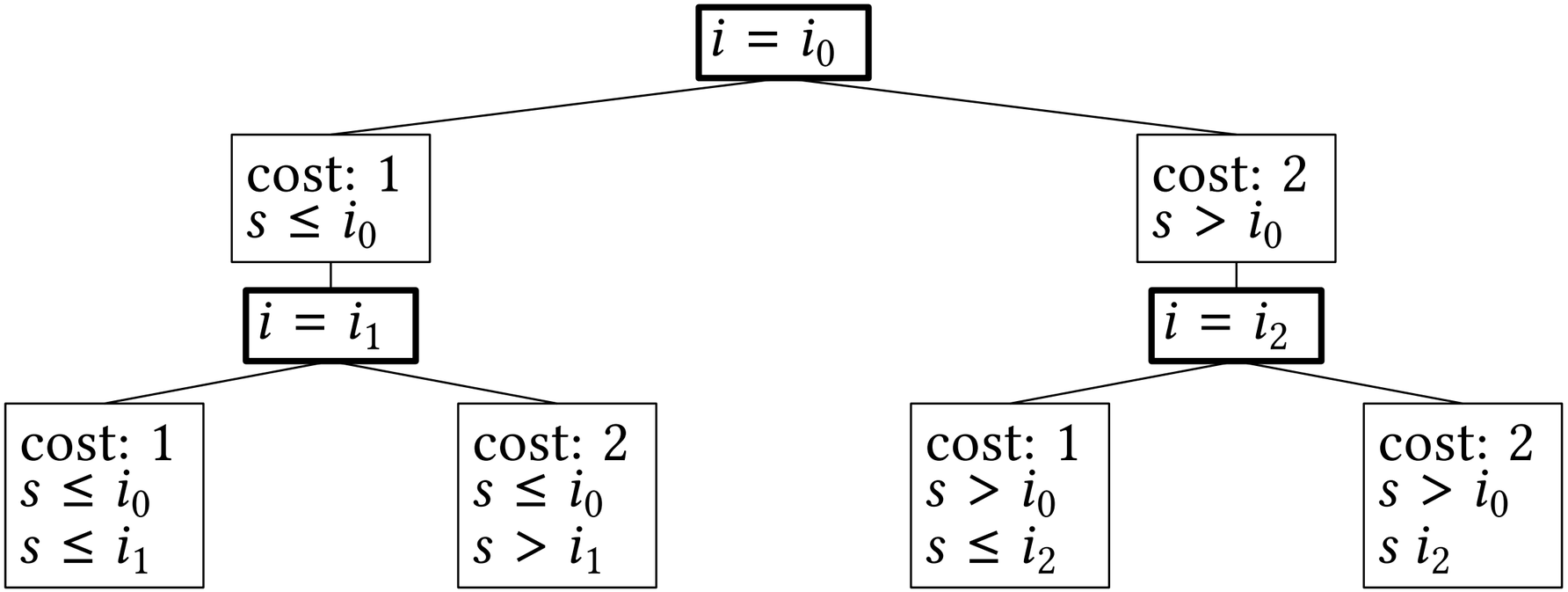
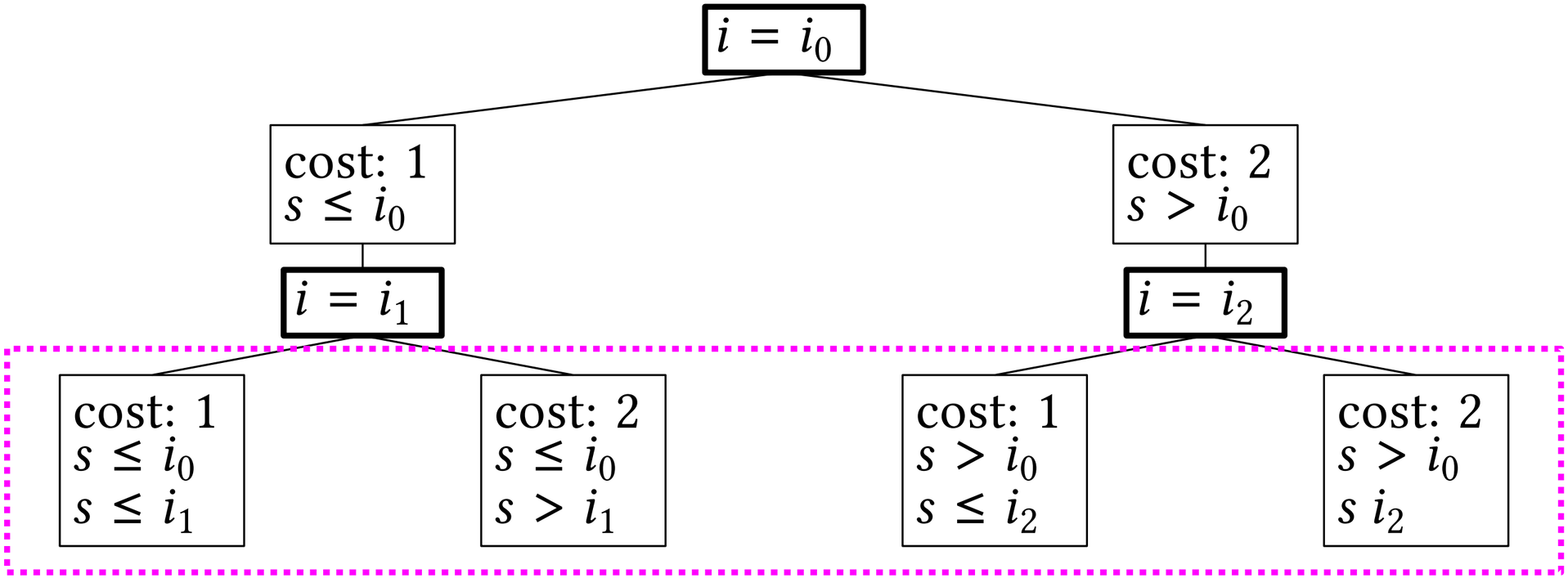
optimal inputs
optimal tree
$\vec{i}^{\,*} \Longrightarrow T^*$

Computing Multi-Step Entropy Symbolically

Computing Multi-Step Entropy Symbolically



Computing Multi-Step Entropy Symbolically



Computing Multi-Step Entropy Symbolically

$s \leq i_0$
$s \leq i_1$

$s \leq i_0$
$s > i_1$

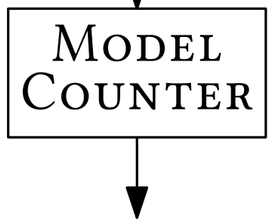
$s > i_0$
$s \leq i_2$

$s > i_0$
$s\ i_2$

Computing Multi-Step Entropy Symbolically

$s \leq i_0$
$s \leq i_1$

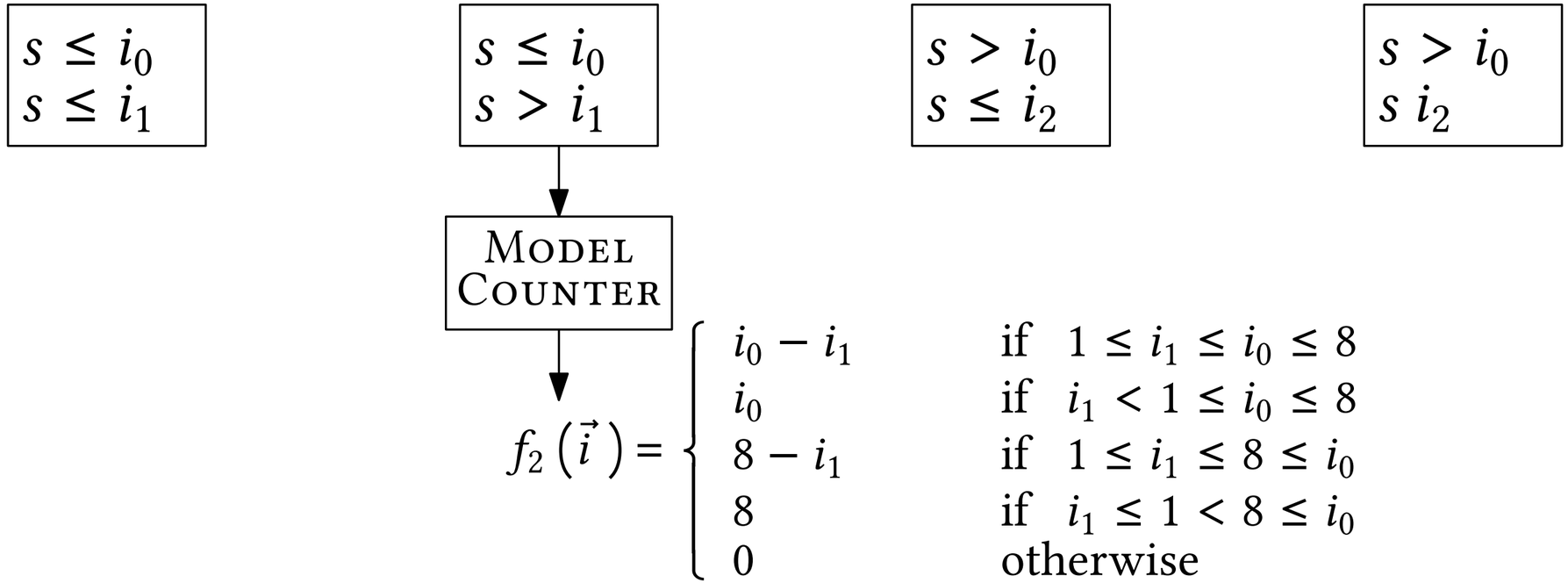
$s \leq i_0$
$s > i_1$



$s > i_0$
$s \leq i_2$

$s > i_0$
$s\ i_2$

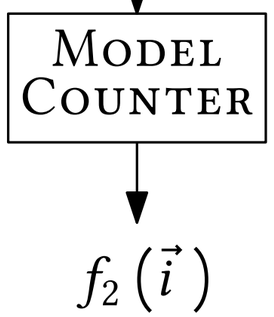
Computing Multi-Step Entropy Symbolically



Computing Multi-Step Entropy Symbolically

$s \leq i_0$
$s \leq i_1$

$s \leq i_0$
$s > i_1$

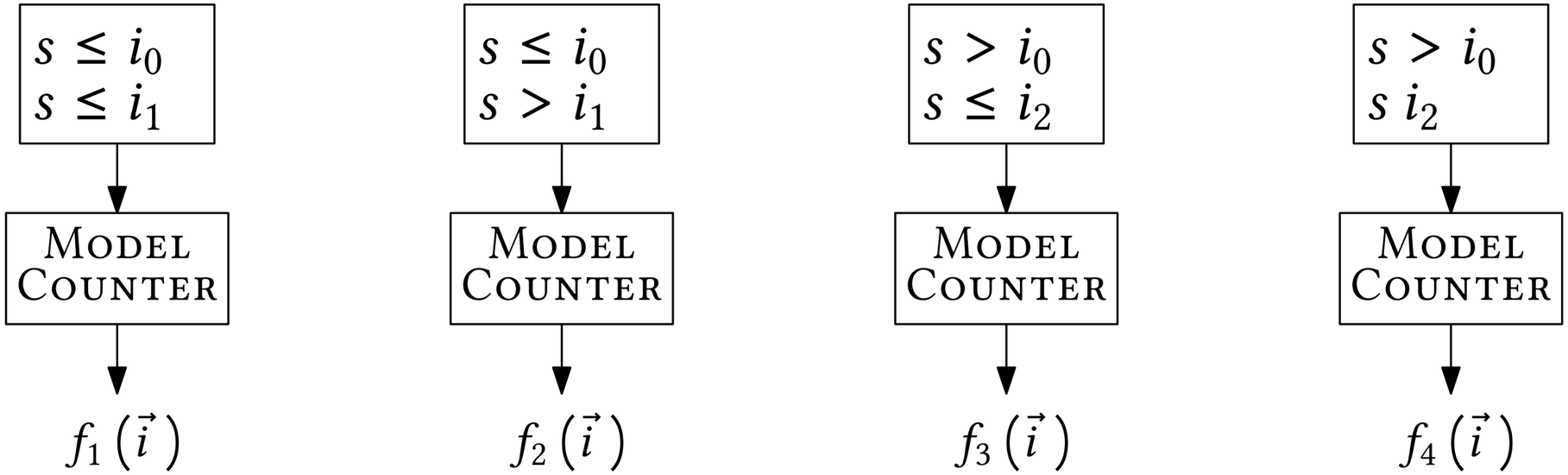


$f_2(\vec{i})$

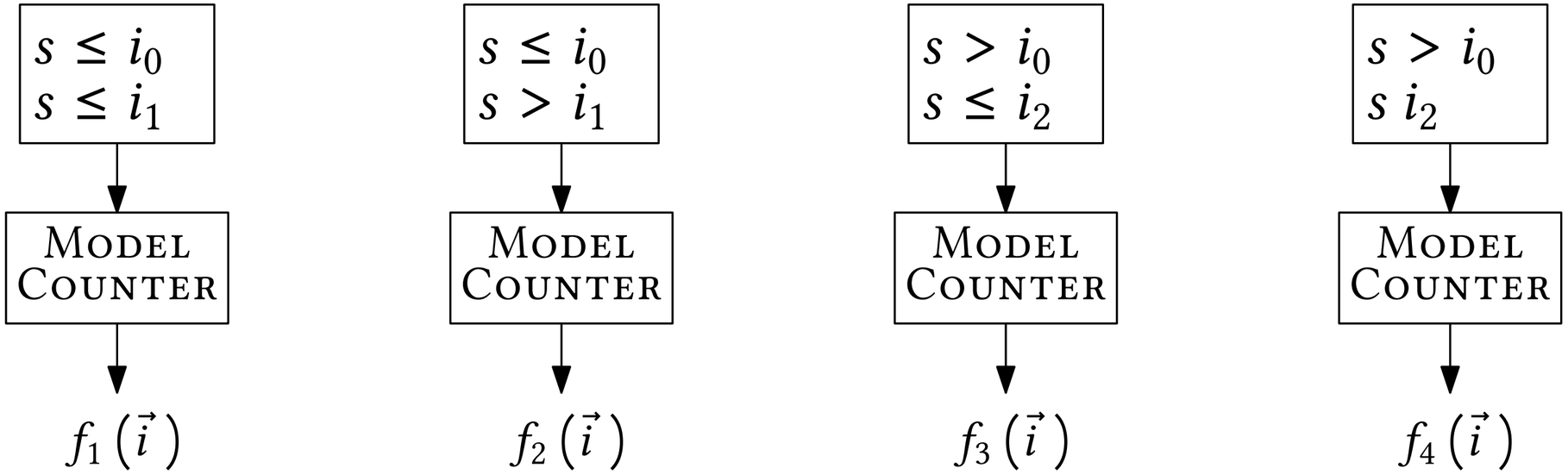
$s > i_0$
$s \leq i_2$

$s > i_0$
$s\ i_2$

Computing Multi-Step Entropy Symbolically

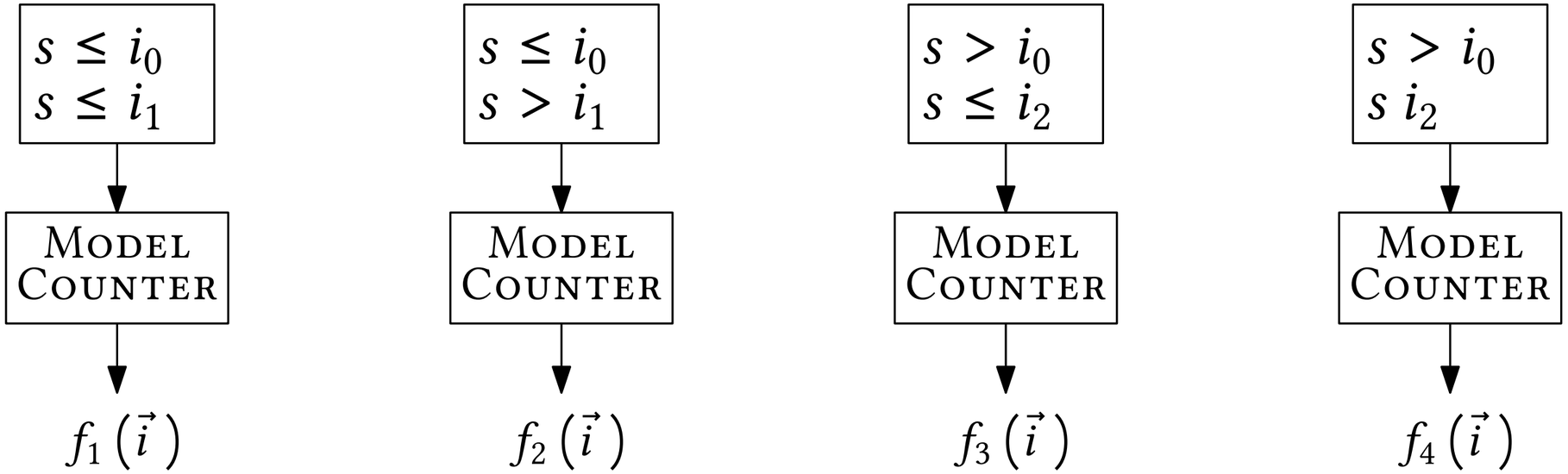


Computing Multi-Step Entropy Symbolically



$$p(s \in \square) = \frac{|\square|}{|\square|} \qquad p_j(\vec{i}) = \frac{f_j(\vec{i})}{|S|}$$

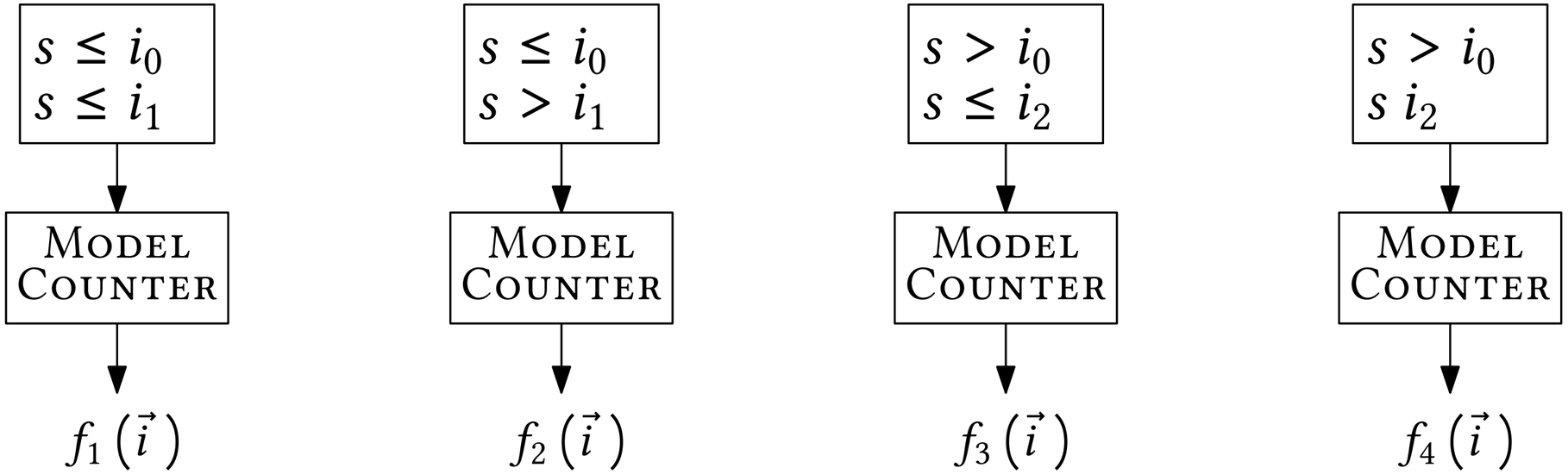
Computing Multi-Step Entropy Symbolically



$$p(s \in \square) = \frac{|\square|}{|\square|} \qquad p_j(\vec{i}) = \frac{f_j(\vec{i})}{|S|}$$

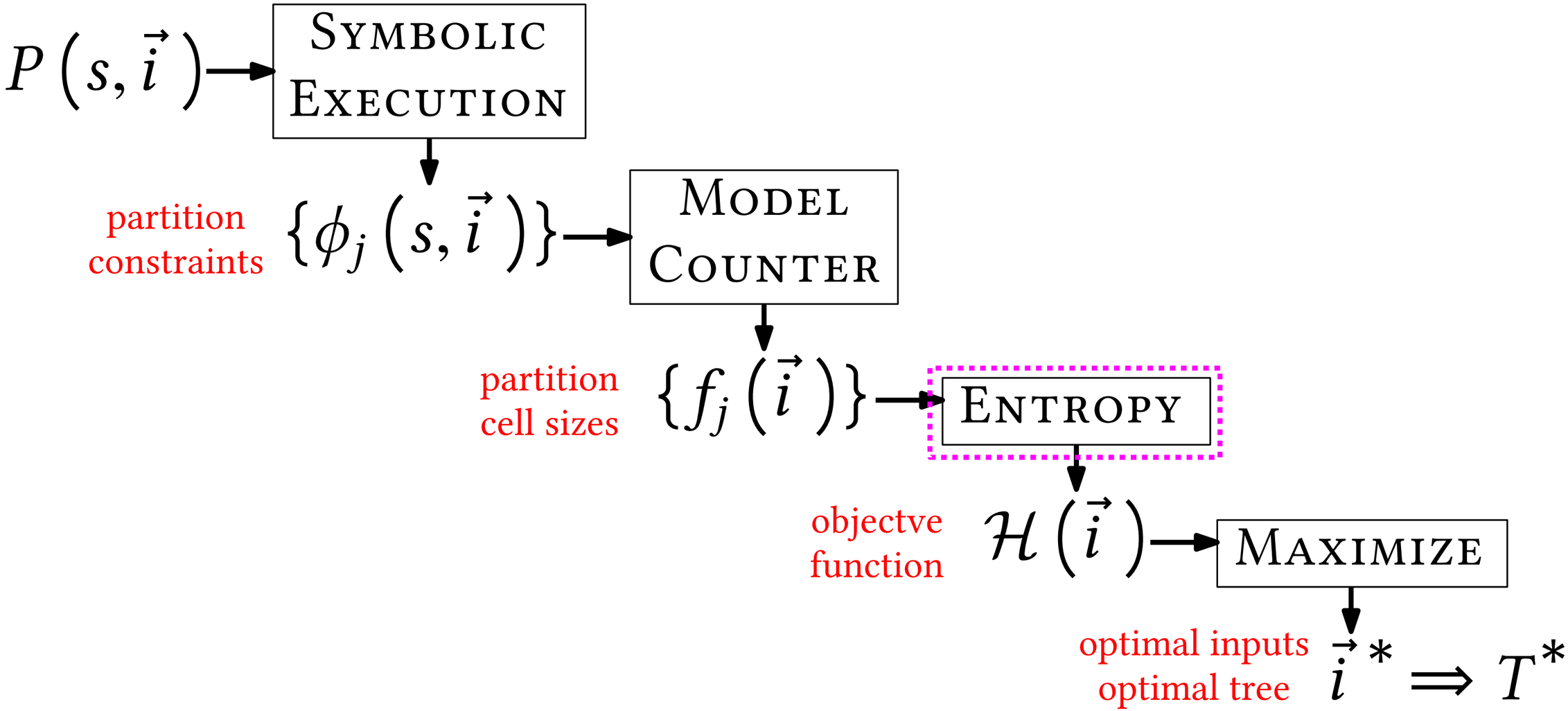
$$\mathcal{H}(\vec{i}) = \sum_{j=1}^{n} p_i \log_2 \frac{1}{p_j}$$

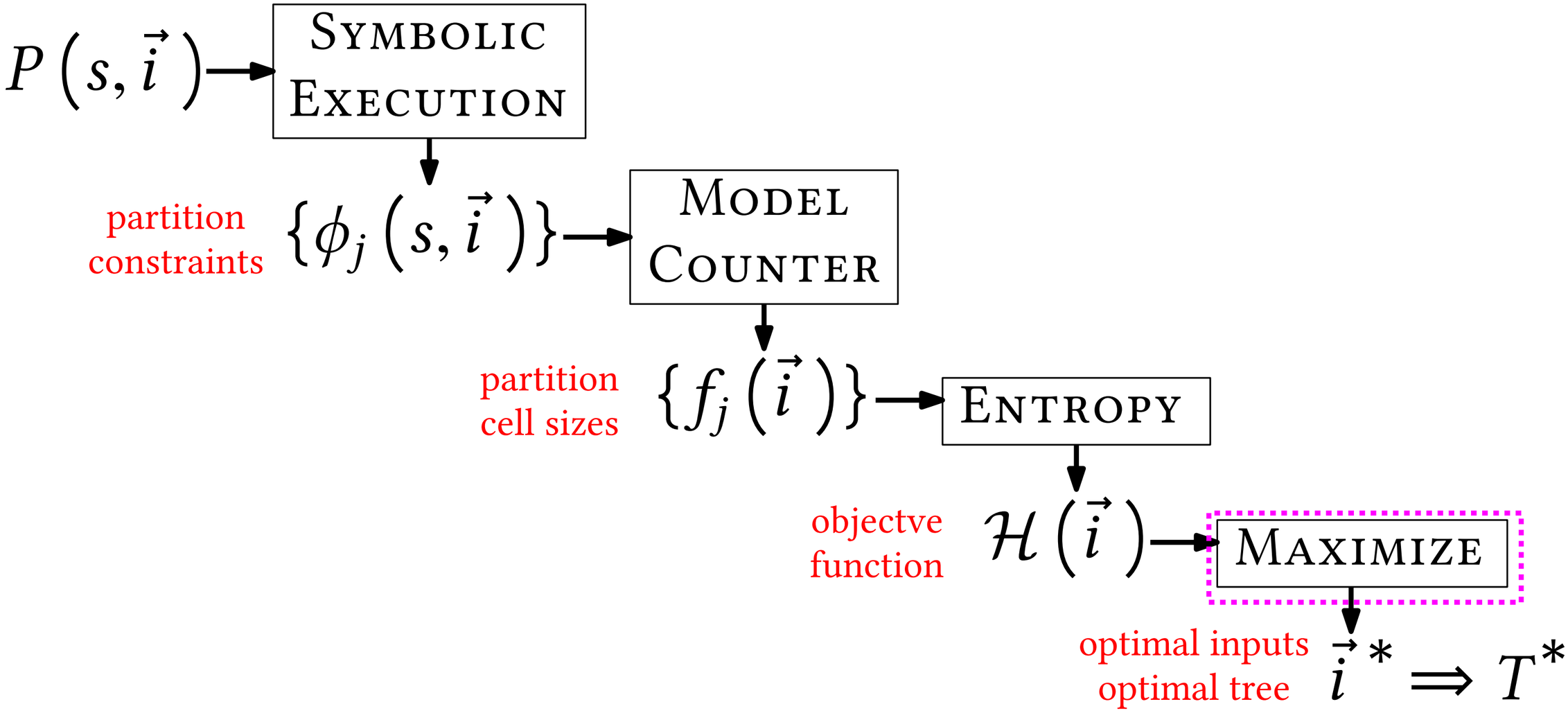
Computing Multi-Step Entropy Symbolically



$$p(s \in \square) = \frac{|\square|}{|\square|} \qquad p_j(\vec{i}) = \frac{f_j(\vec{i})}{|S|}$$

$$\mathcal{H}(\vec{i}) = \sum_{j=1}^{n} p_i \log_2 \frac{1}{p_j} = \frac{f_1(\vec{i})}{8} \log_2 \frac{8}{f_1(\vec{i})} + \frac{f_2(\vec{i})}{8} \log_2 \frac{8}{f_2(\vec{i})} + \frac{f_3(\vec{i})}{8} \log_2 \frac{8}{f_3(\vec{i})} + \frac{f_4(\vec{i})}{8} \log_2 \frac{8}{f_4(\vec{i})}$$


$P\left(s, \vec{i}\right)$
Symbolic Execution
partition constraints
$\{\phi_j\left(s, \vec{i}\right)\}$
Model Counter
partition cell sizes
$\{f_j\left(\vec{i}\right)\}$
Entropy
objectve function
$\mathcal{H}\left(\vec{i}\right)$
Maximize
optimal inputs
optimal tree
$\vec{i}^* \Rightarrow T^*$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Maximize
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optimal tree
$\vec{i}^{\,*} \Rightarrow T^*$

Numeric Maximization

$$\mathcal{H}\left(\vec{i}\right) = \sum_{j=1}^{n} p_i \log_2 \frac{1}{p_j} = \frac{f_1(\vec{i})}{8} \log_2 \frac{8}{f_1(\vec{i})} + \frac{f_2(\vec{i})}{8} \log_2 \frac{8}{f_2(\vec{i})} + \frac{f_3(\vec{i})}{8} \log_2 \frac{8}{f_3(\vec{i})} + \frac{f_4(\vec{i})}{8} \log_2 \frac{8}{f_4(\vec{i})}$$

Numeric Maximization

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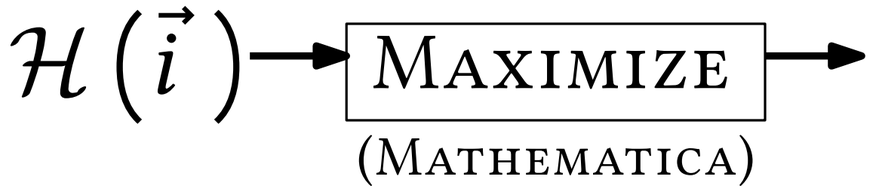
objectve function $\mathcal{H}\left(\vec{i}\right) \rightarrow$ MAXIMIZE

Numeric Maximization

$$\mathcal{H}\left(\vec{i}\right) = \sum_{j=1}^{n} p_i \log_2 \frac{1}{p_j} = \frac{f_1(\vec{i})}{8} \log_2 \frac{8}{f_1(\vec{i})} + \frac{f_2(\vec{i})}{8} \log_2 \frac{8}{f_2(\vec{i})} + \frac{f_3(\vec{i})}{8} \log_2 \frac{8}{f_3(\vec{i})} + \frac{f_4(\vec{i})}{8} \log_2 \frac{8}{f_4(\vec{i})}$$

objectve function



Numeric Maximization

$$\mathcal{H}\left(\vec{i}\right) = \sum_{j=1}^{n} p_i \log_2 \frac{1}{p_j} = \frac{f_1(\vec{i})}{8} \log_2 \frac{8}{f_1(\vec{i})} + \frac{f_2(\vec{i})}{8} \log_2 \frac{8}{f_2(\vec{i})} + \frac{f_3(\vec{i})}{8} \log_2 \frac{8}{f_3(\vec{i})} + \frac{f_4(\vec{i})}{8} \log_2 \frac{8}{f_4(\vec{i})}$$

objectve function

$$\mathcal{H}\left(\vec{i}\right) \rightarrow \boxed{\text{Maximize}} \rightarrow \vec{i}^{\,*} \Longrightarrow T^*$$

(Mathematica)

optimal inputs
optimal tree

Numeric Maximization

$$\mathcal{H}\left(\vec{i}\,\right) = \sum_{j=1}^{n} p_i \log_2 \frac{1}{p_j} = \frac{f_1(\vec{i}\,)}{8} \log_2 \frac{8}{f_1(\vec{i}\,)} + \frac{f_2(\vec{i}\,)}{8} \log_2 \frac{8}{f_2(\vec{i}\,)} + \frac{f_3(\vec{i}\,)}{8} \log_2 \frac{8}{f_3(\vec{i}\,)} + \frac{f_4(\vec{i}\,)}{8} \log_2 \frac{8}{f_4(\vec{i}\,)}$$

objectve function $\mathcal{H}\left(\vec{i}\,\right) \rightarrow$ MAXIMIZE (MATHEMATICA) $\rightarrow \vec{i}^{\,*} \Longrightarrow T^*$ optimal inputs, optimal tree

$$\vec{i}^{\,*} = (i_0^*, i_1^*, i_2^*)$$

Numeric Maximization

$$\mathcal{H}\left(\vec{i}\,\right) = \sum_{j=1}^{n} p_i \log_2 \frac{1}{p_j} = \frac{f_1(\vec{i}\,)}{8} \log_2 \frac{8}{f_1(\vec{i}\,)} + \frac{f_2(\vec{i}\,)}{8} \log_2 \frac{8}{f_2(\vec{i}\,)} + \frac{f_3(\vec{i}\,)}{8} \log_2 \frac{8}{f_3(\vec{i}\,)} + \frac{f_4(\vec{i}\,)}{8} \log_2 \frac{8}{f_4(\vec{i}\,)}$$

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$$\vec{i}^{\,*} = (i_0^*, i_1^*, i_2^*)$$

$$\vec{i}^{\,*} = (4, 2, 6)$$

Numeric Maximization

$$\mathcal{H}\left(\vec{i}\,\right) = \sum_{j=1}^{n} p_i \log_2 \frac{1}{p_j} = \frac{f_1(\vec{i}\,)}{8} \log_2 \frac{8}{f_1(\vec{i}\,)} + \frac{f_2(\vec{i}\,)}{8} \log_2 \frac{8}{f_2(\vec{i}\,)} + \frac{f_3(\vec{i}\,)}{8} \log_2 \frac{8}{f_3(\vec{i}\,)} + \frac{f_4(\vec{i}\,)}{8} \log_2 \frac{8}{f_4(\vec{i}\,)}$$

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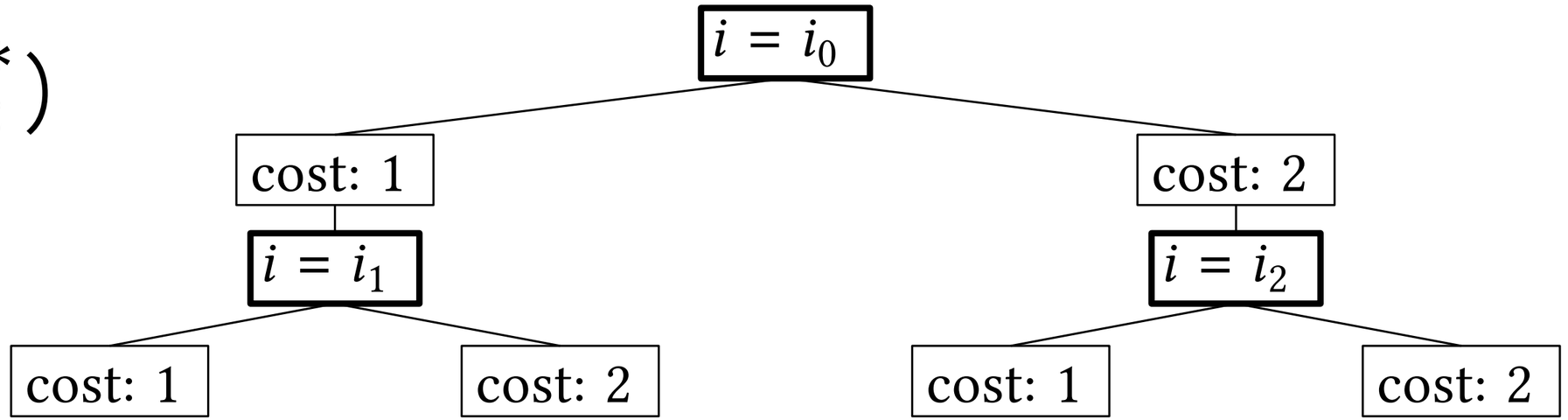

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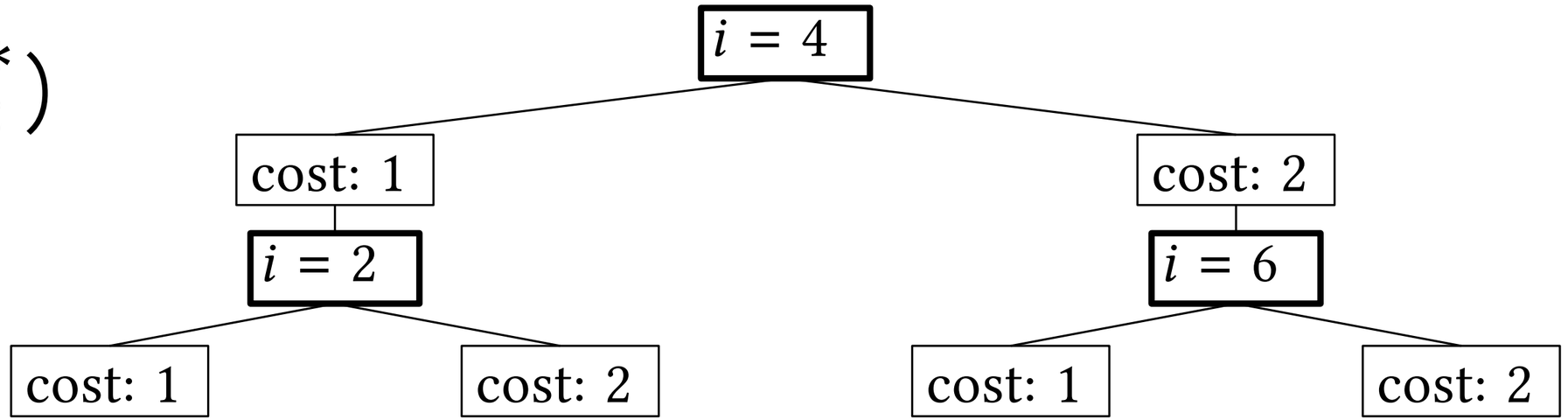

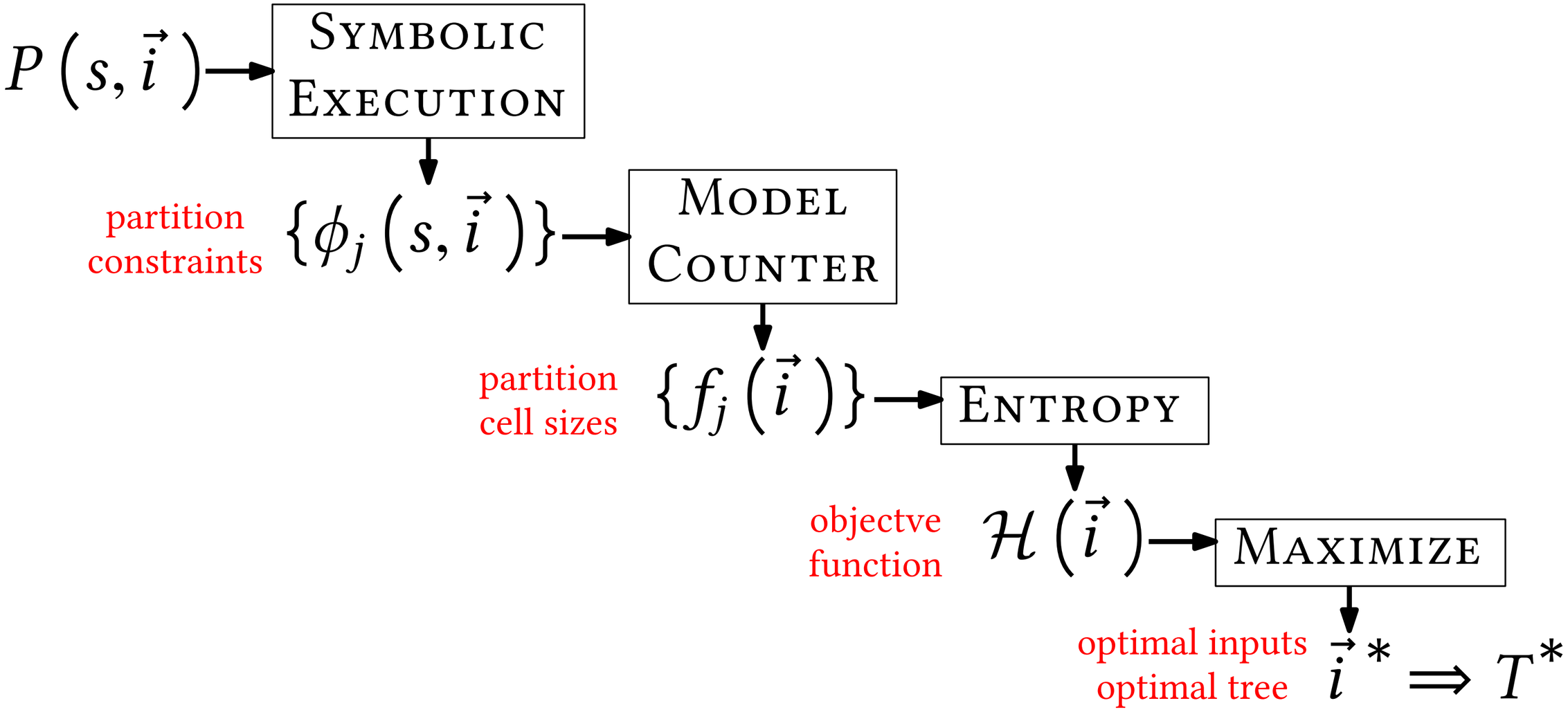
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Other Methods

Other Methods

My approach: reduce attack synthesis to **numeric optimization** problem.

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Limited by model counter.

Numeric optimum not guaranteed.

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- Limited by model counter.
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MaxSMT: reduce attack synthesis to **Max SAT** problem.

- Reduces everything to bits.
- Upper bound on information leakage.

Other Methods

My approach: reduce attack synthesis to **numeric optimization** problem.

- Limited by model counter.
- Numeric optimum not guaranteed.

MaxSMT: reduce attack synthesis to **Max SAT** problem.

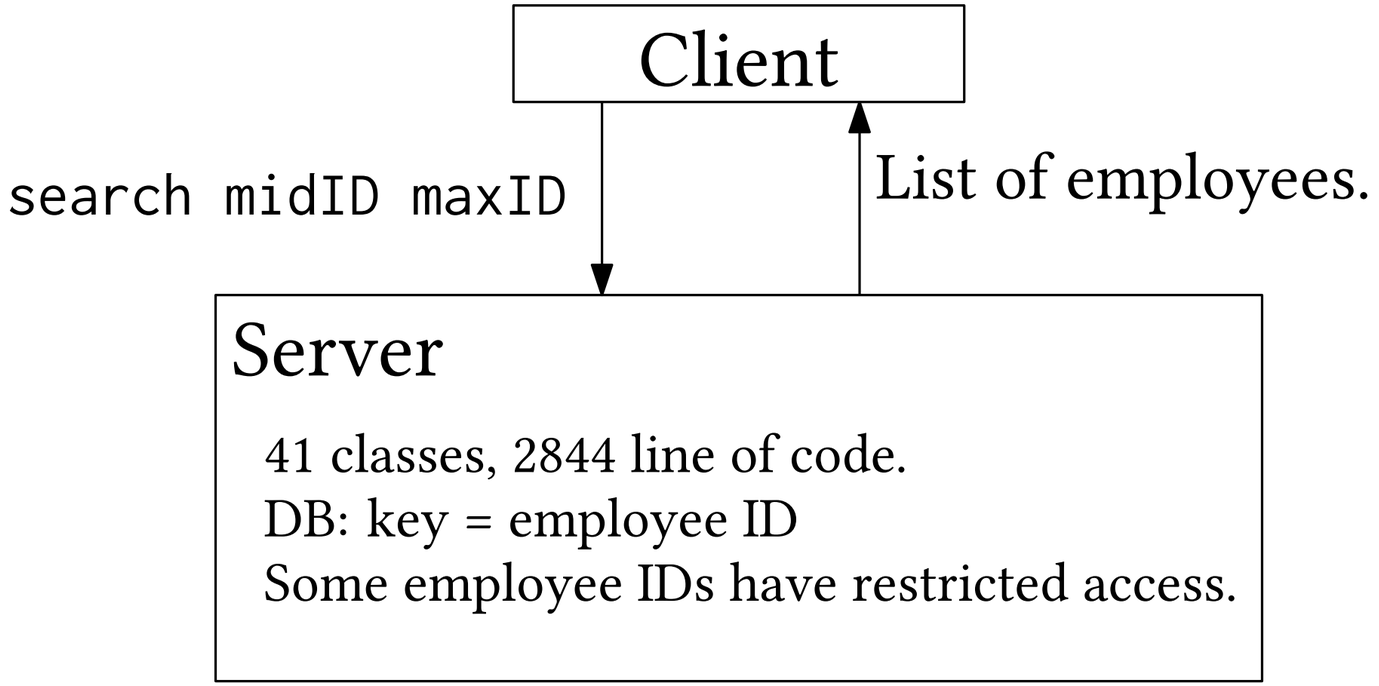
- Reduces everything to bits.
- Upper bound on information leakage.

MARCO: reduce attack synthesis to **Maximum SAT Subsets** problem.

- Reduces everything to bits.
- Exact optimal information leakage guaranteed.

Case Study: LawDB

From DARPA Space-Time Analysis for Cybersecurity (STAC)



LawDB Partition Constraints

$$
\begin{aligned}
&\{h \leq l_1 \wedge 85 \leq l_1 \wedge 64 \leq l_1 \wedge 64 \geq l_2 \wedge h > 85 \wedge h > 64 \wedge h \neq 85 \wedge h \neq 64,\\
&h > l_1 \wedge 85 \leq l_1 \wedge 64 \leq l_1 \wedge 64 \geq l_2 \wedge h > 85 \wedge h > 64 \wedge h \neq 85 \wedge h \neq 64,\\
&85 > l_1 \wedge 64 \leq l_1 \wedge 64 \geq l_2 \wedge h > 85 \wedge h > 64 \wedge h \neq 85 \wedge h \neq 64,\\
&64 > l_1 \wedge 64 \geq l_2 \wedge h > 85 \wedge h > 64 \wedge h \neq 85 \wedge h \neq 64,\\
&h \leq l_1 \wedge 85 \leq l_1 \wedge 85 \geq l_2 \wedge 64 < l_2 \wedge h > 85 \wedge h > 64 \wedge h \neq 85 \wedge h \neq 64,\\
&h > l_1 \wedge 85 \leq l_1 \wedge 85 \geq l_2 \wedge 64 < l_2 \wedge h > 85 \wedge h > 64 \wedge h \neq 85 \wedge h \neq 64,\\
&85 > l_1 \wedge 85 \geq l_2 \wedge 64 < l_2 \wedge h > 85 \wedge h > 64 \wedge h \neq 85 \wedge h \neq 64,\\
&h \leq l_1 \wedge h \geq l_2 \wedge 85 < l_2 \wedge 64 < l_2 \wedge h > 85 \wedge h > 64 \wedge h \neq 85 \wedge h \neq 64,\\
&h > l_1 \wedge h \geq l_2 \wedge 85 < l_2 \wedge 64 < l_2 \wedge h > 85 \wedge h > 64 \wedge h \neq 85 \wedge h \neq 64,\\
&h < l_2 \wedge 85 < l_2 \wedge 64 < l_2 \wedge h > 85 \wedge h > 64 \wedge h \neq 85 \wedge h \neq 64,\\
&85 \leq l_1 \wedge h \leq l_1 \wedge 64 \leq l_1 \wedge 64 \geq l_2 \wedge h \leq 85 \wedge h > 64 \wedge h \neq 85 \wedge h \neq 64,\\
&85 > l_1 \wedge h \leq l_1 \wedge 64 \leq l_1 \wedge 64 \geq l_2 \wedge h \leq 85 \wedge h > 64 \wedge h \neq 85 \wedge h \neq 64,\\
&h > l_1 \wedge 64 \leq l_1 \wedge 64 \geq l_2 \wedge h \leq 85 \wedge h > 64 \wedge h \neq 85 \wedge h \neq 64,\\
&64 > l_1 \wedge 64 \geq l_2 \wedge h \leq 85 \wedge h > 64 \wedge h \neq 85 \wedge h \neq 64,\\
&85 \leq l_1 \wedge h \leq l_1 \wedge h \geq l_2 \wedge 64 < l_2 \wedge h \leq 85 \wedge h > 64 \wedge h \neq 85 \wedge h \neq 64,
\end{aligned}
$$

Case Study: LawDB, DB size = 100

Keep pushing tree deeper until partitions have size 1.

	Tree depth	Time
Numeric	7	57s
MaxSMT	17	21s
MARCO	7	2m 36s

Case Study: LawDB, DB size = 100

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Proposed Experiments

DARPA Space-Time Analysis for Cybersecurity (STAC)

Canonical Side-Channel Vulnerability Benchmark

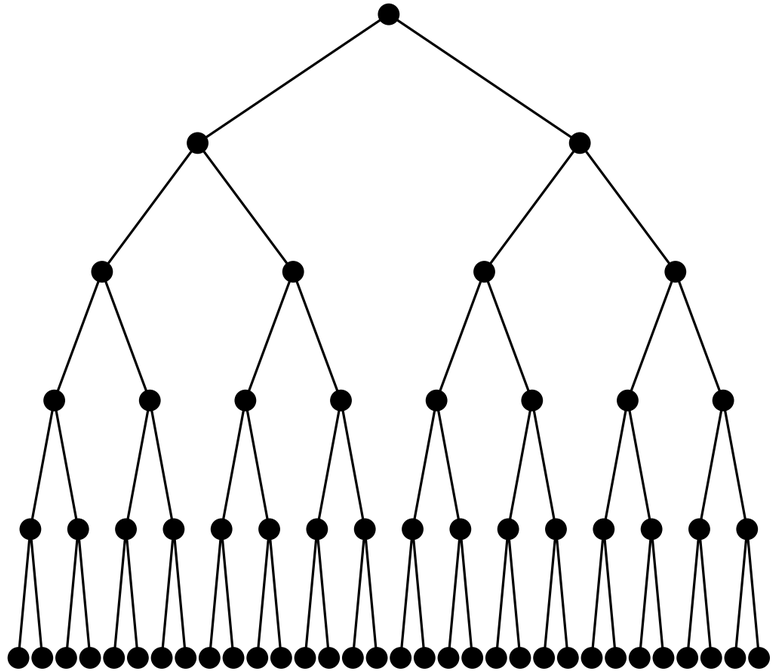
https://github.com/Apogee-Research/STAC/

7 Applications, 1 to 3 variants each

14 total programs

Challenges and Solutions

Fully Offline Static



Quantify over all $s \in S$

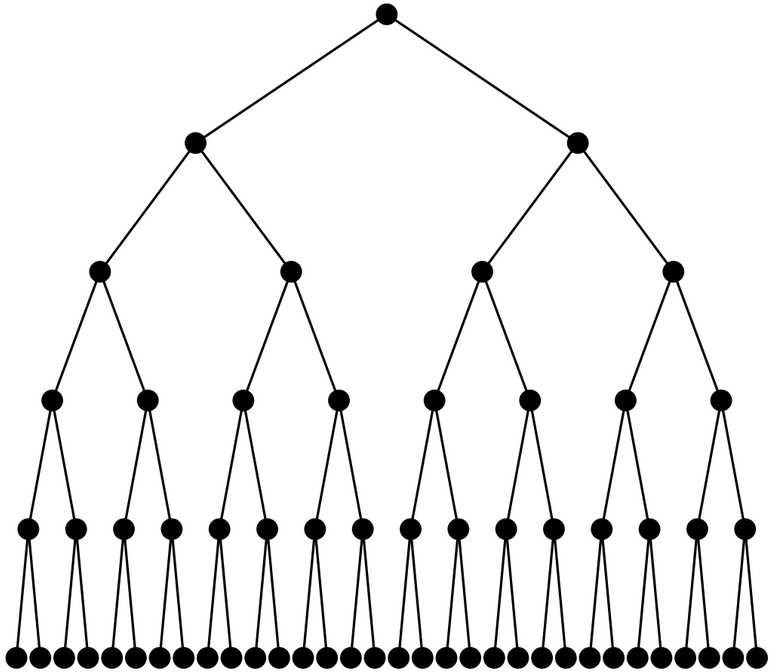
Exponential blowup

Cost model: overly ideal, not realistic

Ignores HW / OS properties

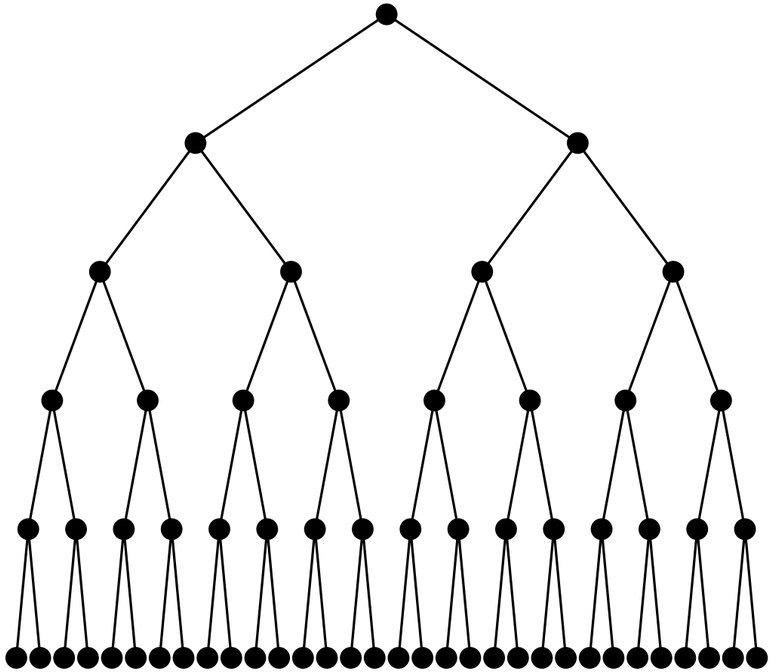
Challenges and Solutions

Fully Offline Static



Quantify over all $s \in S$
Exponential blowup
Cost model: overly ideal, not realistic
Ignores HW / OS properties

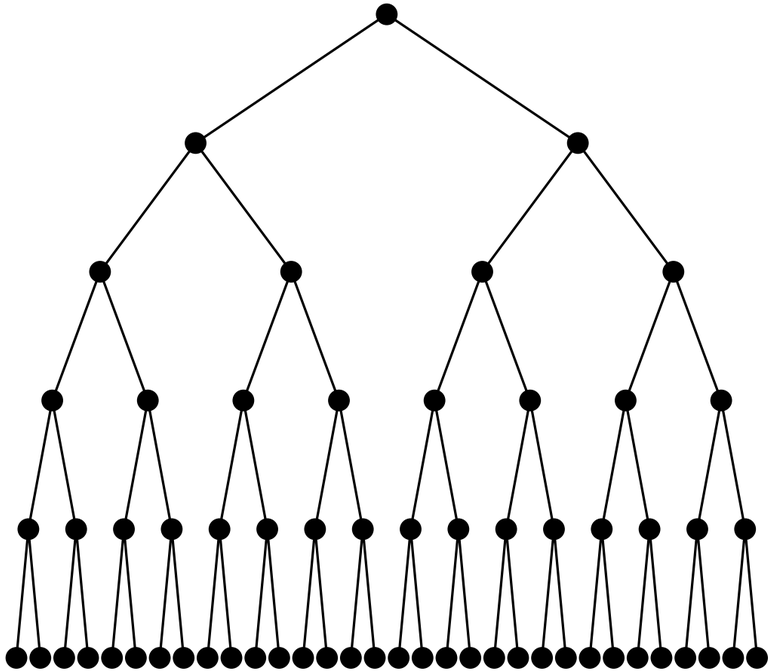
Static + Dynamic



Real system has one $s \in S$

Challenges and Solutions

Fully Offline Static



Quantify over all $s \in S$
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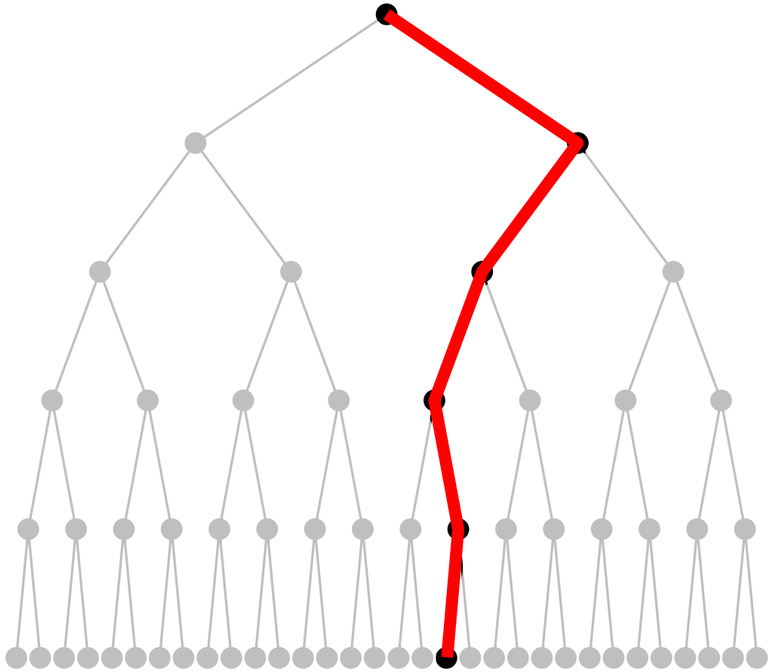
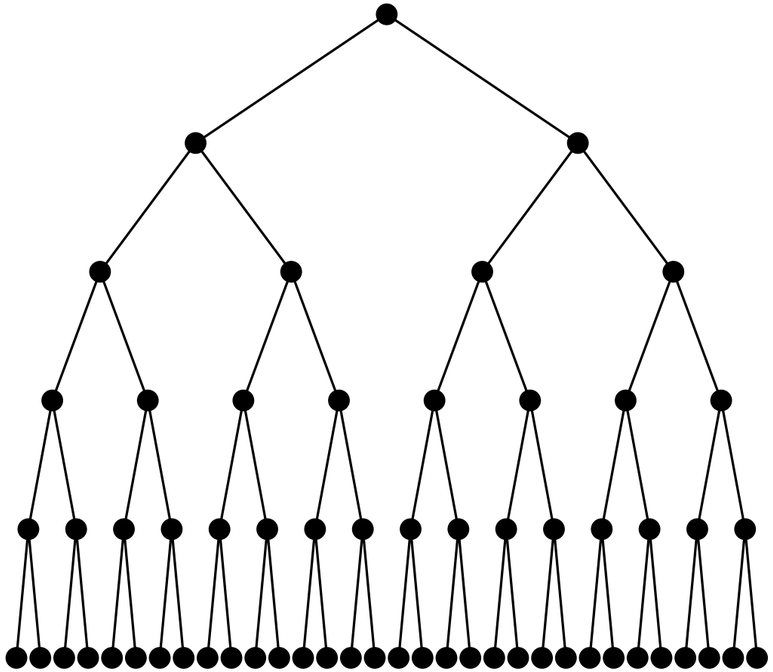
Static + Dynamic



Real system has one $s \in S$

Challenges and Solutions

Fully Offline Static



Quantify over all $s \in S$
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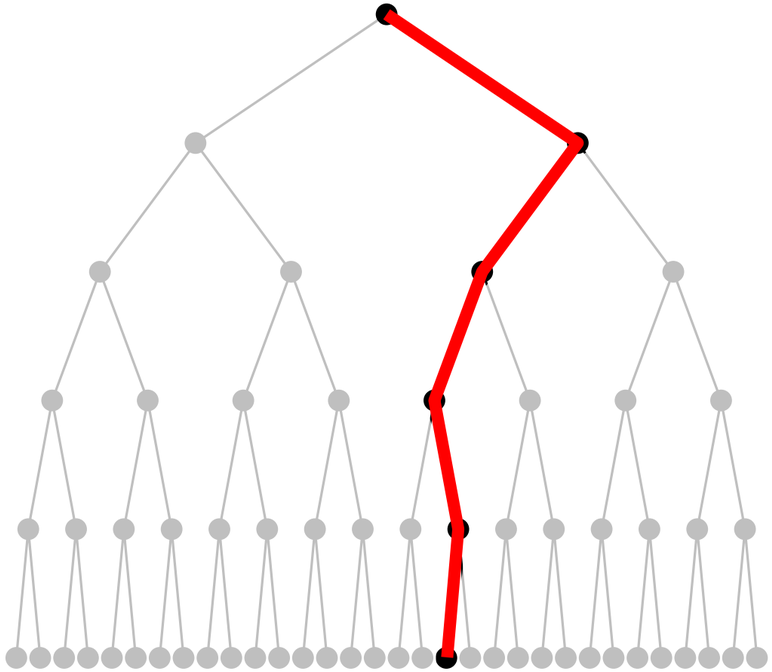

Real system has one $s \in S$
Put program on a real system
Dynamic cost profiling

Online Attack Synthesis

Online Attack Synthesis Proposed Work

```
1  private s = getMaxBytes();
2
3
4  public int compare(int i){
5    if(s <= i)
6     some computation; // 1 s
7    else
8      log.write("too many bits"); // 2s
9    return 0;
10 }
```

```
1  private s = getMaxBytes();
2
3
4  public int compare(int i){
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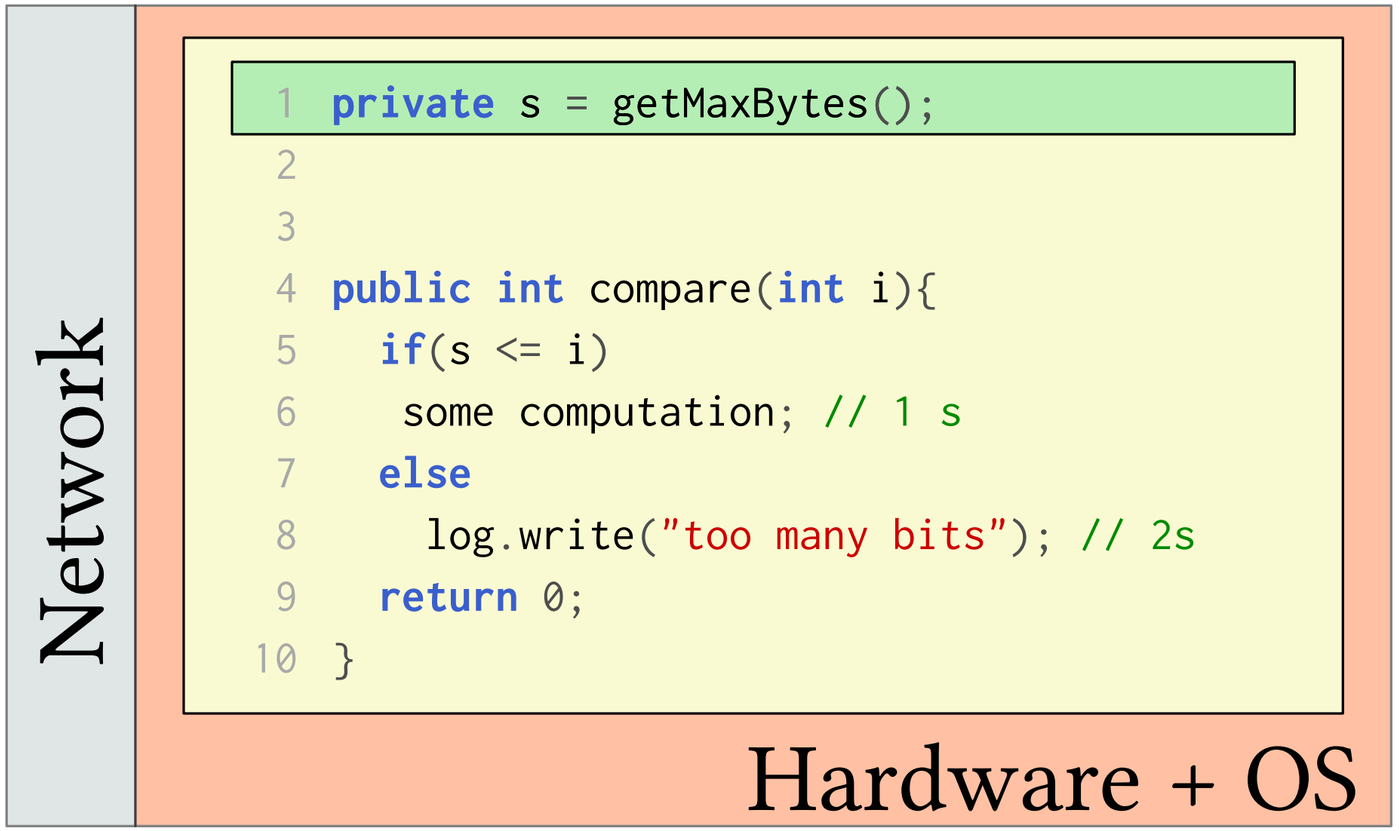
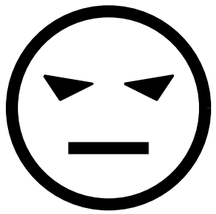
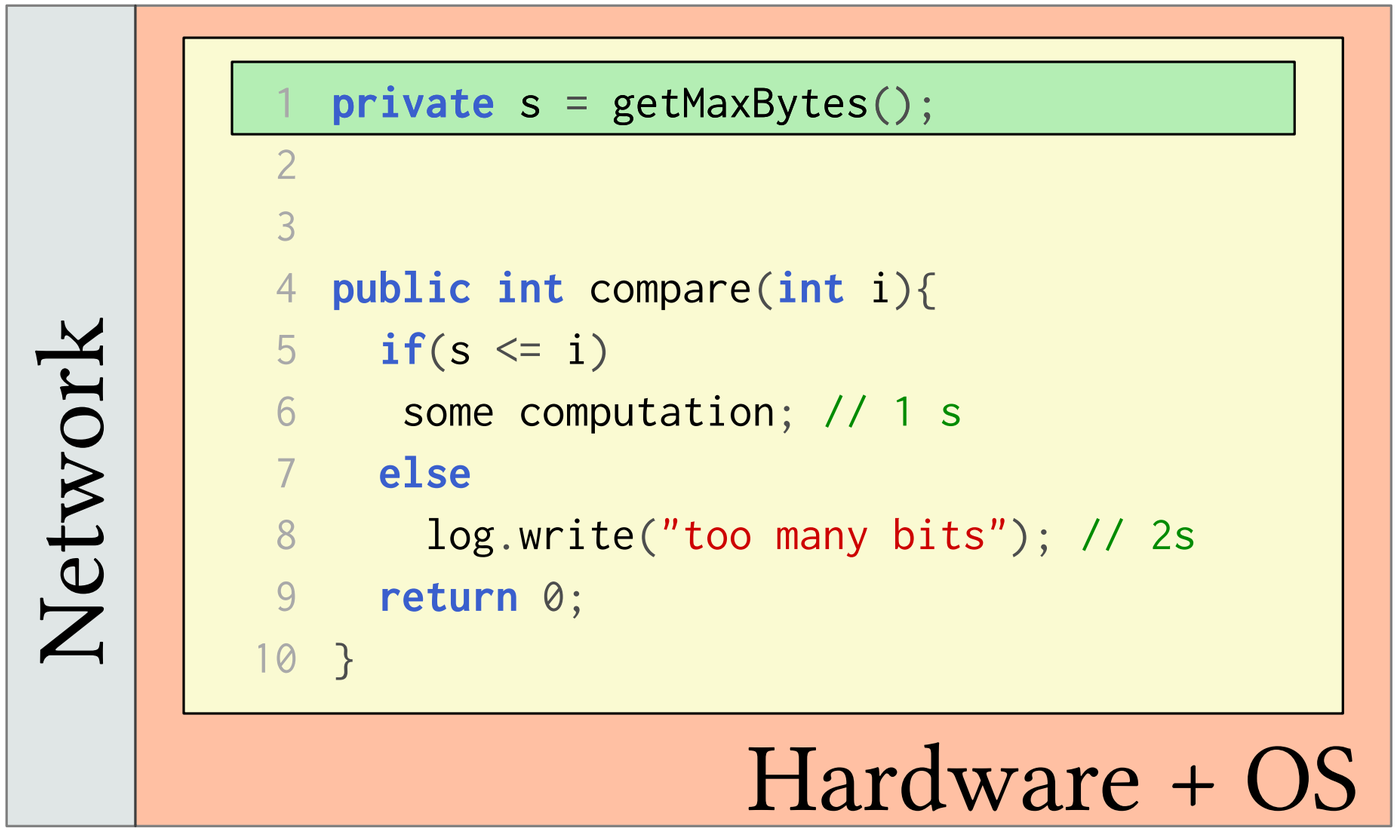
Hardware + OS


Network
1 private s = getMaxBytes();
2
3
4 public int compare(int i){
5 if(s <= i)
6 some computation; // 1 s
7 else
8 log.write("too many bits"); // 2s
9 return 0;
10 }
Hardware + OS



s?


Network
1 private s = getMaxBytes();
2
3
4 public int compare(int i){
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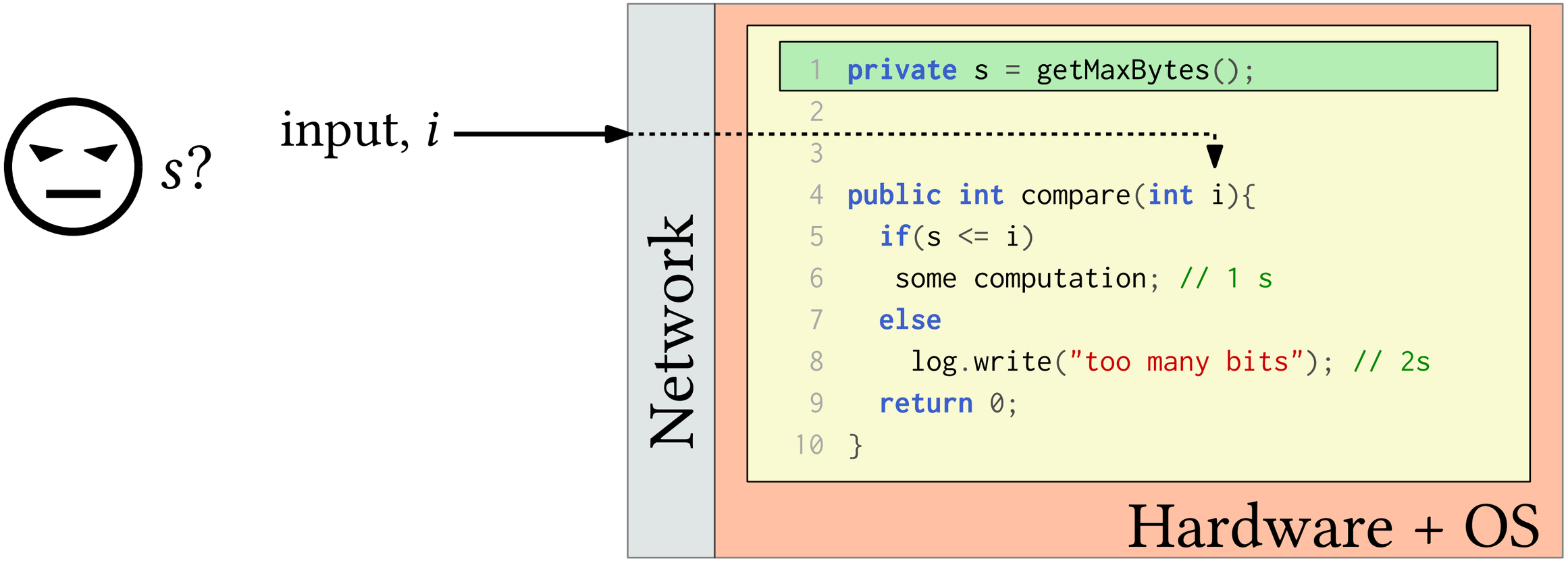
6 some computation; // 1 s
7 else
8 log.write("too many bits"); // 2s
9 return 0;
10 }
Hardware + OS


s?
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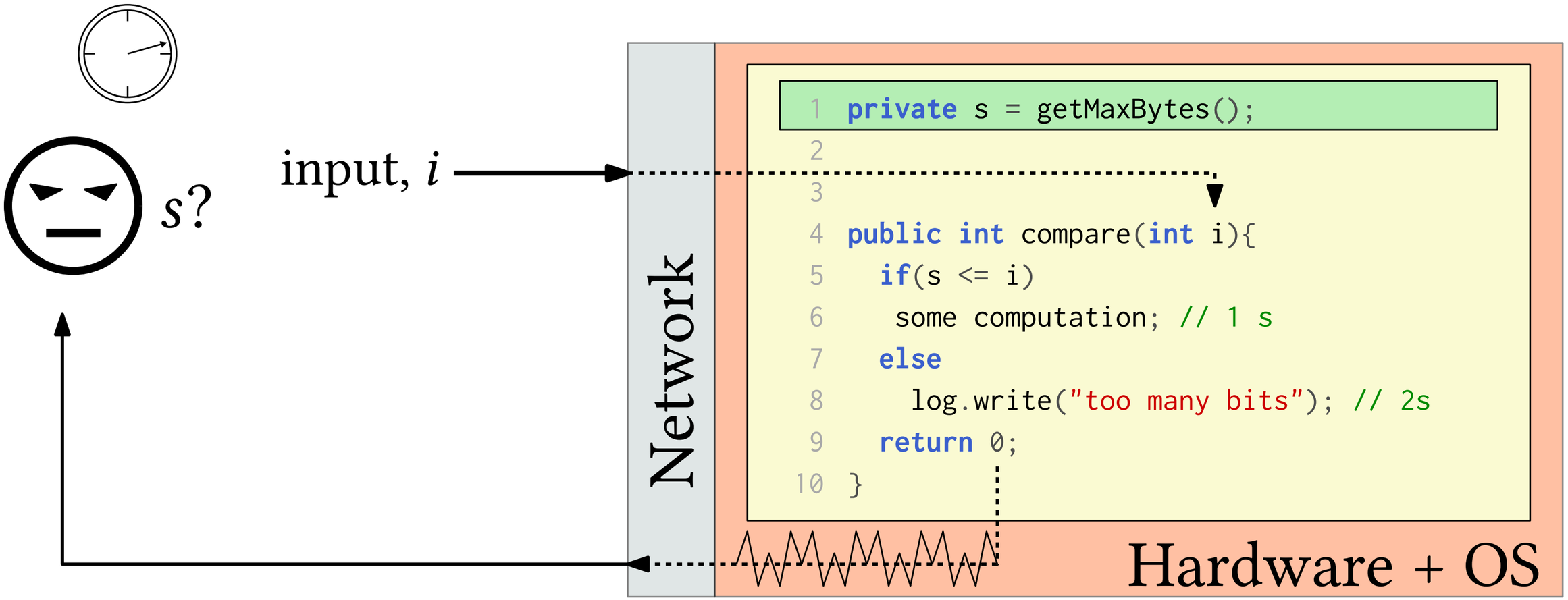
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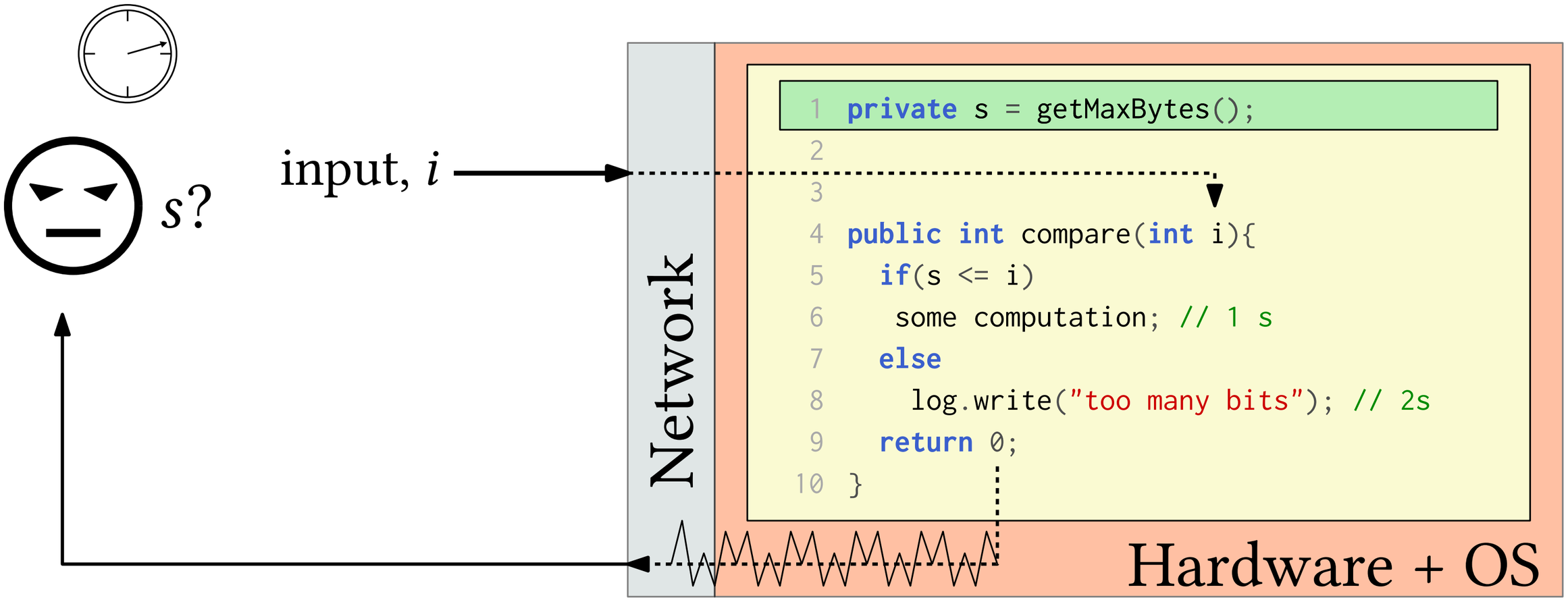
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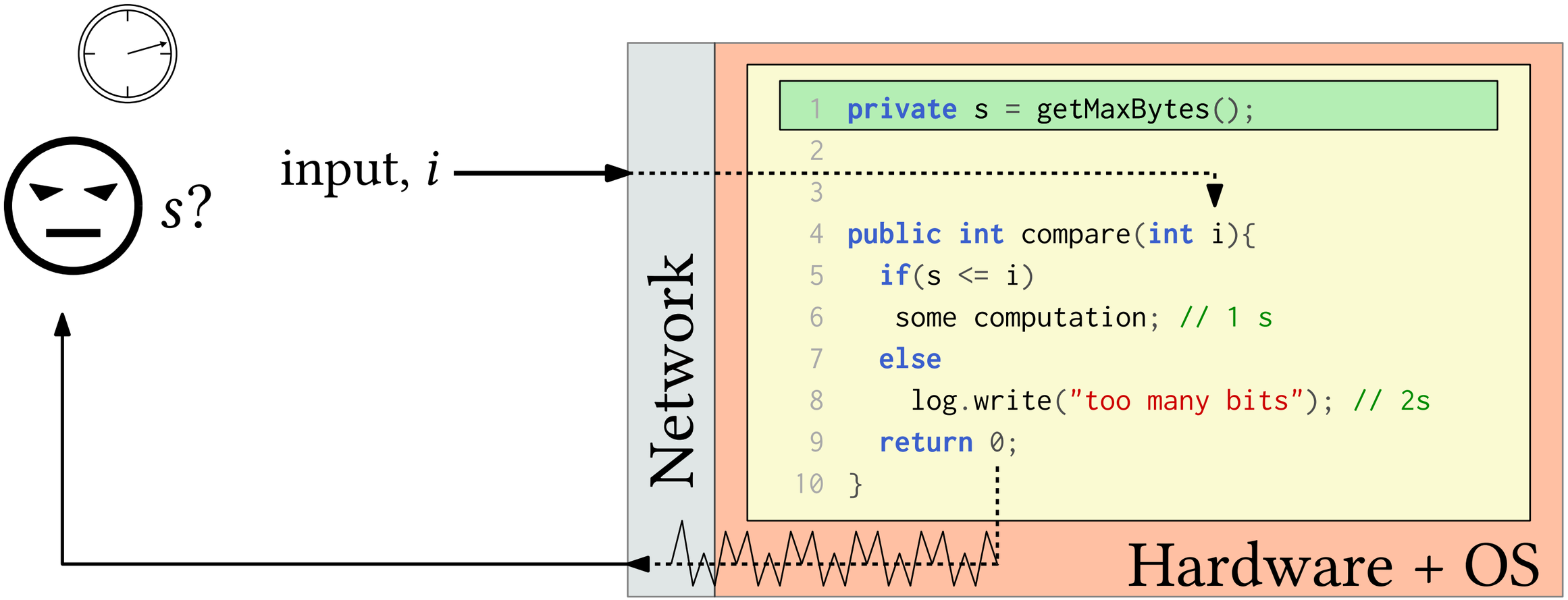
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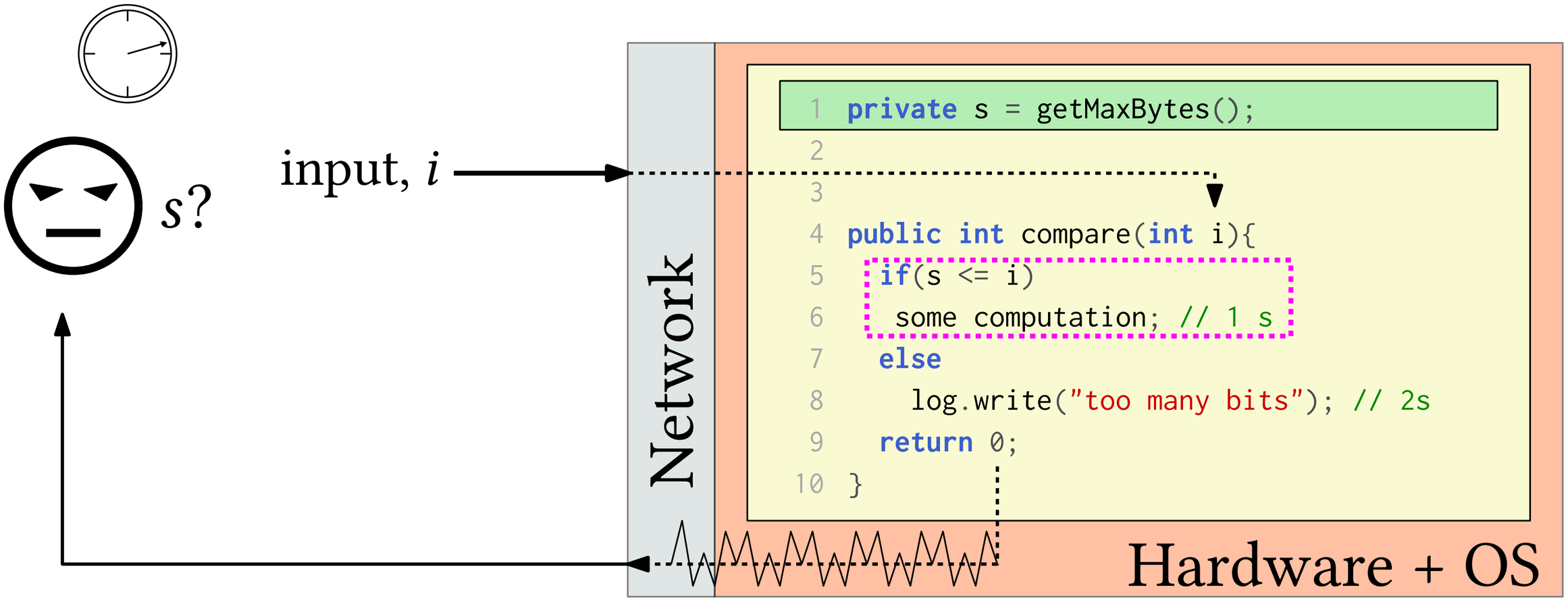
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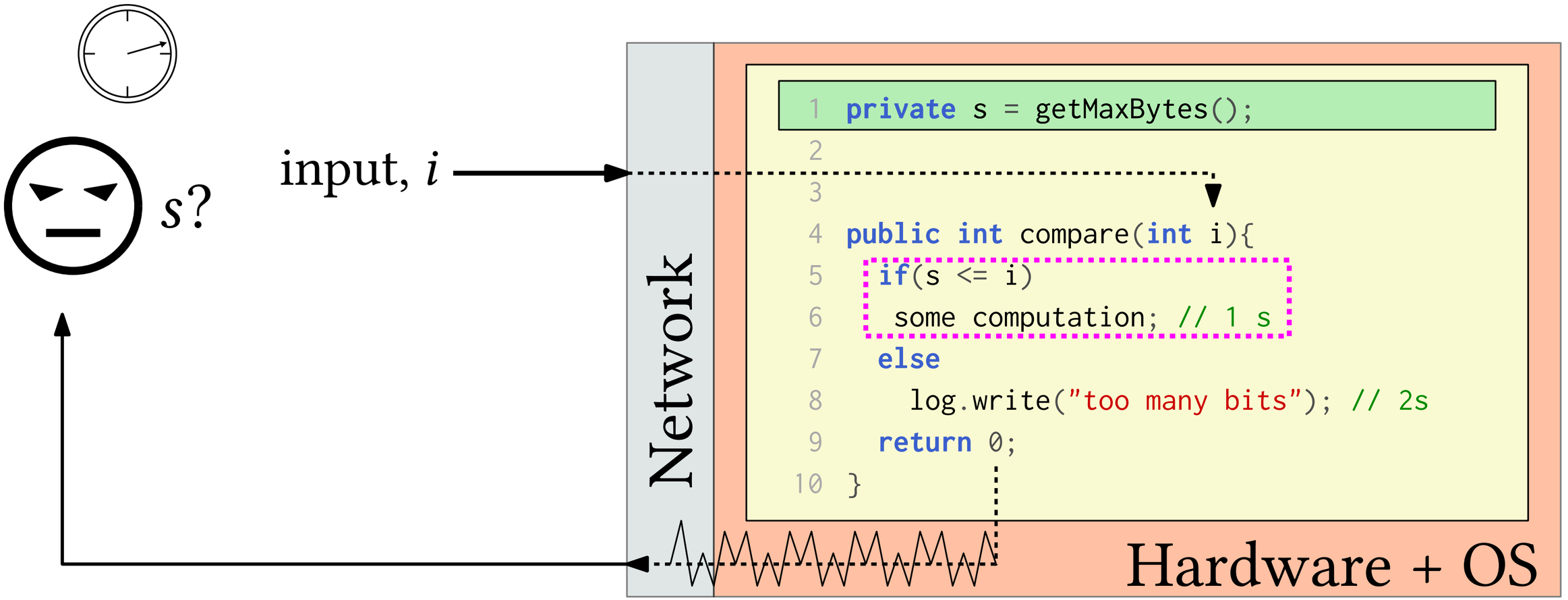
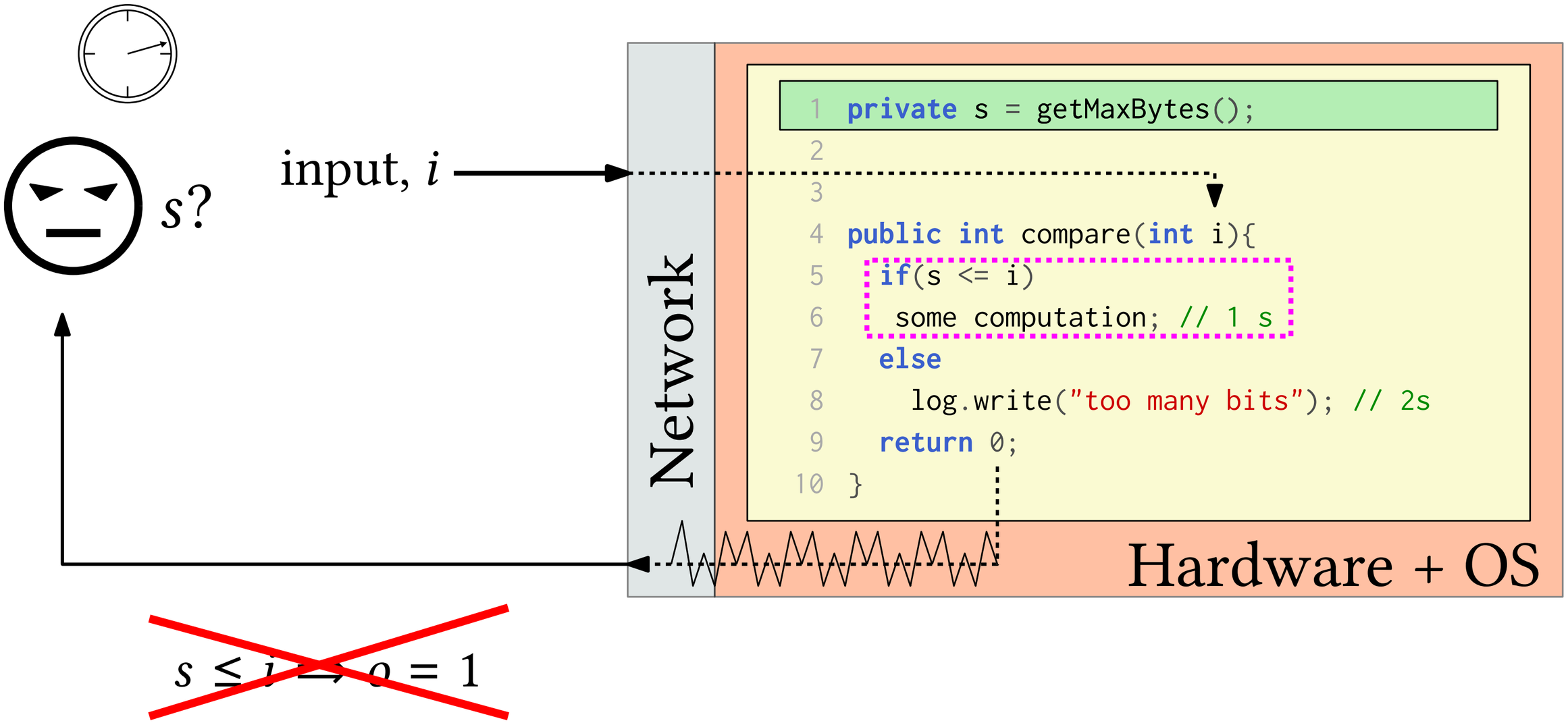
Hardware + OS



$$s \leq i \Longrightarrow o = 1$$


s?
input, i
Network
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7 else
8 log.write("too many bits"); // 2s
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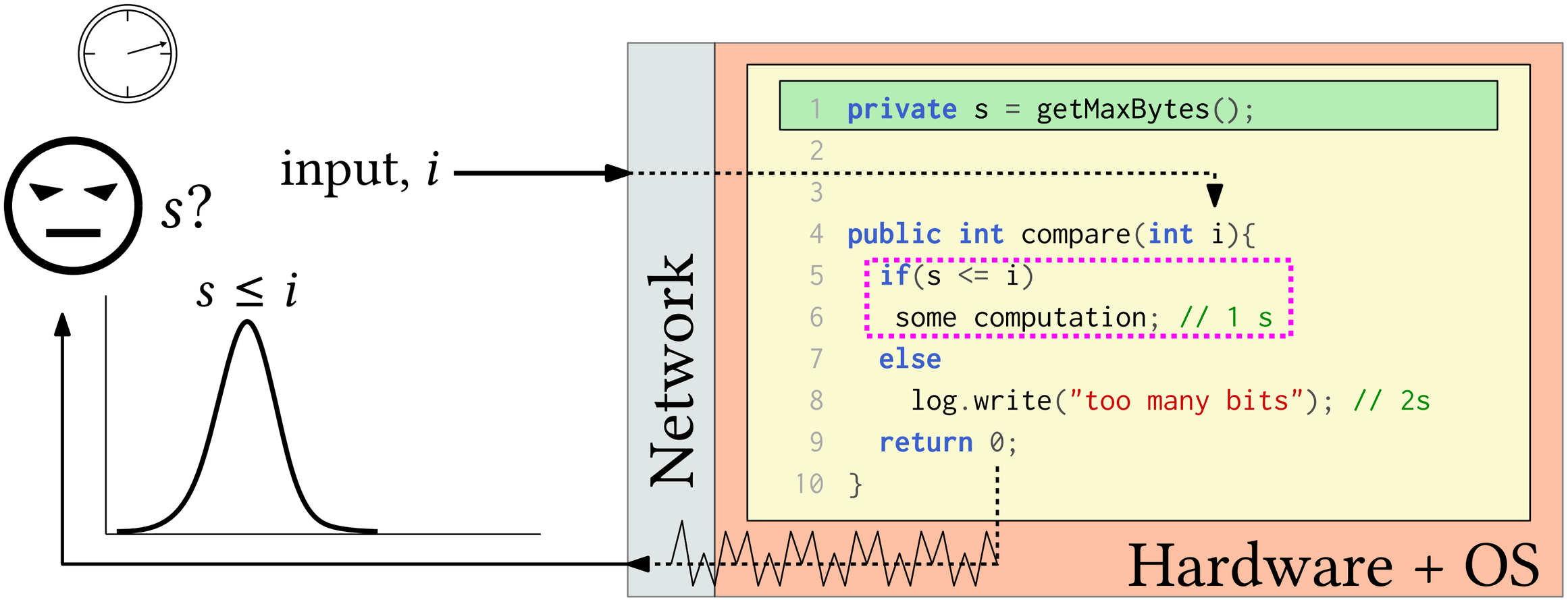
Hardware + OS
s ≤ i ⟶ o = 1


input, i
s?
$s \leq i$
Network
1 private s = getMaxBytes();
2
3
4 public int compare(int i){
5 if(s <= i)
6 some computation; // 1 s
7 else
8 log.write("too many bits"); // 2s
9 return 0;
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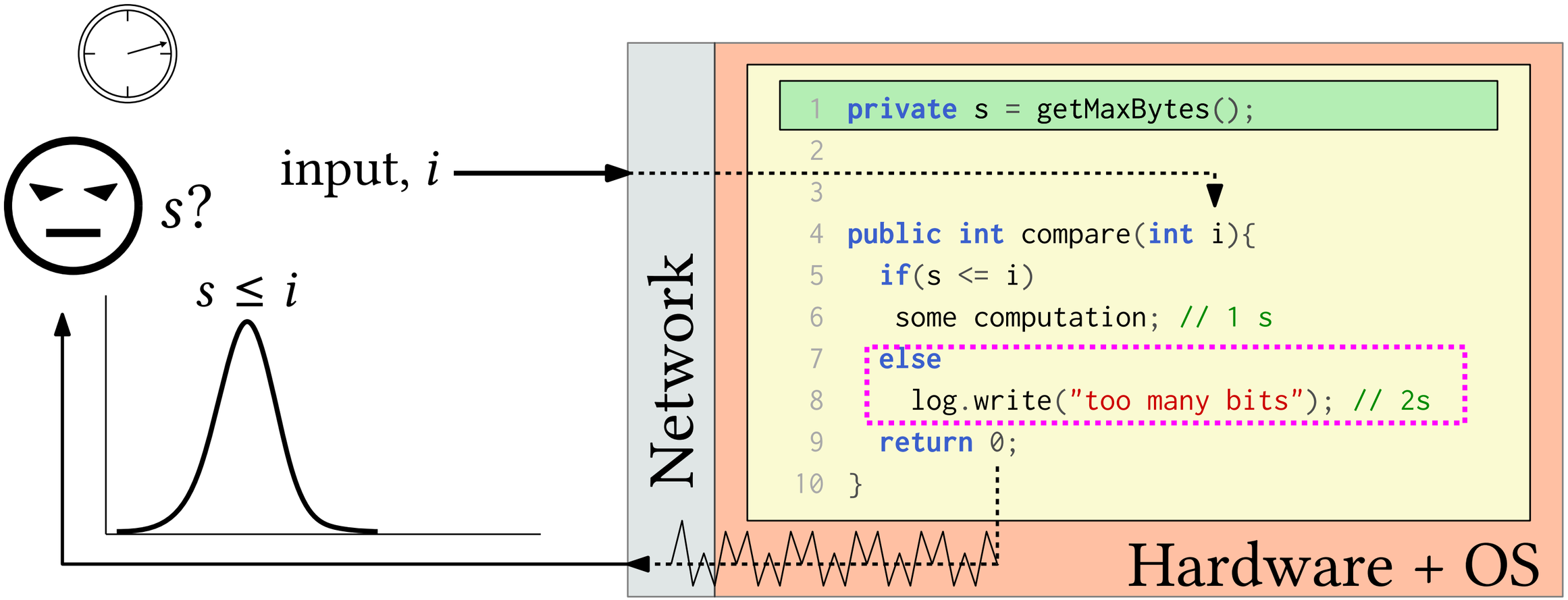
Hardware + OS


input, i
s?
$s \leq i$
Network
1 private s = getMaxBytes();
2
3
4 public int compare(int i){
5 if(s <= i)
6 some computation; // 1 s
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8 log.write("too many bits"); // 2s
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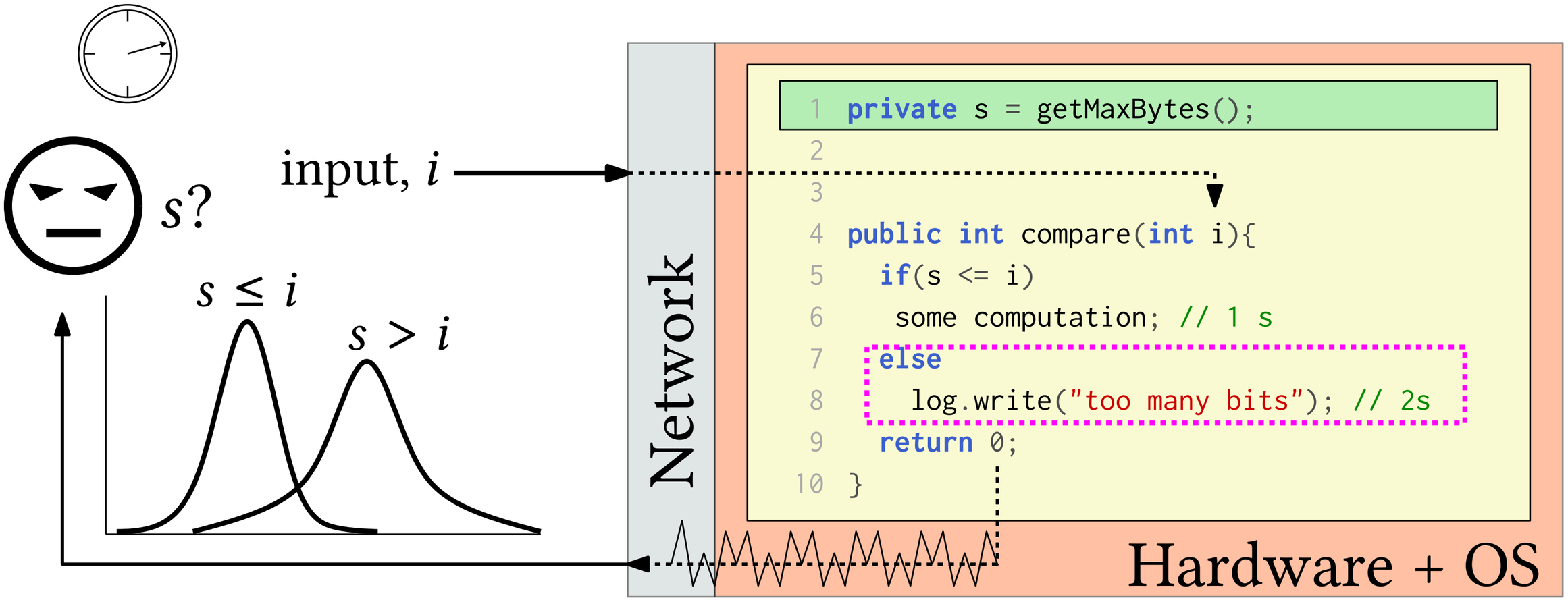
Hardware + OS


s?
input, i
s ≤ i
s > i
Network
1 private s = getMaxBytes();
2
3
4 public int compare(int i){
5 if(s <= i)
6 some computation; // 1 s
7 else
8 log.write("too many bits"); // 2s
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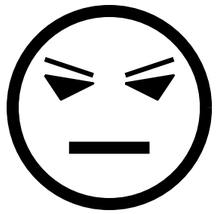
Hardware + OS

Challenges: Uncertainty Everywhere

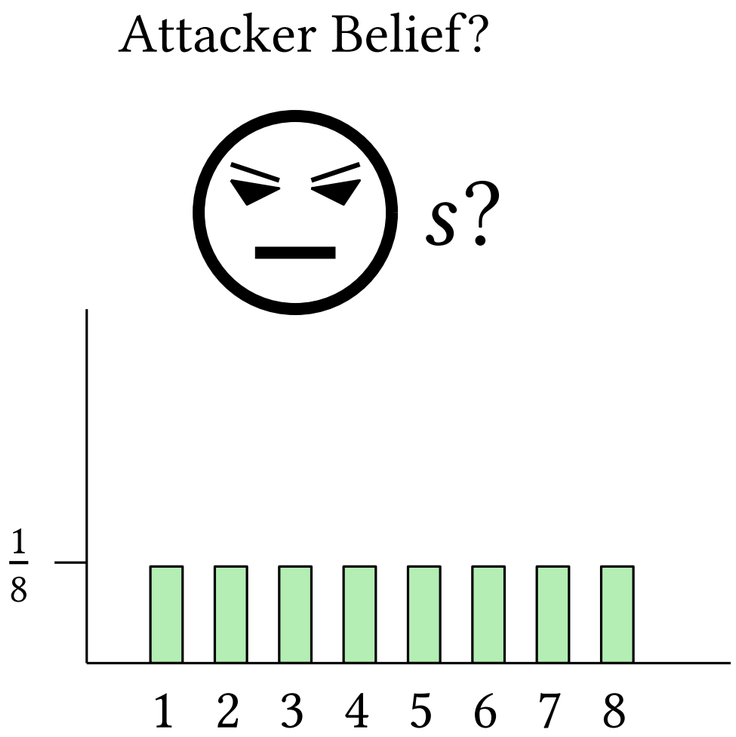
Challenges: Uncertainty Everywhere

Attacker Belief?



s?

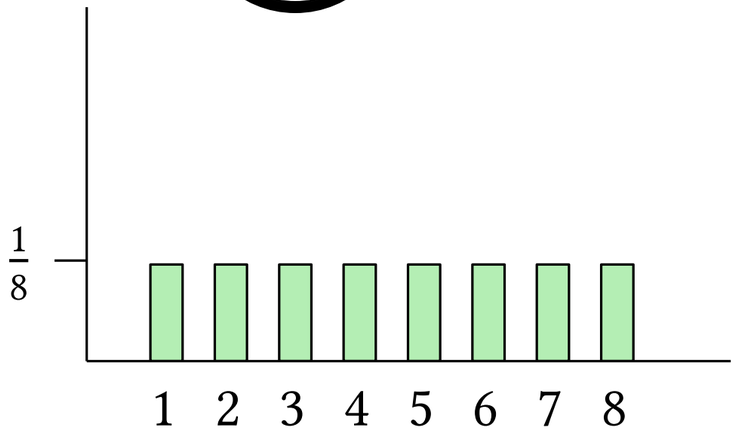
Challenges: Uncertainty Everywhere



Challenges: Uncertainty Everywhere

Attacker Belief?

$s?$

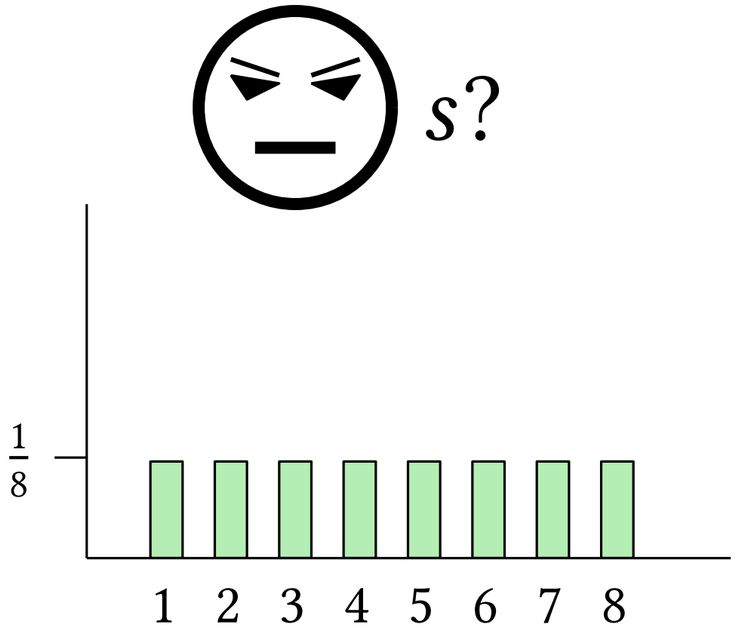


Input Choice?

i^*

Challenges: Uncertainty Everywhere

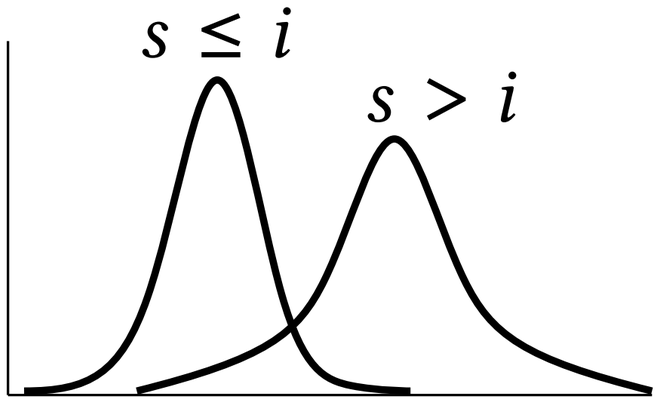
Attacker Belief?



Input Choice?

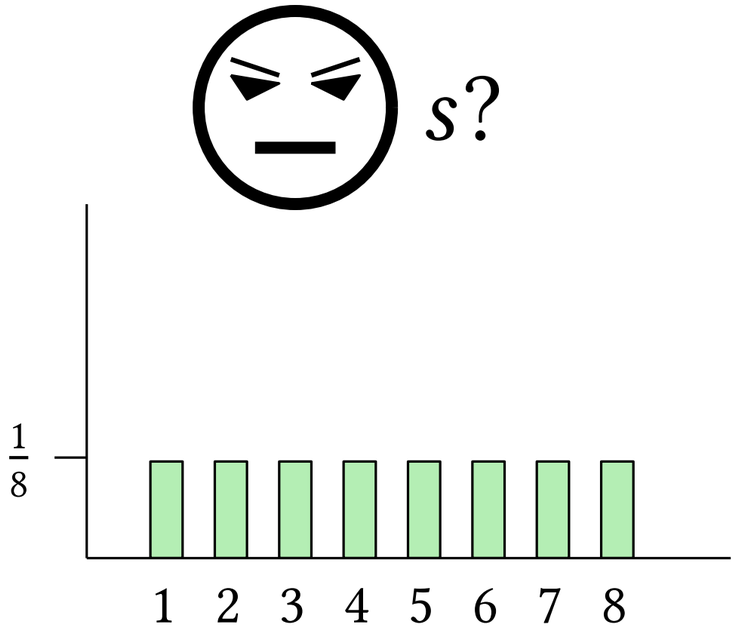
i^*

Observation noise?



Challenges: Uncertainty Everywhere

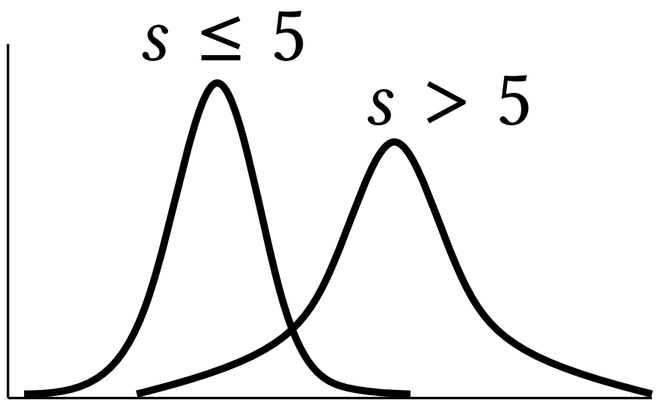
Attacker Belief?



Input Choice?

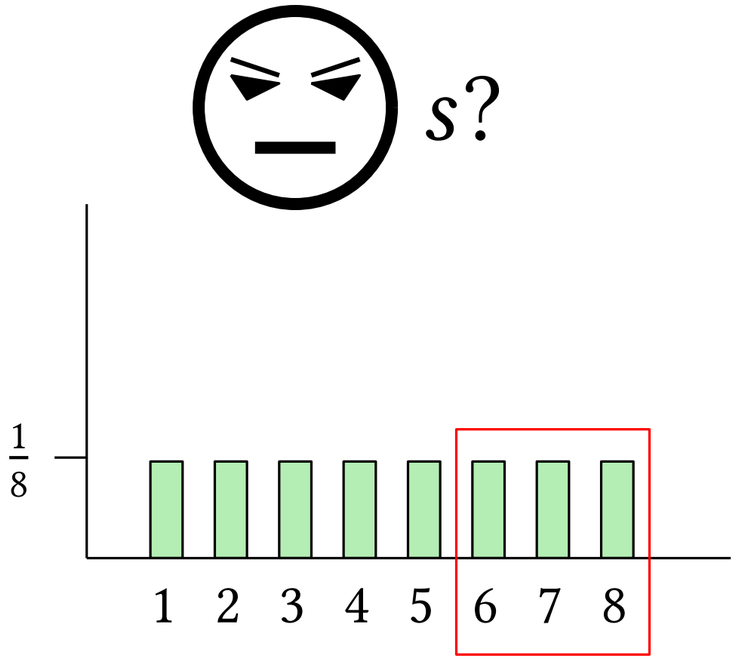
$$i^* = 5$$

Observation noise?



Challenges: Uncertainty Everywhere

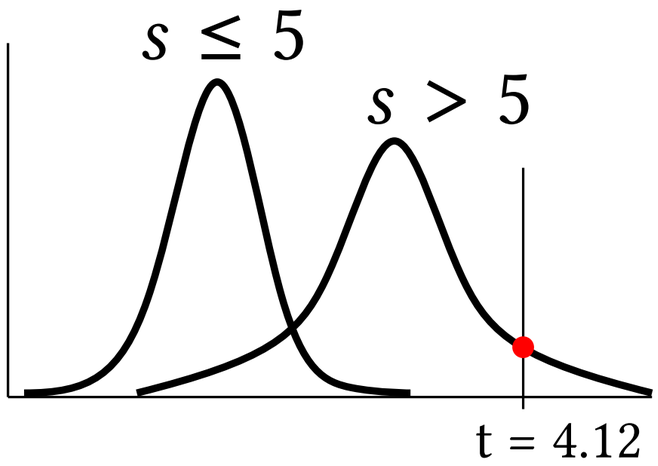
Attacker Belief?



Input Choice?

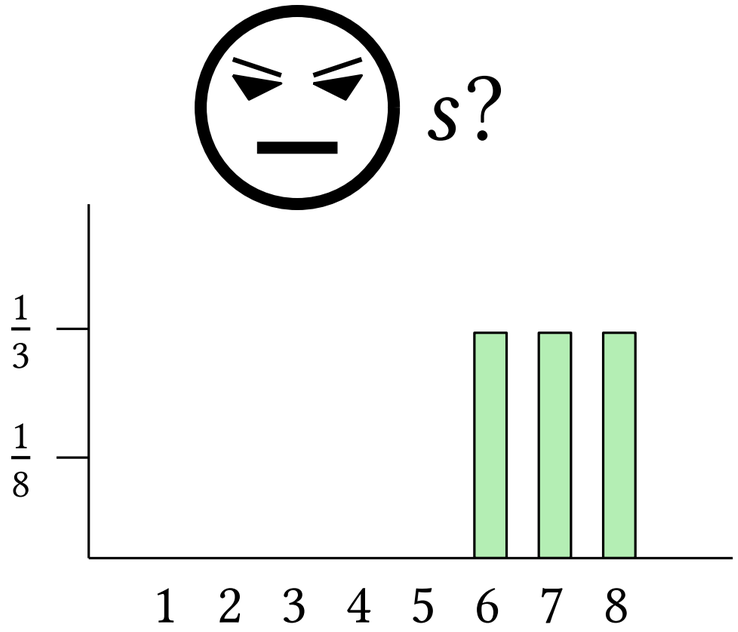
$$i^* = 5$$

Observation noise?



Challenges: Uncertainty Everywhere

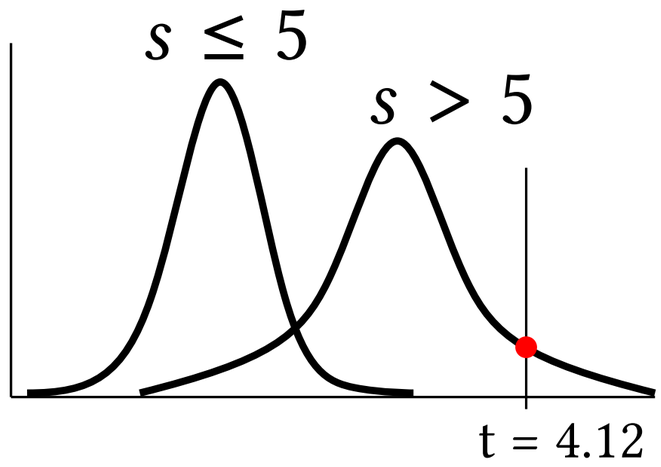
Attacker Belief?



Input Choice?

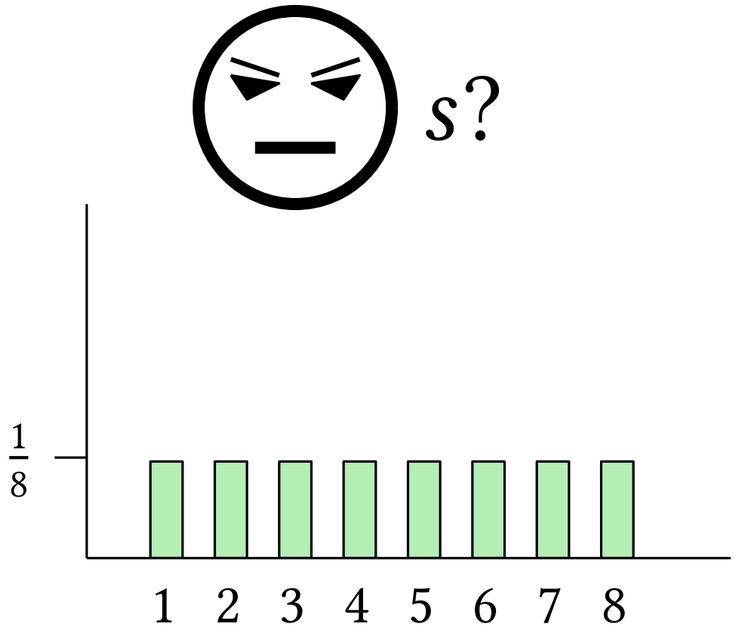
$$i^* = 5$$

Observation noise?



Challenges: Uncertainty Everywhere

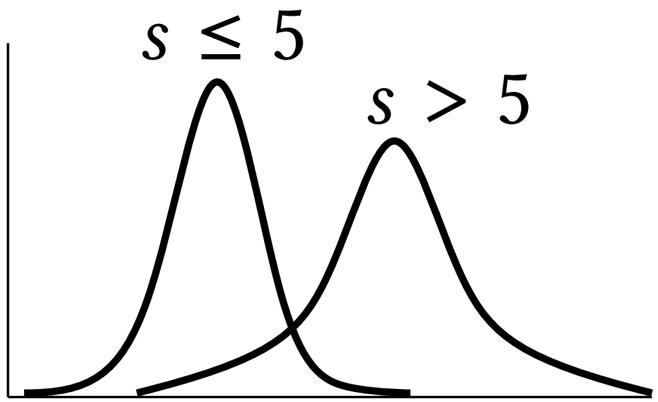
Attacker Belief?



Input Choice?

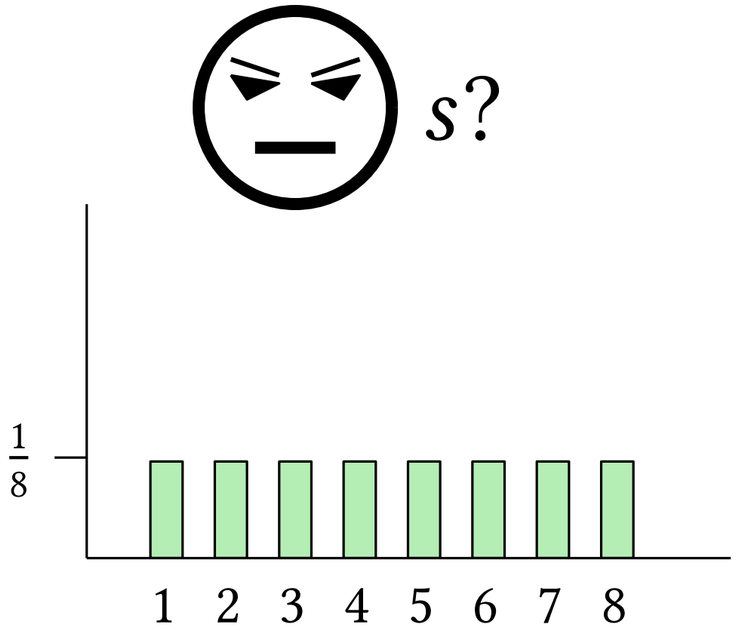
$$i^* = 5$$

Observation noise?



Challenges: Uncertainty Everywhere

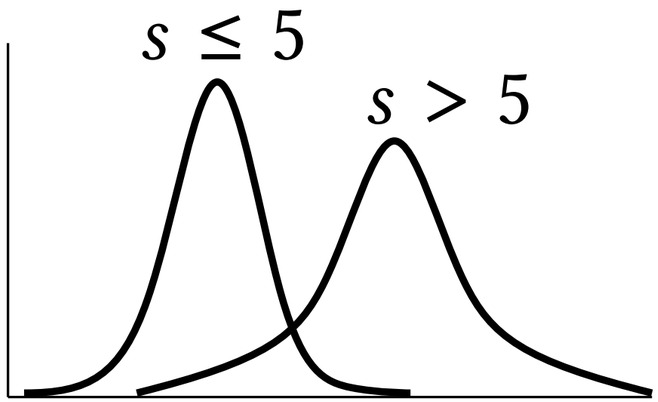
Attacker Belief?



Input Choice?

$$i^* = 5$$

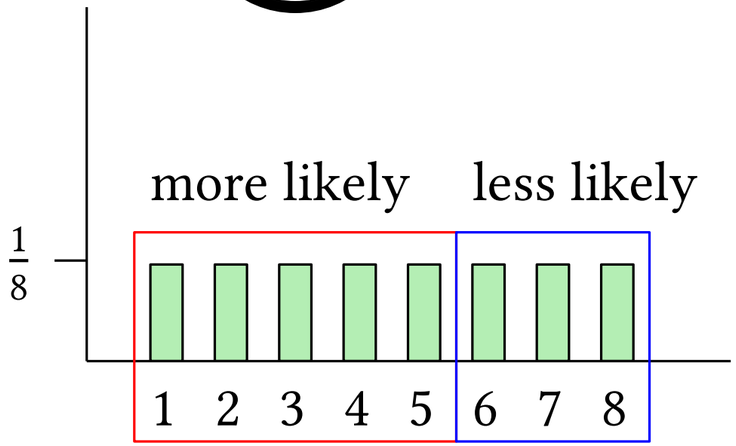
Observation noise?



Challenges: Uncertainty Everywhere

Attacker Belief?

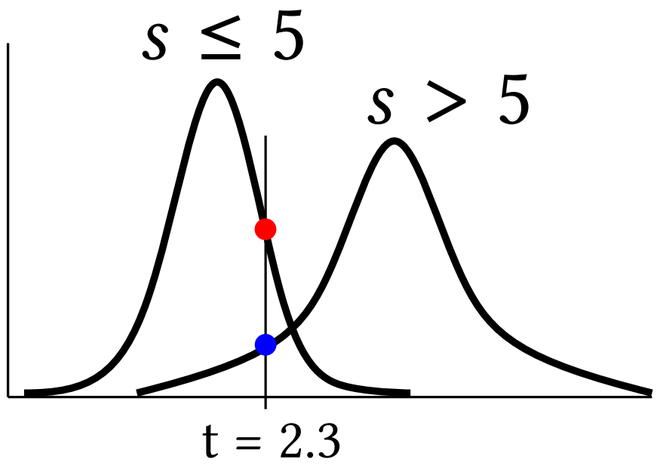
$s?$



Input Choice?

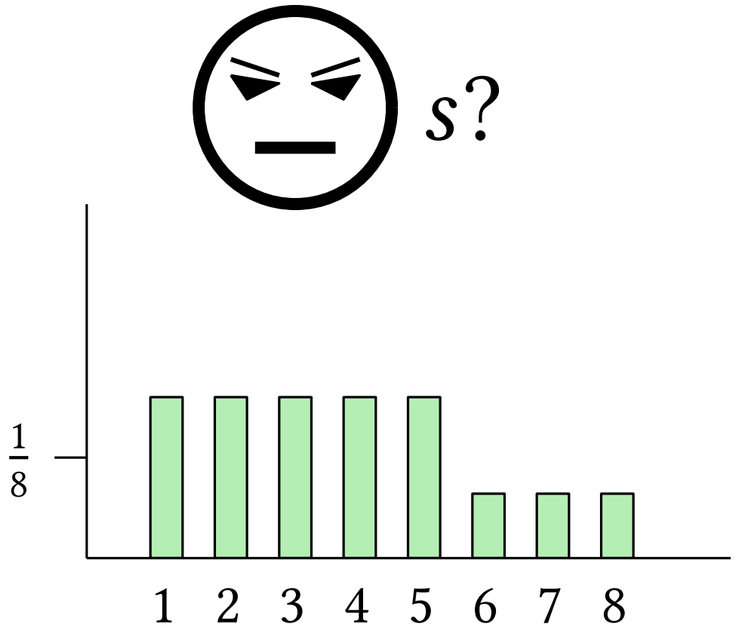
$$i^* = 5$$

Observation noise?



Challenges: Uncertainty Everywhere

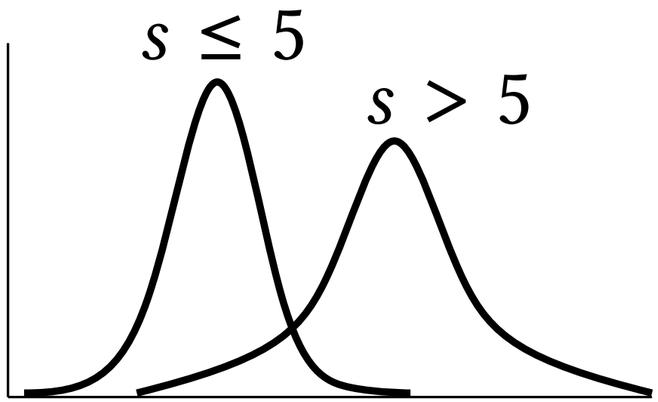
Attacker Belief?



Input Choice?

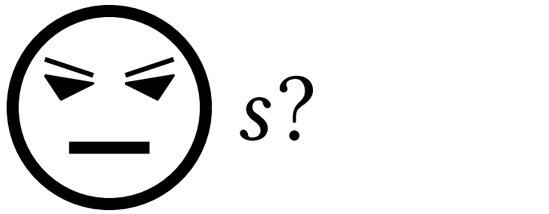
$$i^* = 5$$

Observation noise?

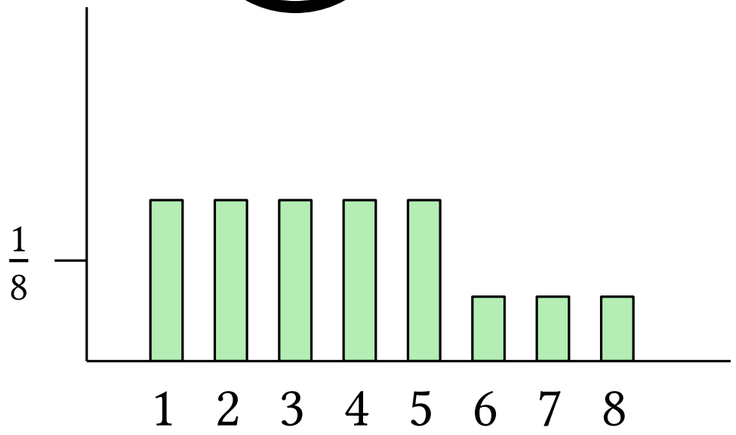


Challenges: Uncertainty Everywhere

Attacker Belief?



$s?$

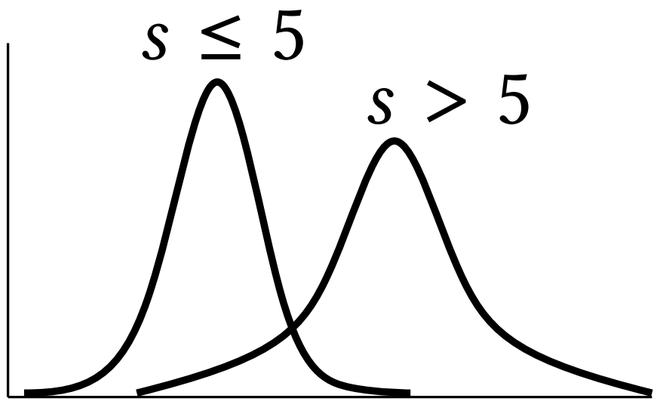


$p(s|o, i^*)$

Input Choice?

$i^* = 5$

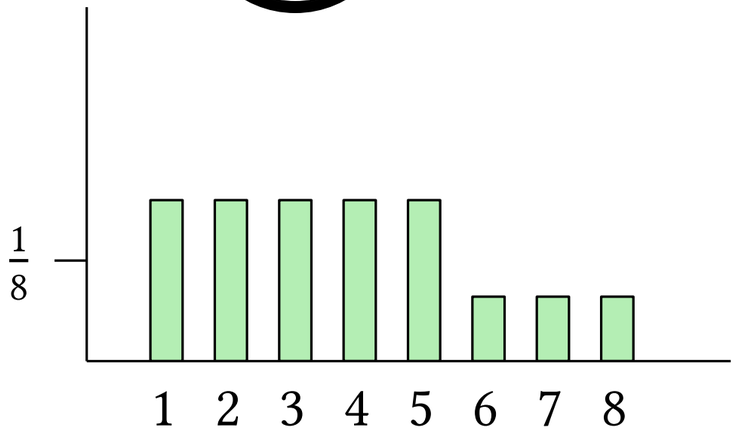
Observation noise?



Challenges: Uncertainty Everywhere

Attacker Belief?

$s?$



$p(s|o, i^*)$

Input Choice?

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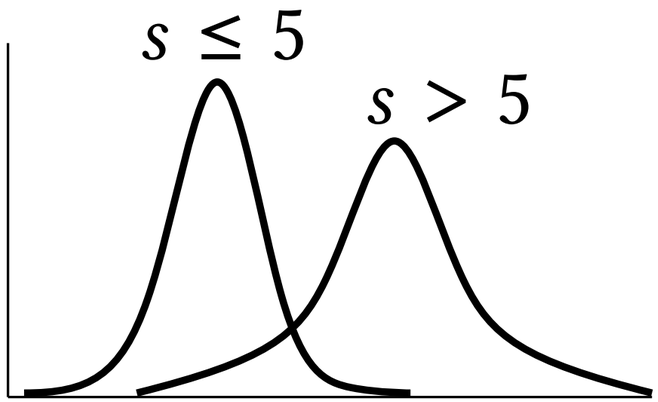
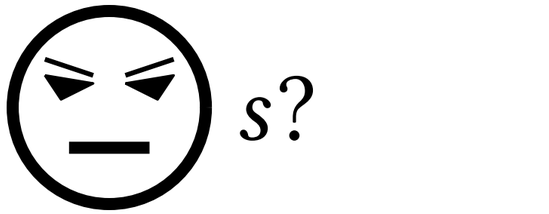
Observation noise?

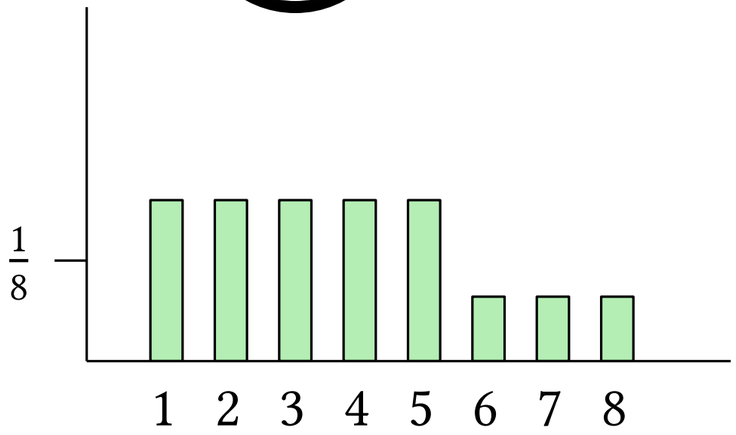


Challenges: Uncertainty Everywhere

Attacker Belief?



$s?$

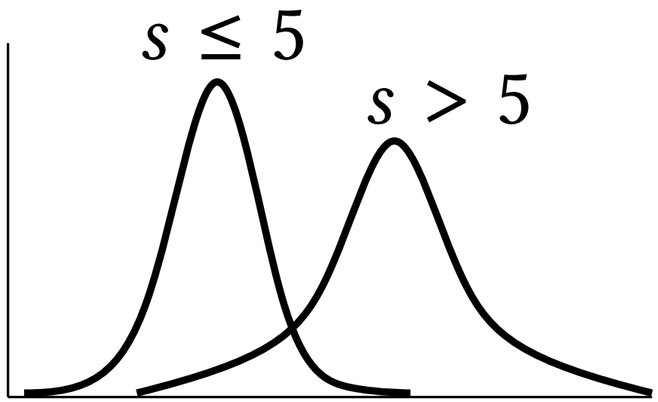


$p(s|o, i^*)$

Input Choice?

$i^* = 5$

Observation noise?

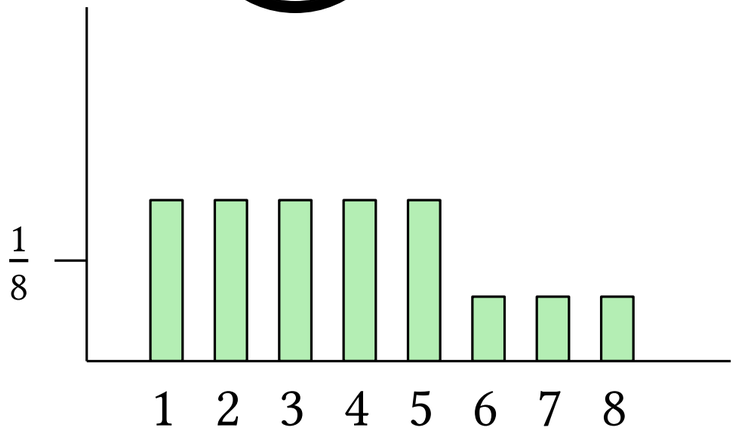


$p(o|s, i)$

Challenges: Uncertainty Everywhere

Attacker Belief?

$s?$

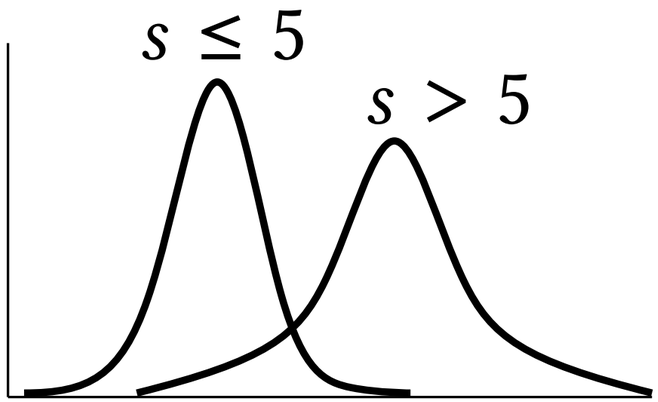


$p(s|o, i^*)$

Input Choice?

$i^* = 5$

Observation noise?

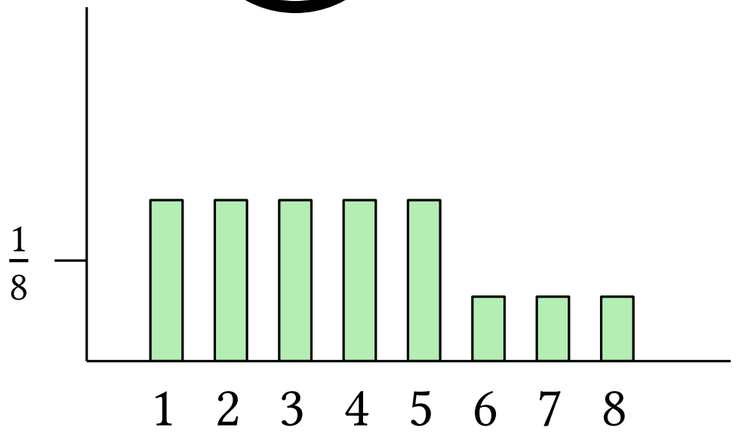


$p(o|s, i)$

Challenges: Uncertainty Everywhere

Attacker Belief?

$s?$



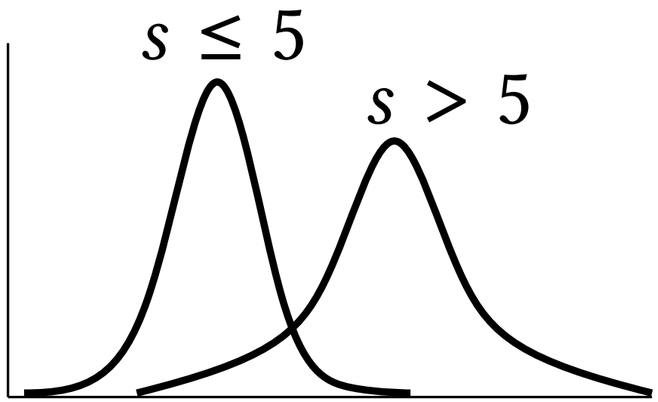
$p(s|o, i^*)$

Input Choice?

$i^* = 5$

$p(o|s, i)$

Observation noise?



$p(o|s, i)$

Challenges: Uncertainty Everywhere

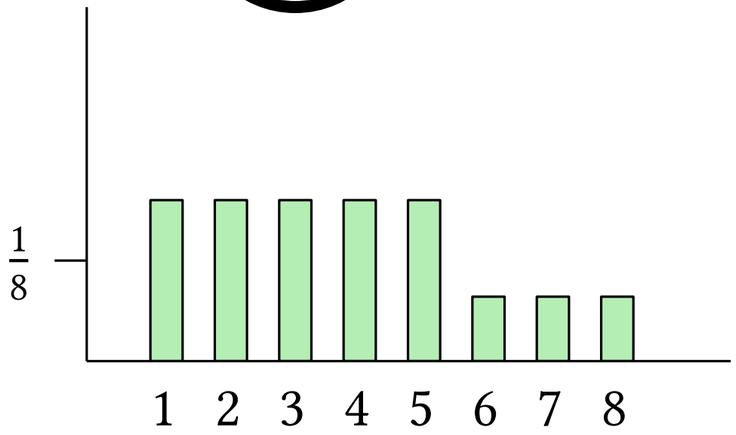
Attacker Belief?

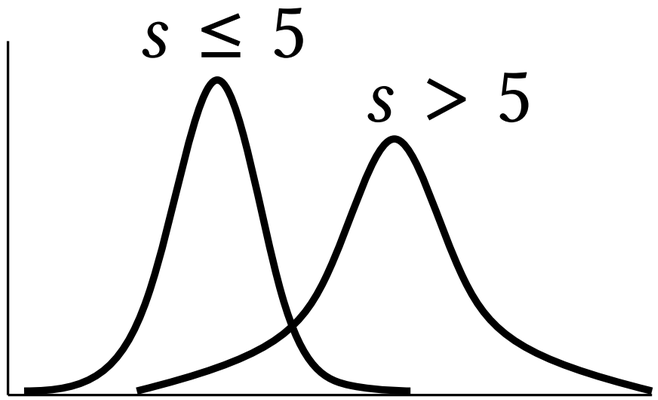
Input Choice?

Observation noise?

$s?$

$i^* = 5$





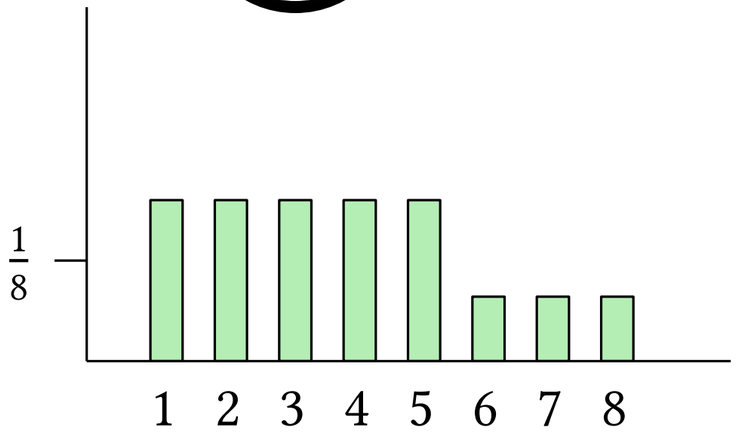
$p(o|s, i^*)$

$p(s|o, i^*)$ ← $p(o|s, i)$

Challenges: Uncertainty Everywhere

Attacker Belief?

$s?$



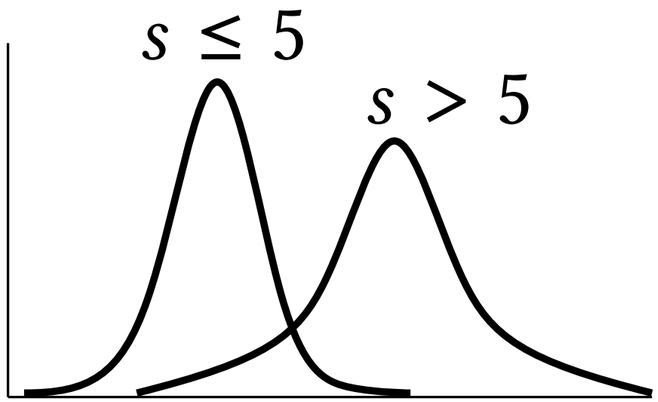
$p(s|o, i^*)$

Input Choice?

$i^* = 5$

$p(o|s, i^*)$

Observation noise?

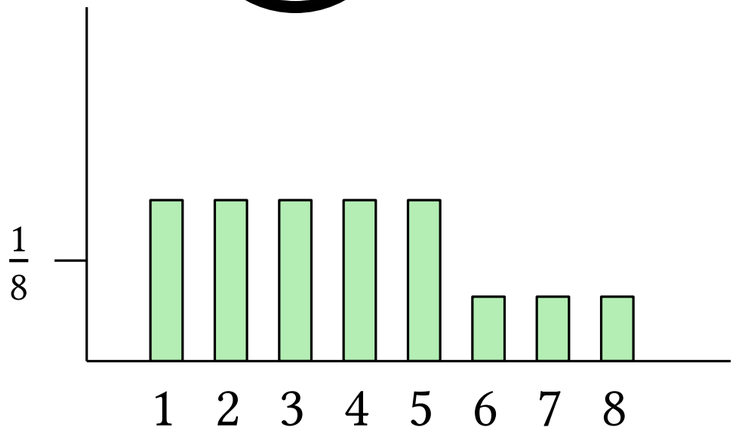


$p(o|s, i)$

Challenges: Uncertainty Everywhere

Attacker Belief?

$s?$



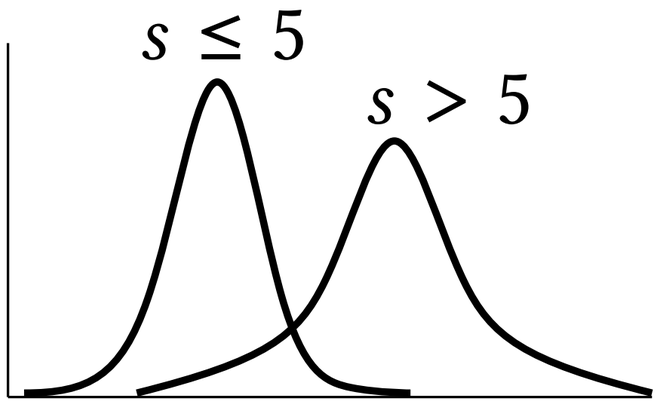
$p(s|o, i^*)$

Input Choice?

$i^* = 5$

$p(s|o, i^*)$

Observation noise?

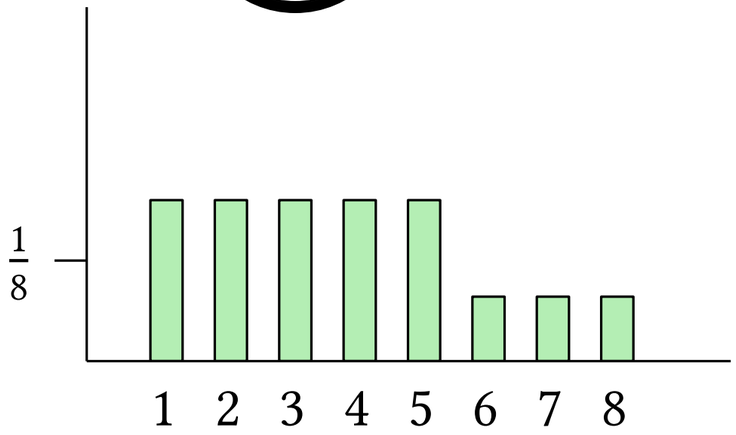


$p(o|s, i)$

Challenges: Uncertainty Everywhere

Attacker Belief?

$s?$

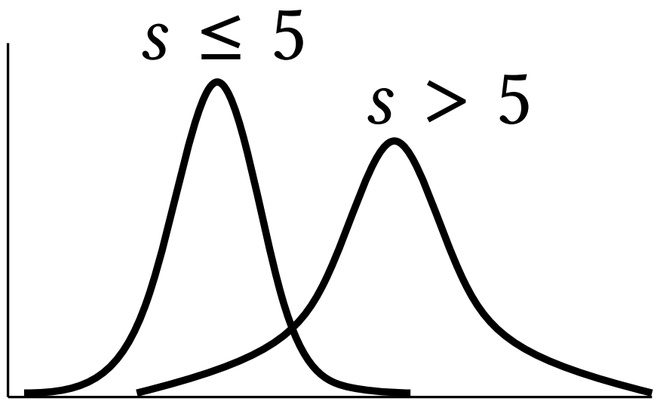


$p(s|o, i^*)$

Input Choice?

$i^* = 5$

Observation noise?



$p(o|s, i)$

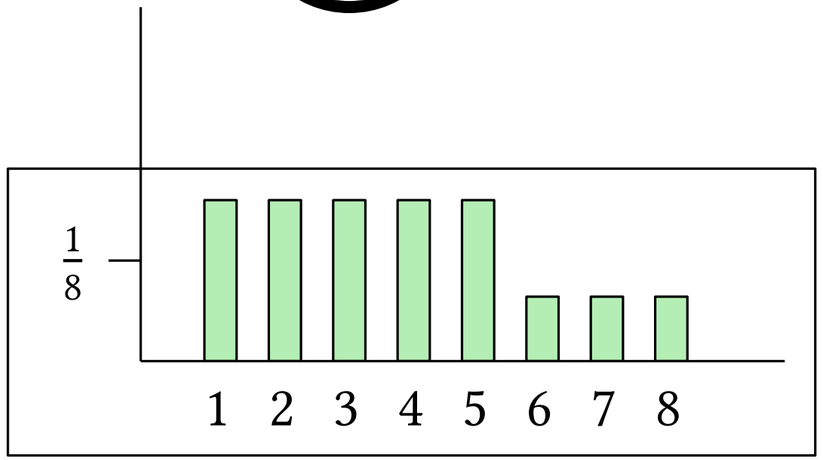
$p(s|o, i^*)$

Bayes Rule

Challenges: Uncertainty Everywhere

Attacker Belief?

$s?$

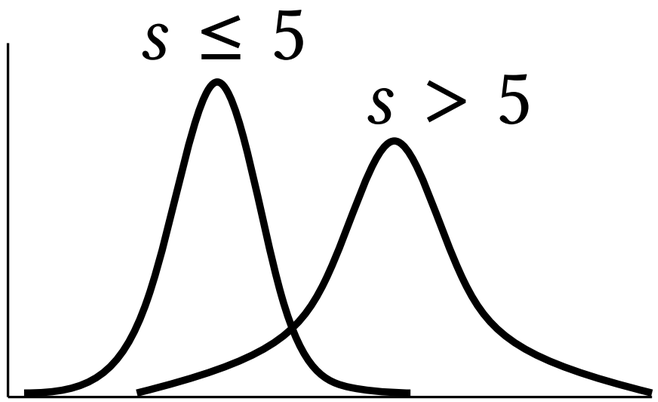


$p(s|o, i^*)$

Input Choice?

$i^* = 5$

Observation noise?



$p(o|s, i)$

$p(s|o, i^*)$

Bayes Rule

Challenges: Uncertainty Everywhere

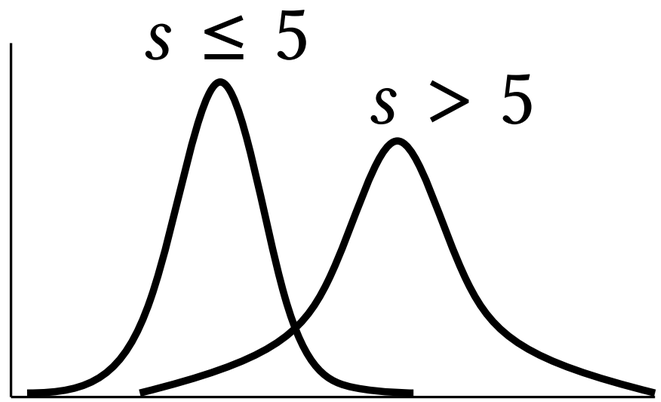
Attacker Belief?

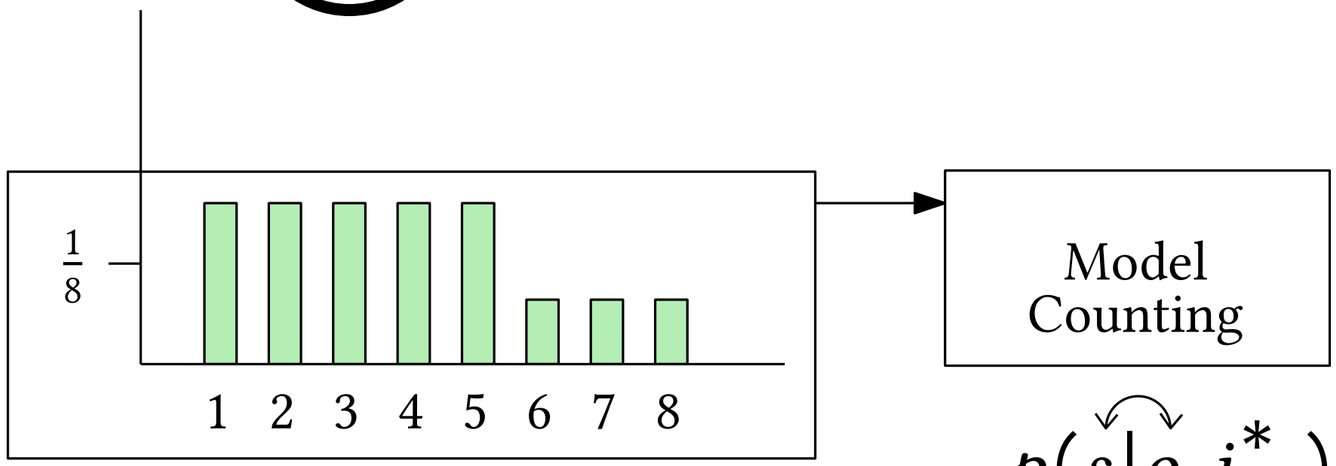
Input Choice?

Observation noise?

$s?$

$i^* = 5$





Model Counting

$p(s|o, i^*)$

$p(s|o, i^*)$

Bayes Rule

$p(o|s, i)$

Challenges: Uncertainty Everywhere

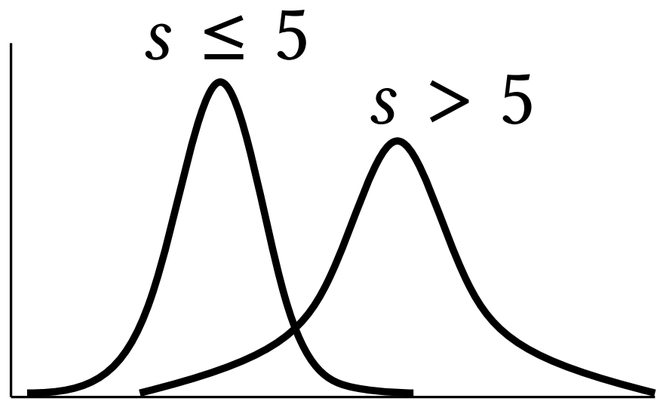
Attacker Belief?

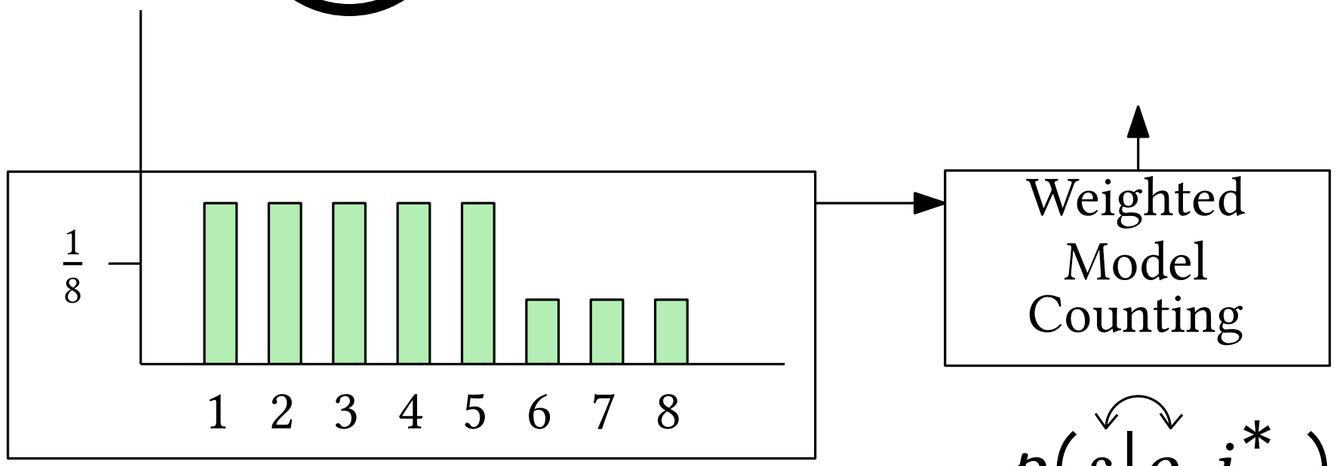
Input Choice?

Observation noise?

$s?$

$i^* = 5$





Weighted Model Counting

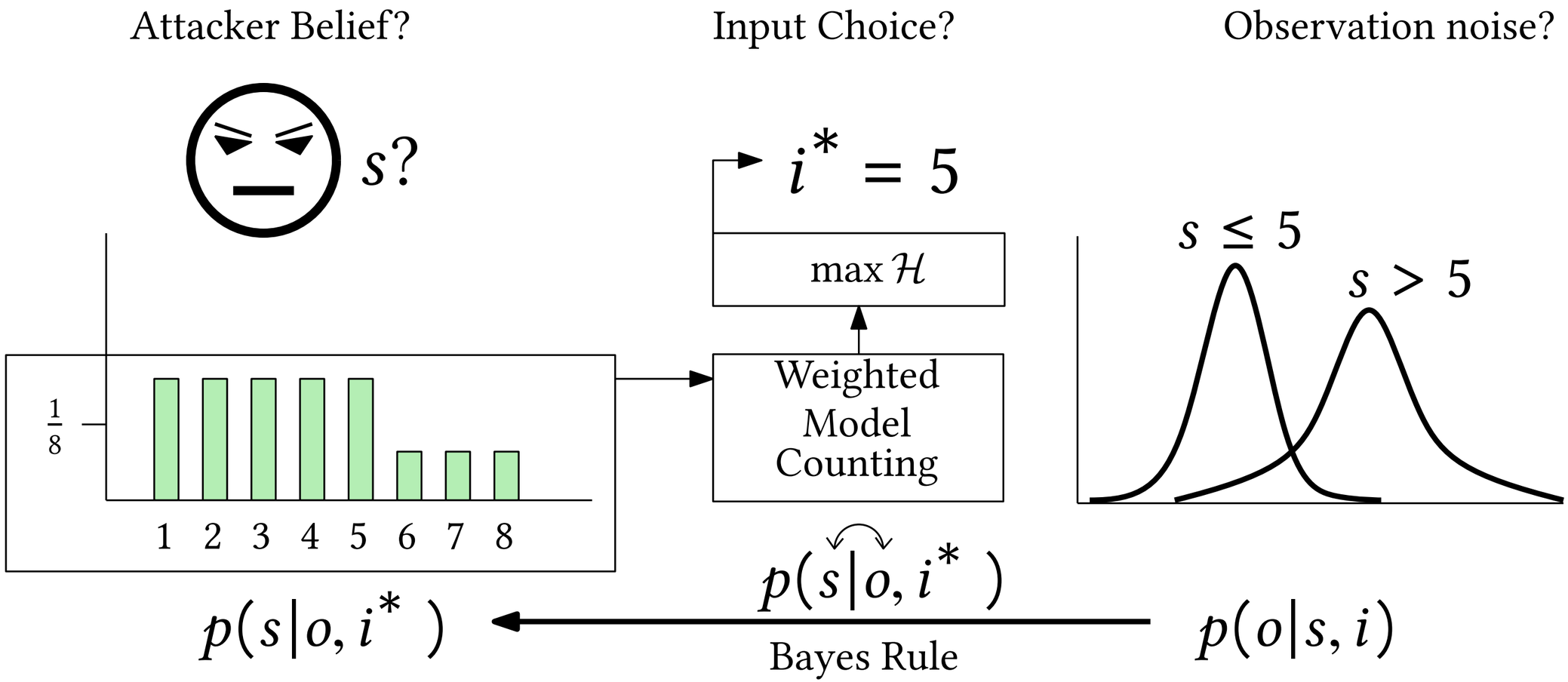
$p(s|o, i^*)$

$p(s|o, i^*)$

$p(o|s, i)$

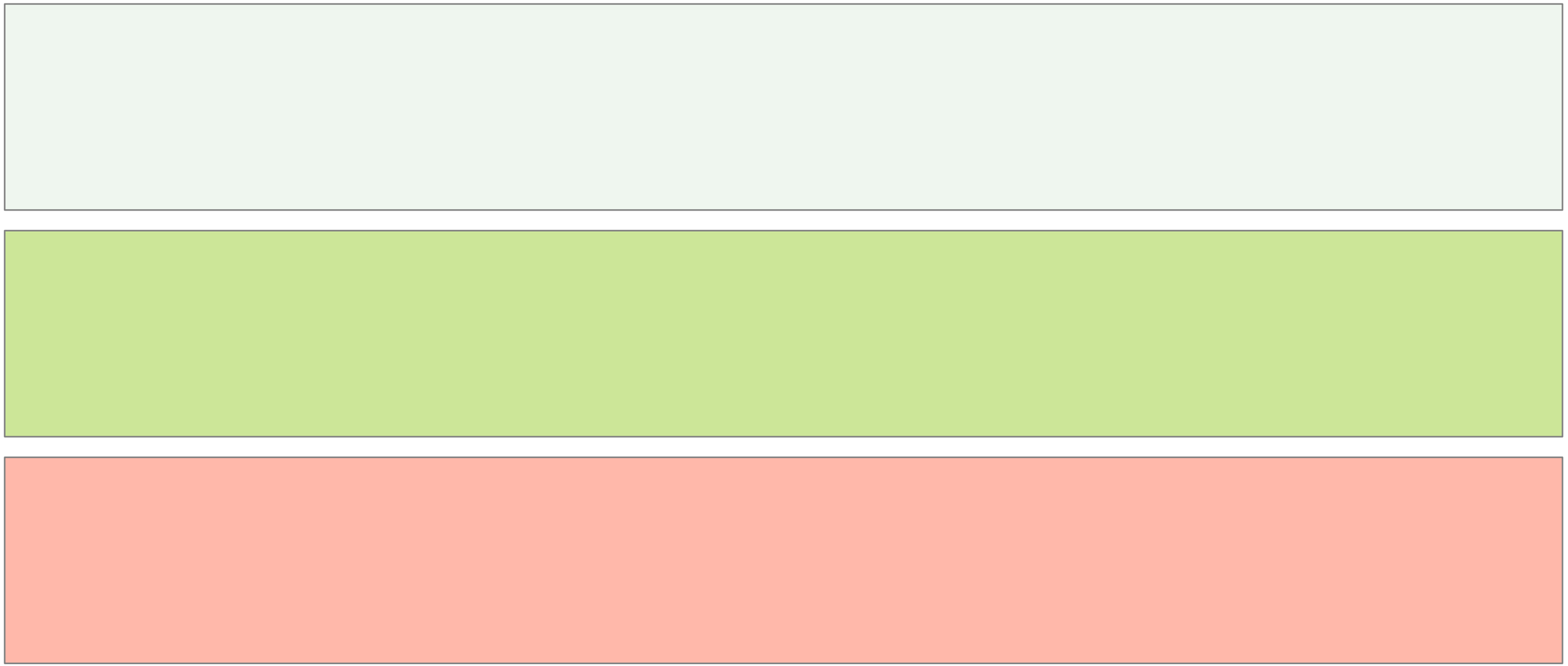
Bayes Rule

Challenges: Uncertainty Everywhere



Proposed Approach

Proposed Approach



Proposed Approach

1. Offline Static Analysis

Proposed Approach

1. Offline Static Analysis

2. Offline Dynamic Analysis

Proposed Approach

1. Offline Static Analysis

2. Offline Dynamic Analysis

3. Online Attack Synthesis

Proposed Approach

1. Offline Static Analysis

2. Offline Dynamic Analysis

3. Online Attack Synthesis

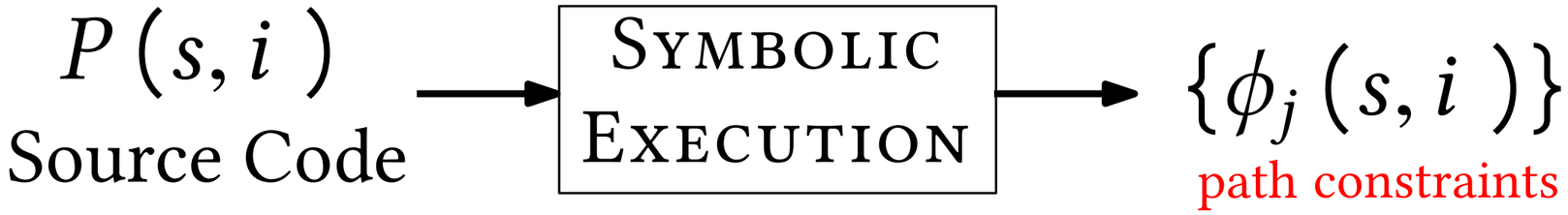
Proposed Approach

Proposed Approach

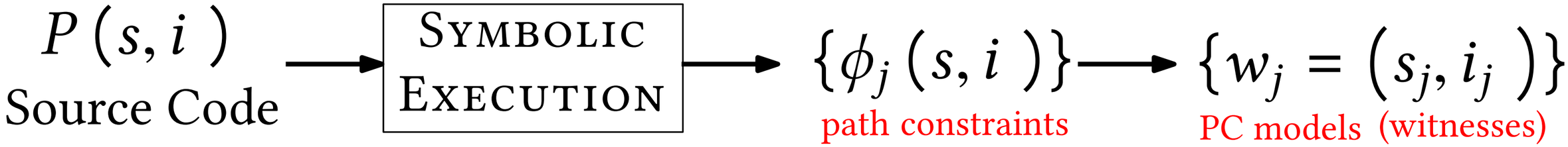
$$P(s, i)$$

Source Code

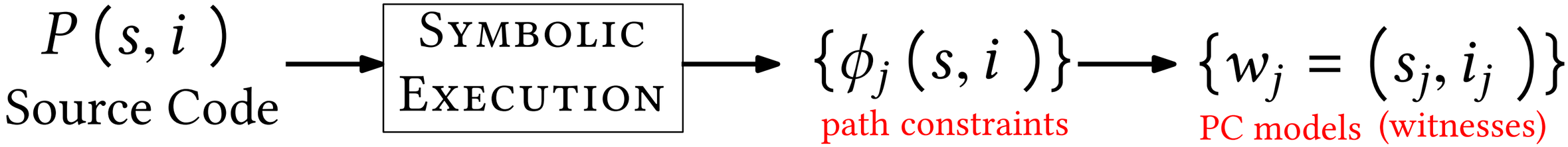
Proposed Approach



Proposed Approach

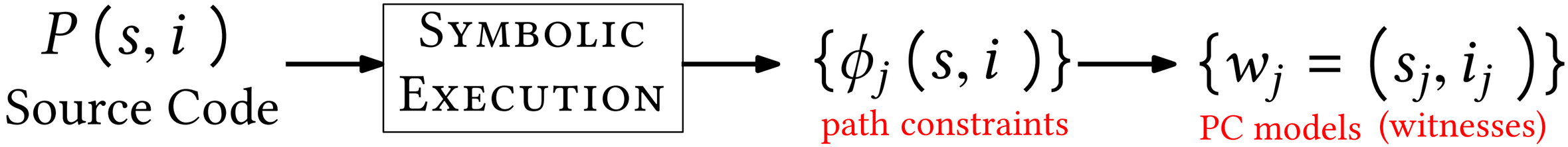


Proposed Approach



Idea: each PC characterizes an observable program behavior

Proposed Approach



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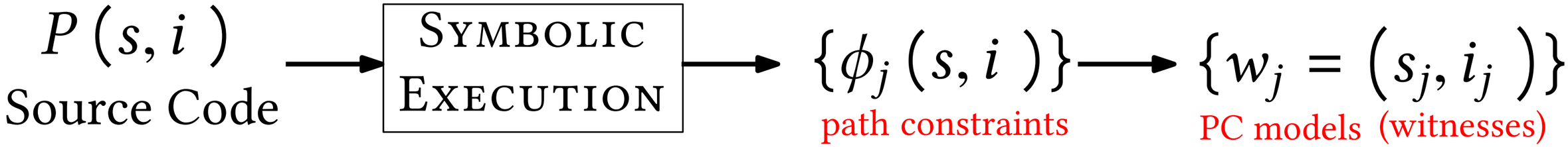
$$(s_j, i_j) \models \phi_j \qquad (s'_j, i'_j) \models \phi_j$$

Proposed Approach



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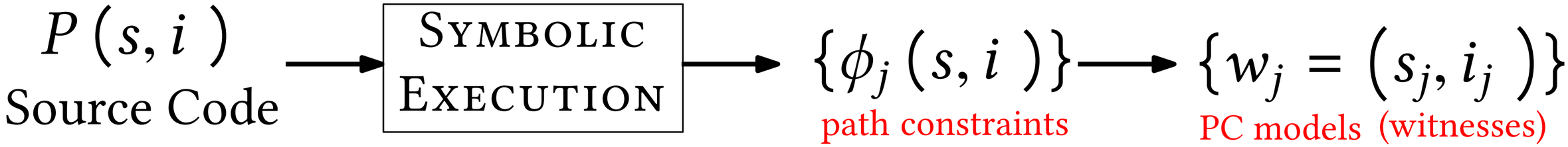
$$P(s_j, i_j) \qquad P(s'_j, i'_j)$$

Proposed Approach



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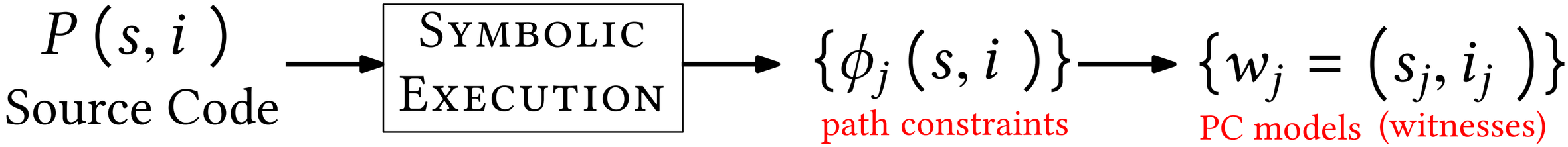
$$P(s_j, i_j) \quad ? \; 😒 \; ? \quad P(s'_j, i'_j)$$

Proposed Approach



Idea: each PC characterizes an observable program behavior

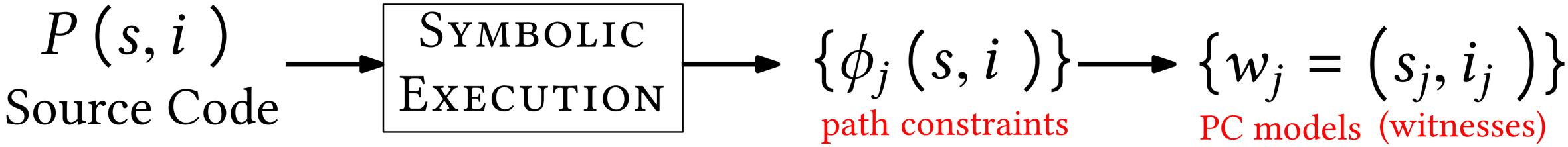
$$(s_j, i_j) \models \phi_j \qquad (s'_j, i'_j) \models \phi_j$$

$$P(s_j, i_j) \quad ? \; 😒 \; ? \quad P(s'_j, i'_j)$$

$\phi_j(s, i)$ characterizes observationally indistinguishable behaviors

$P(s_j, i_j)$ is a representative of all behaviors in that class

Proposed Approach



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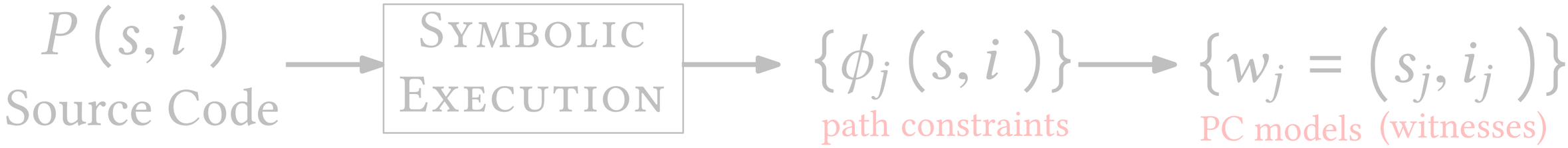
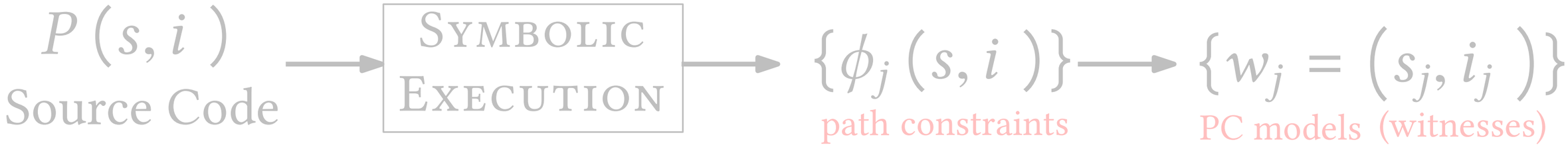


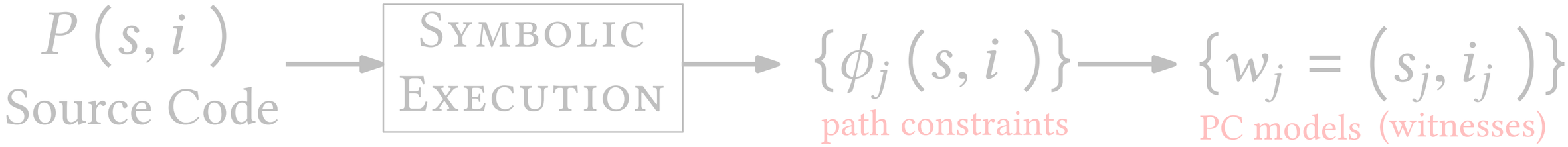
Proposed Approach



2. Offline Dynamic Analysis

3. Online Attack Synthesis

Proposed Approach



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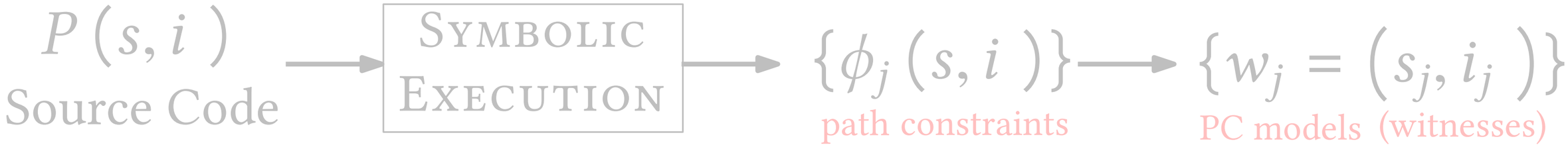
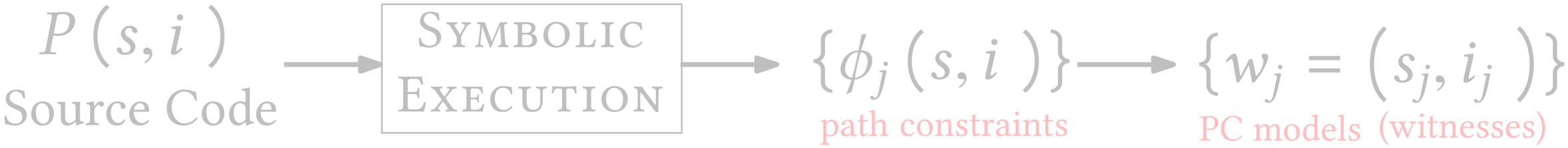
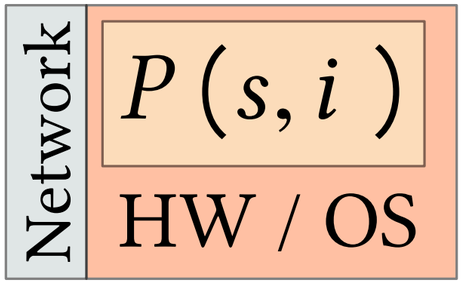


Proposed Approach





Proposed Approach

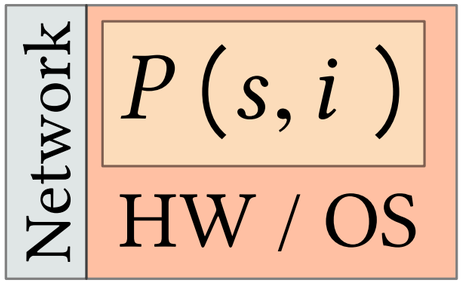
$P(s, i)$
Source Code

→ SYMBOLIC EXECUTION →

$\{\phi_j(s, i)\}$
path constraints

→ $\{w_j = (s_j, i_j)\}$
PC models (witnesses)

$$\{w_j = (s_i, i_j)\}$$



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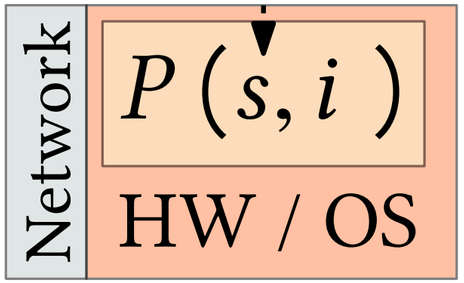

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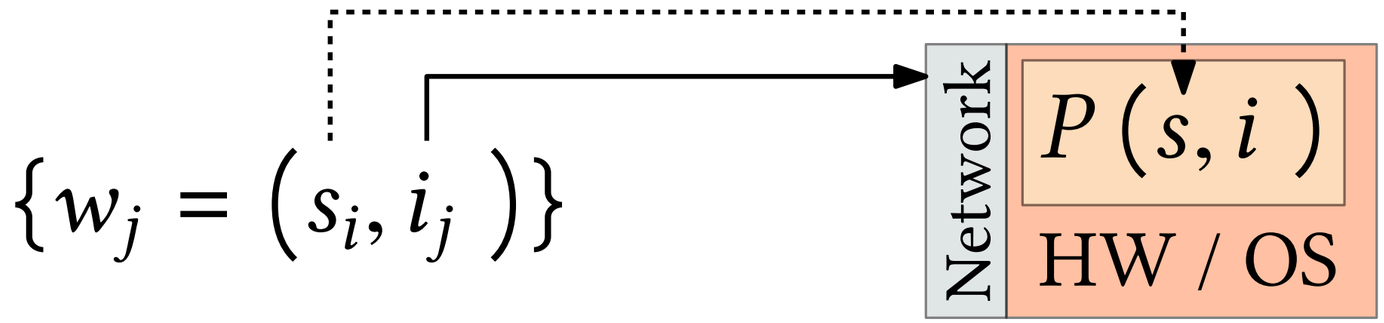

Proposed Approach

$P(s, i)$
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path constraints

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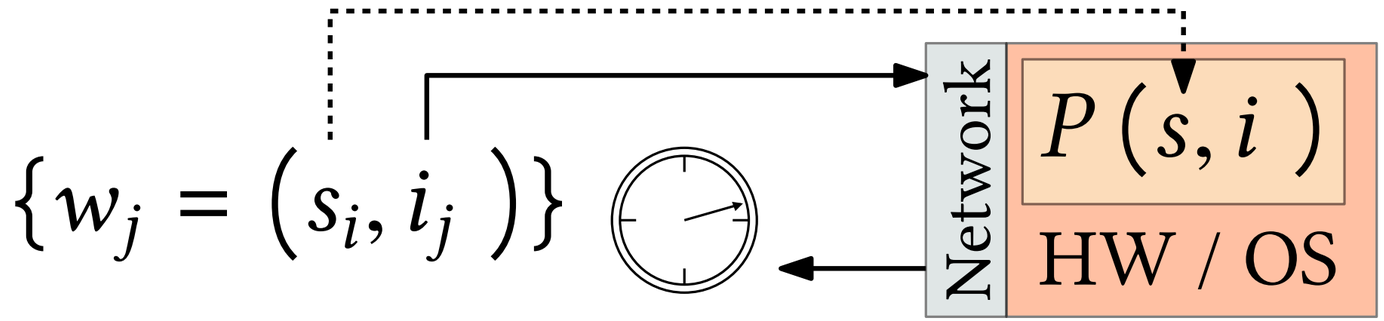
PC models (witnesses)



Proposed Approach

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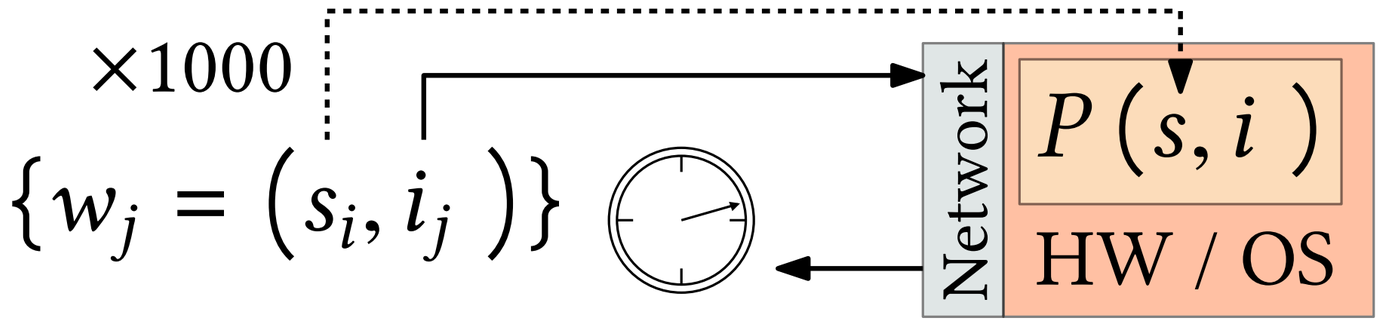

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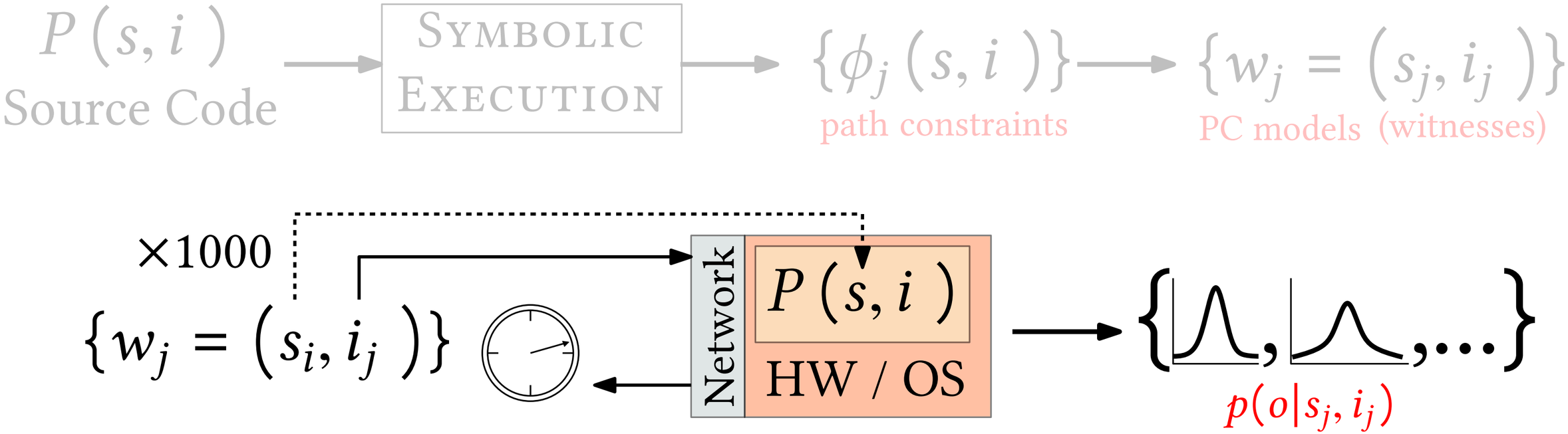

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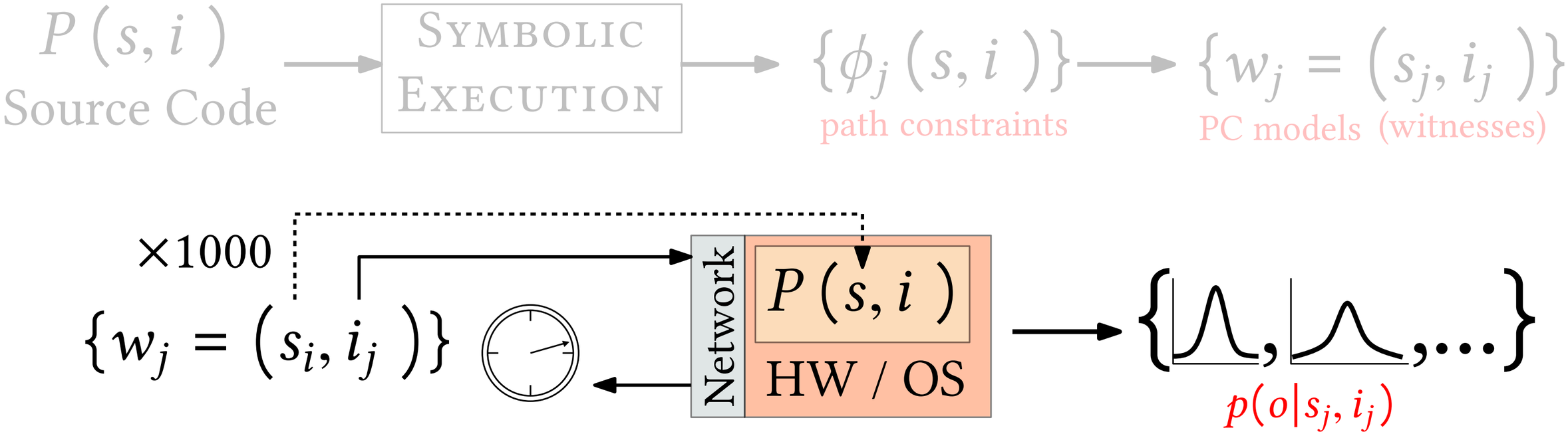
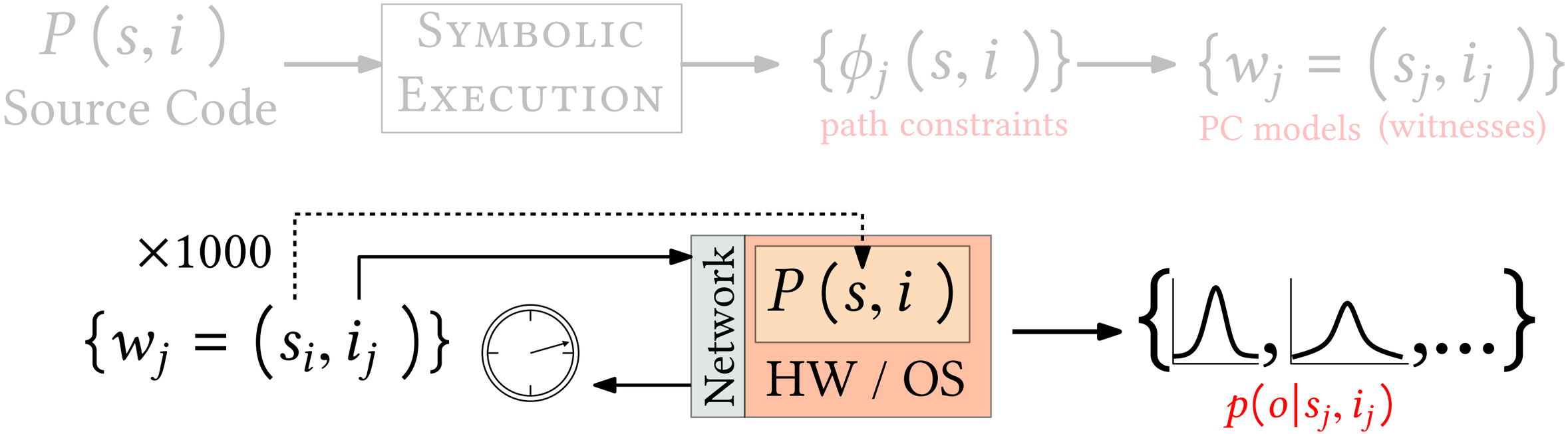


Idea: characterize effect of noise on each class of program behaviors using the witness for that behavior.

Proposed Approach



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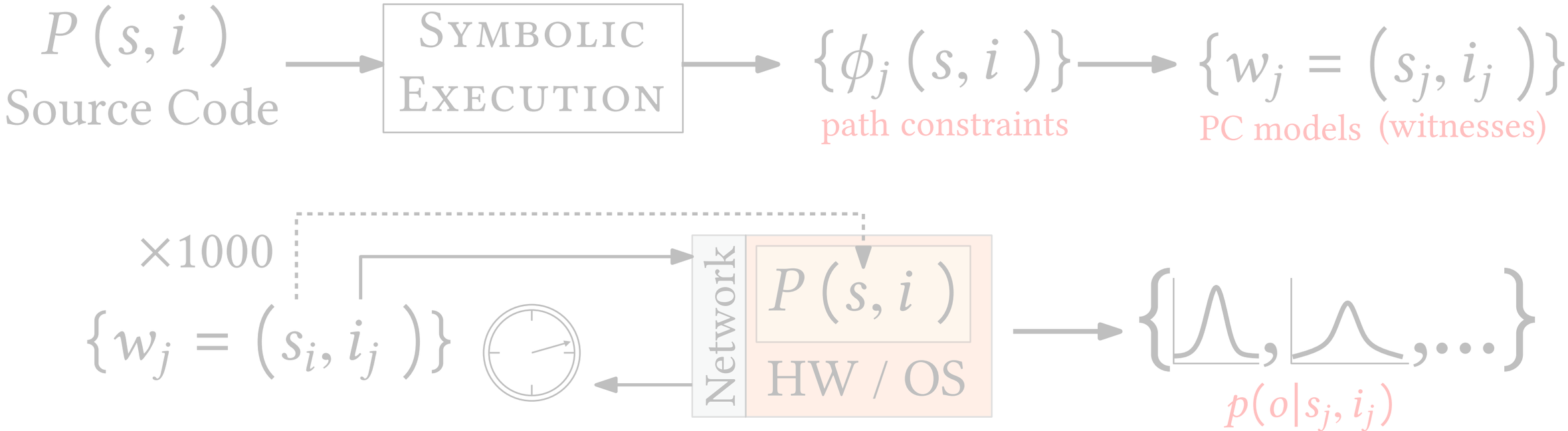
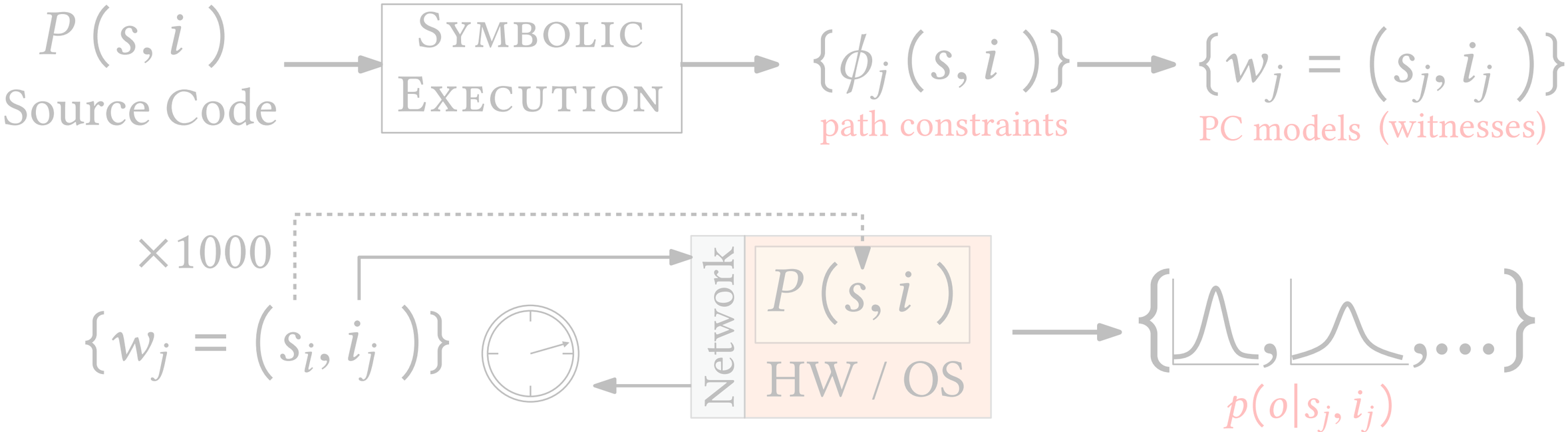
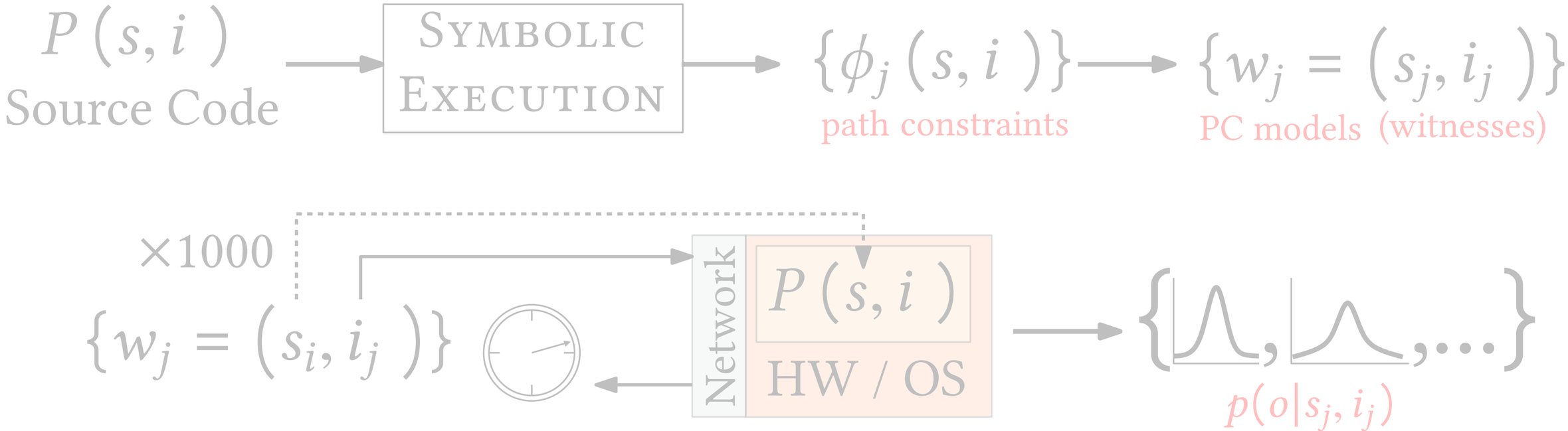


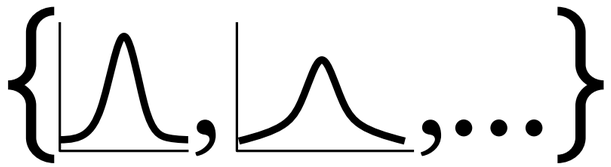
Proposed Approach



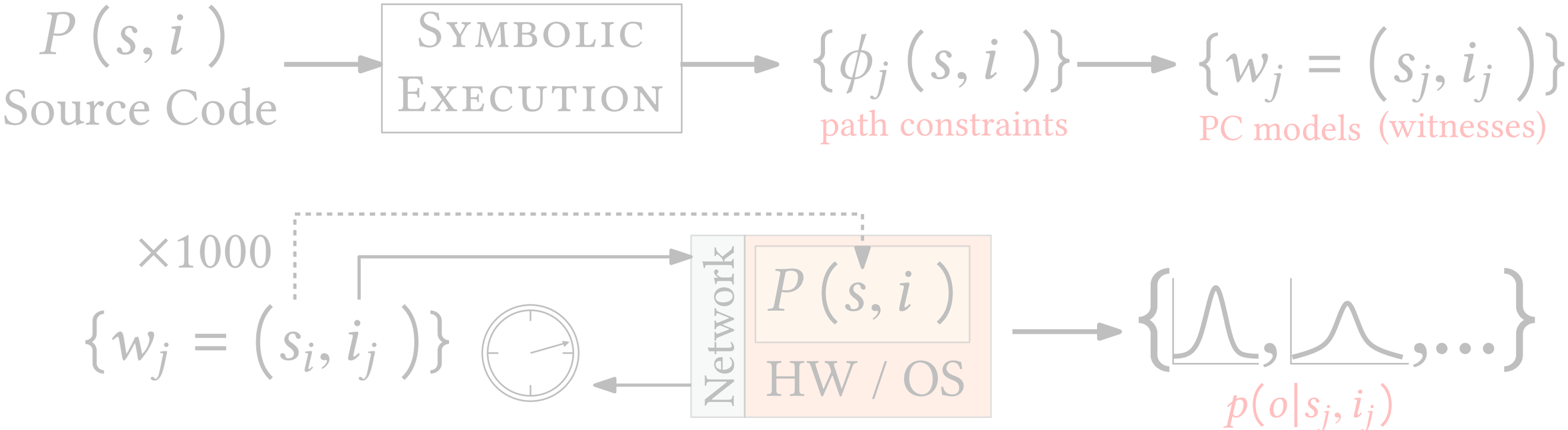
3. Online Attack Synthesis

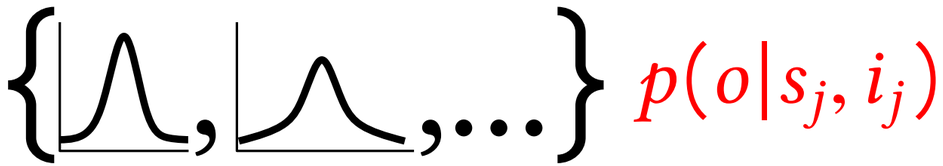
Proposed Approach





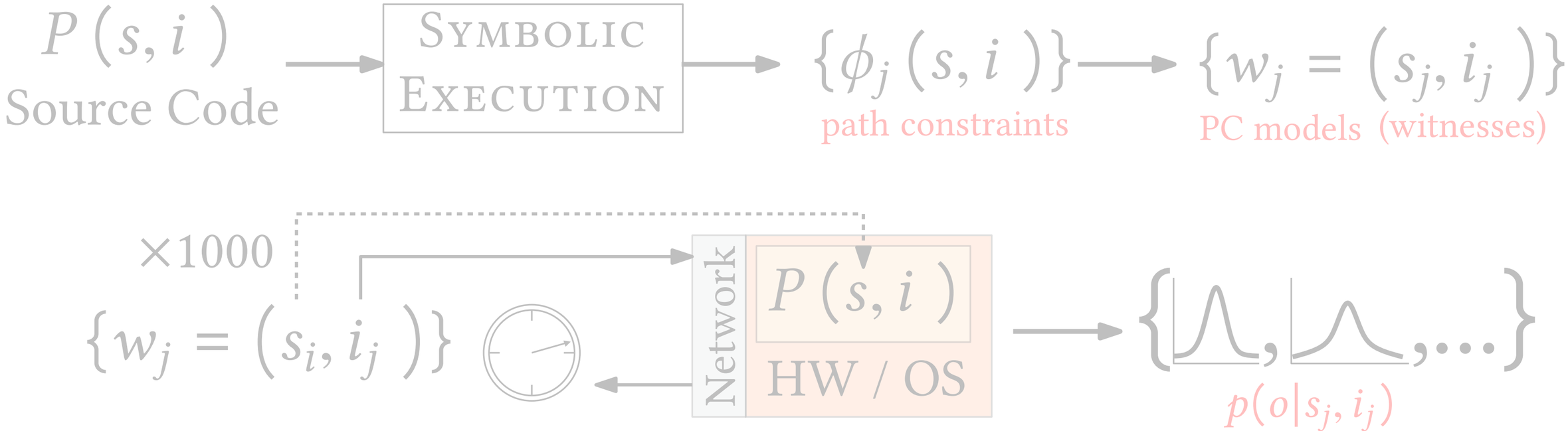
Proposed Approach

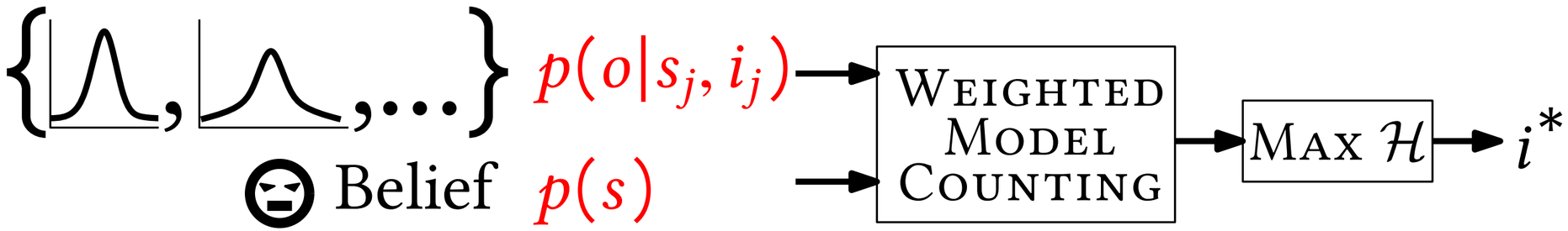




Belief $p(s)$

Proposed Approach





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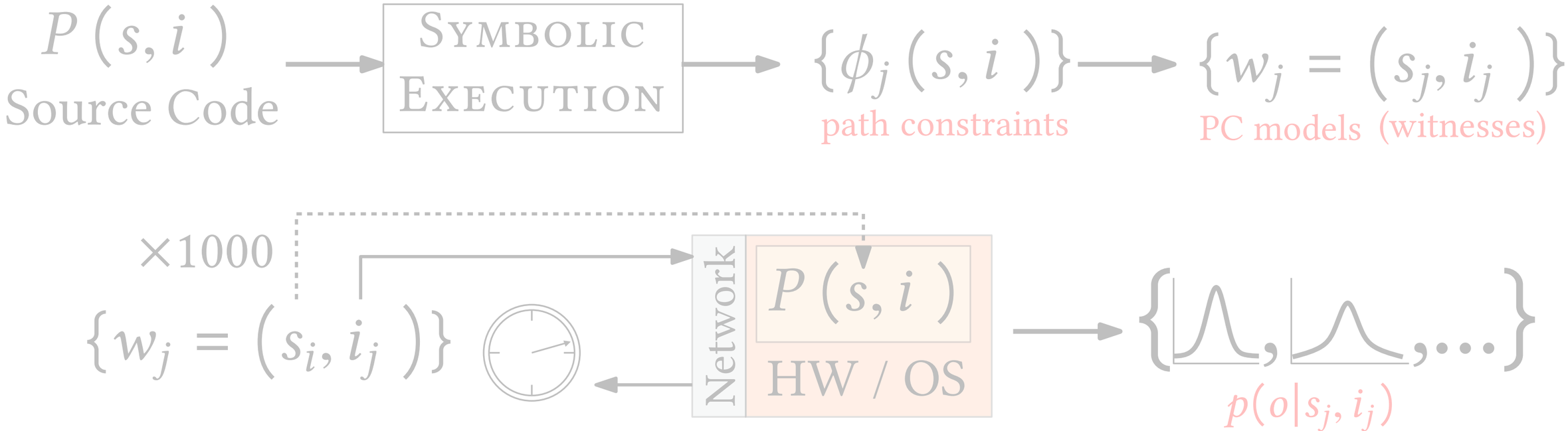

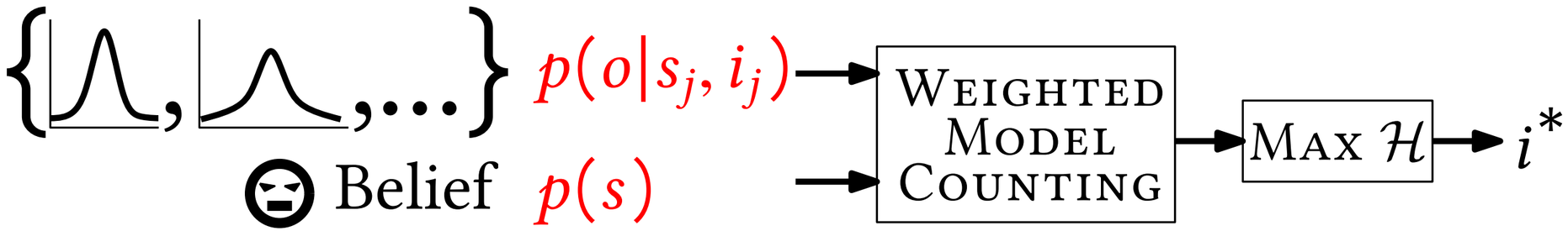

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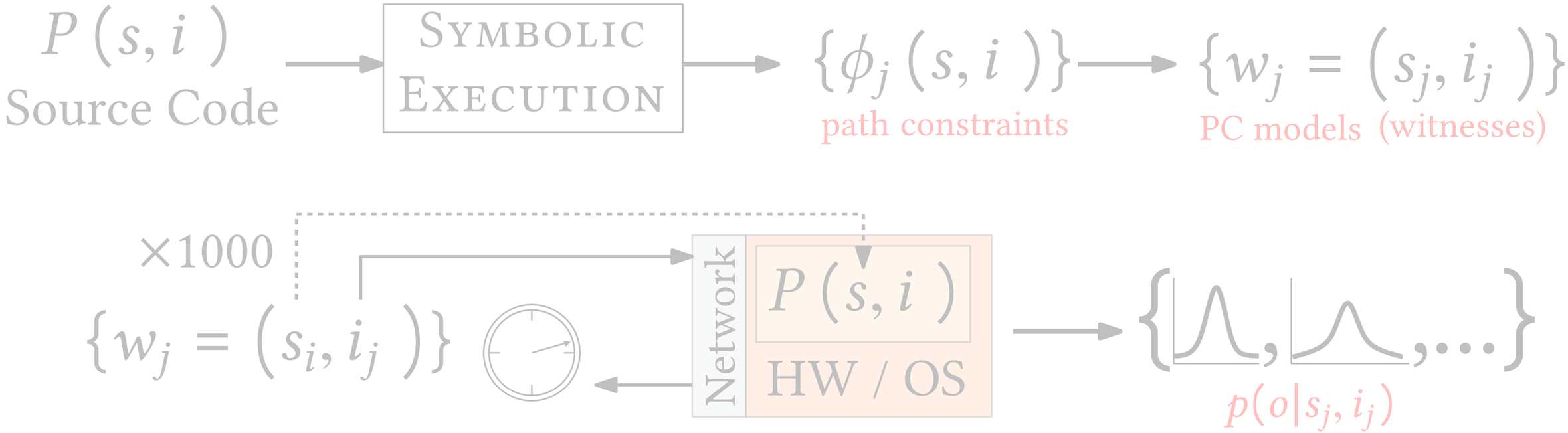

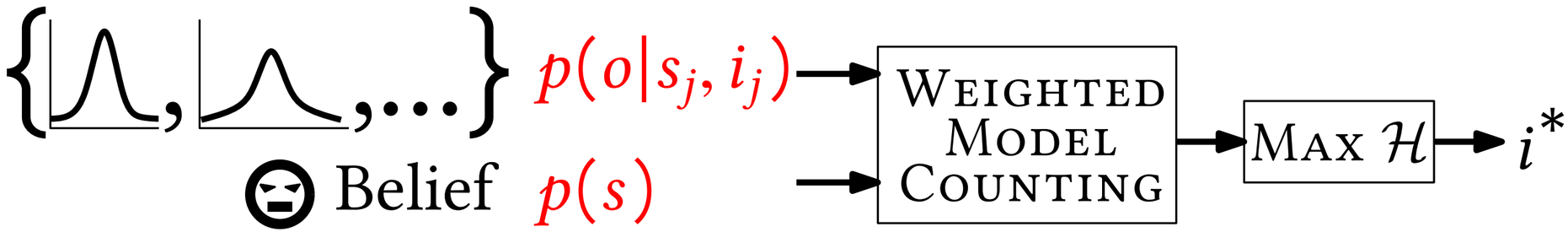

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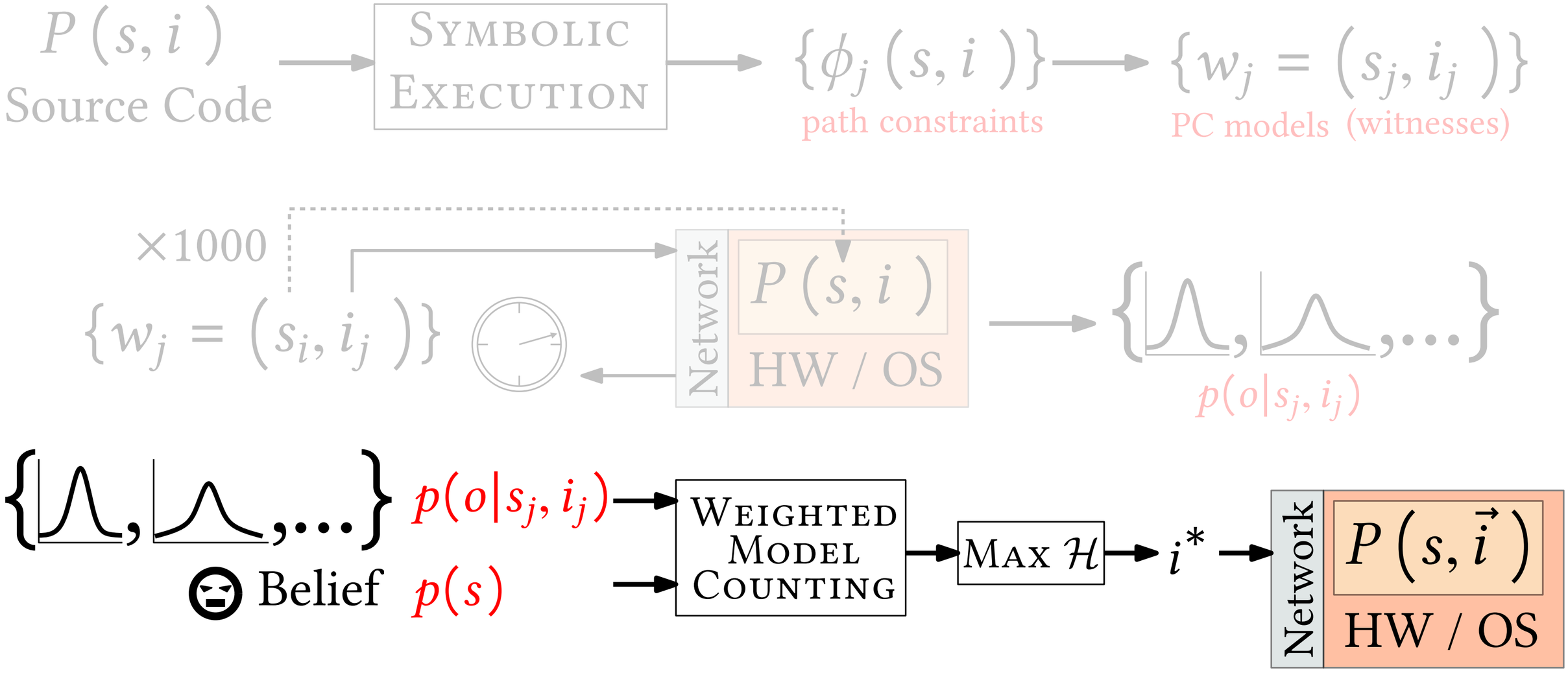

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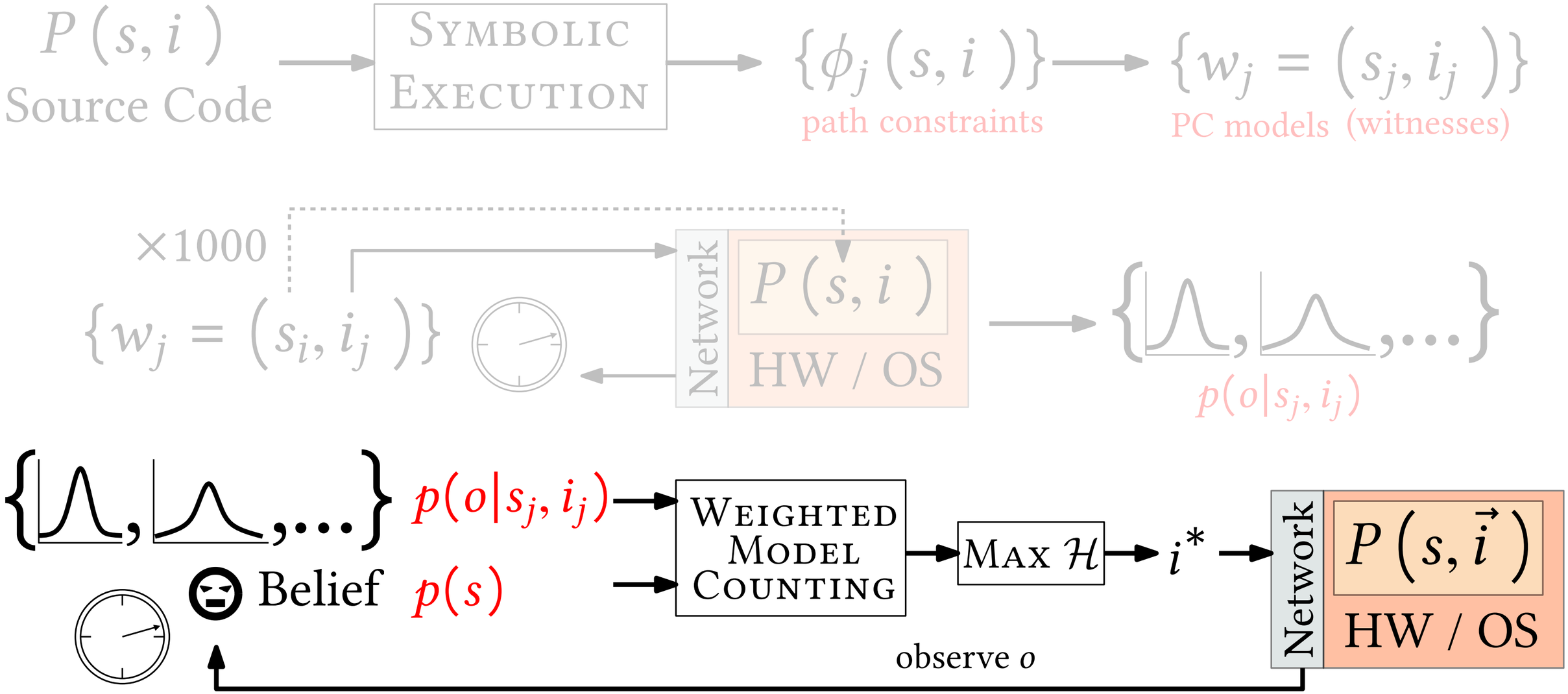

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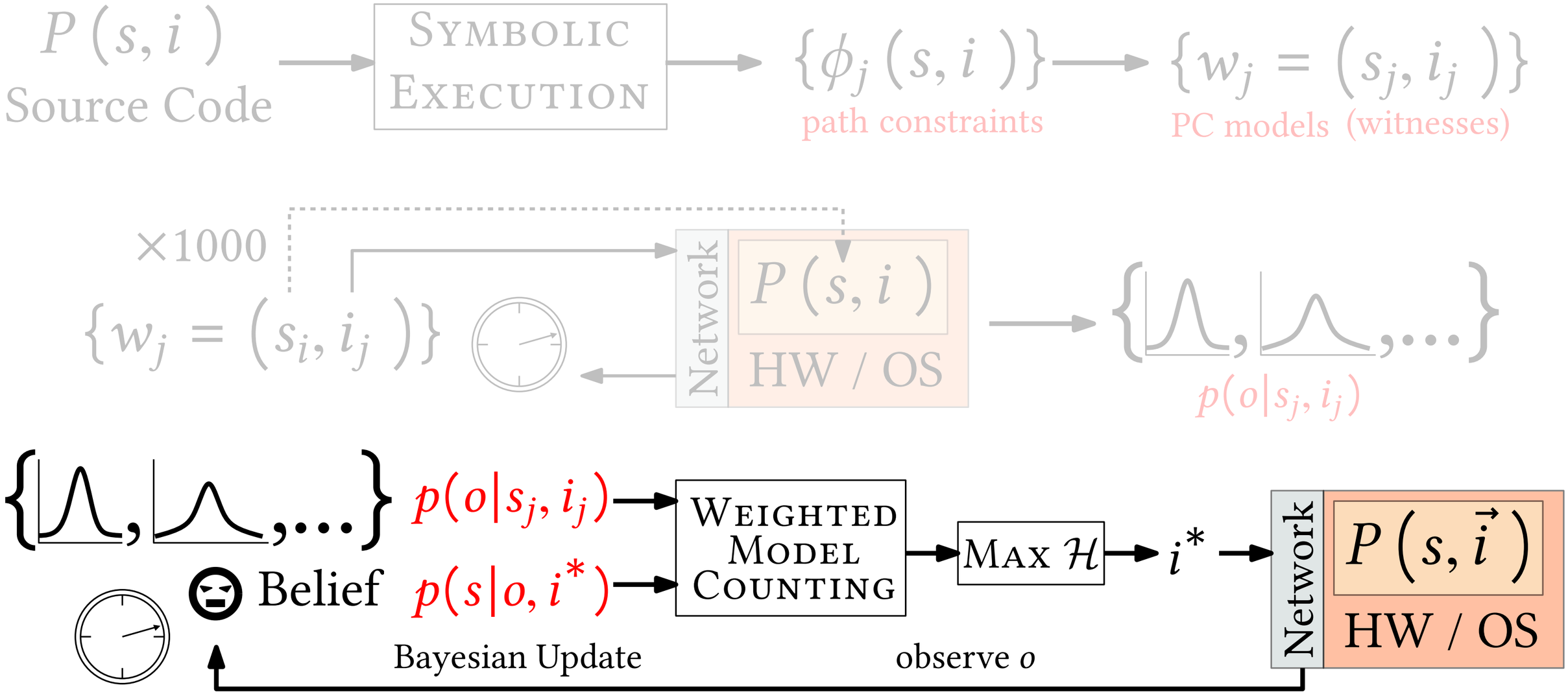

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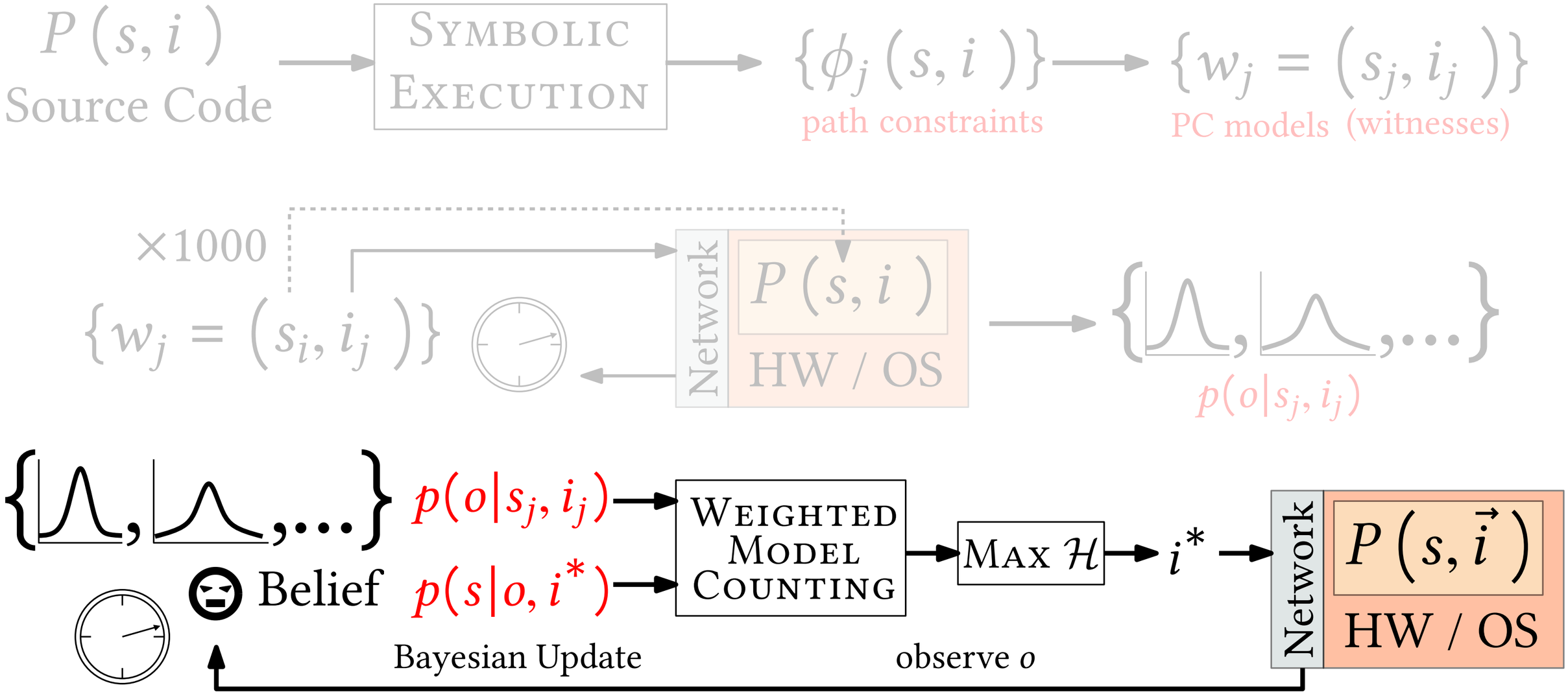
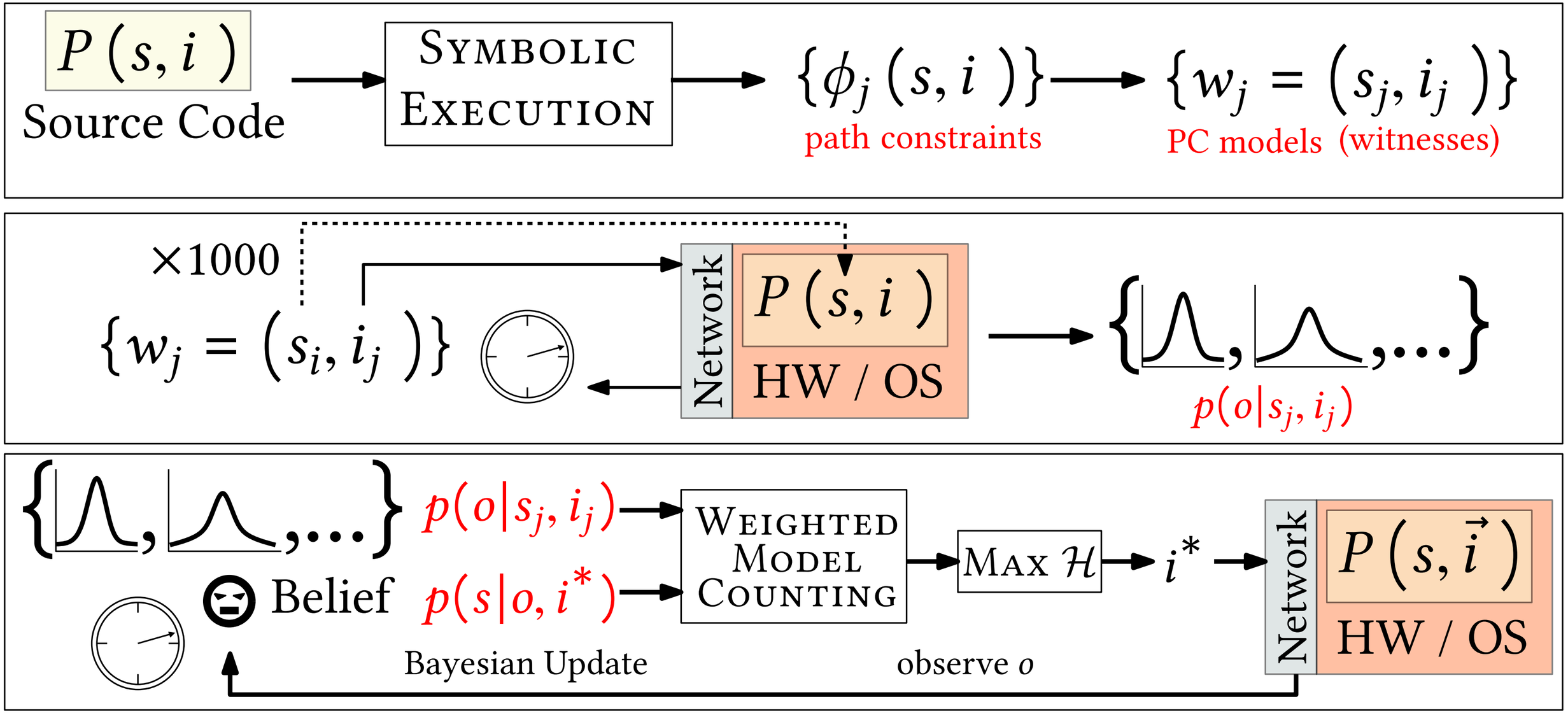
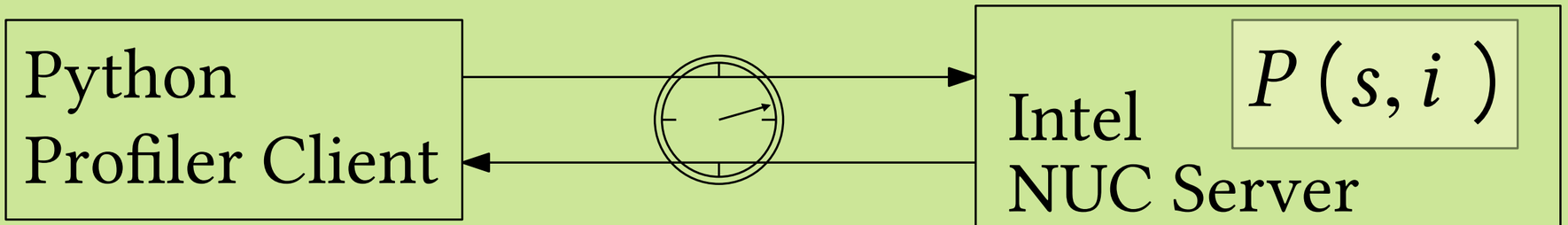


Proposed Approach



Prototype Implementation

NASA Symbolic PathFinder (SPF) + Z3 Constraint Solver



Barvinok
Weighted Symbolic
Model Counting

Mathematica
Symbolic Entropy Computation
Numeric Maximization

Proposed Experiments

DARPA Space-Time Analysis for Cybersecurity (STAC)

Canonical Side-Channel Vulnerability Benchmark

https://github.com/Apogee-Research/STAC/

7 Applications, 1 to 3 variants each

14 total programs

Compare the two approaches.

Proposed Work Summary

1. Offline Static Analysis

2. Offline Dynamic Analysis

3. Online Attack Synthesis

Publications

- Aydin, **Bang**, Bultan: Automata-Based Model Counting for String Constraints. CAV ’15.
- **Bang**, Aydin, Bultan: Automatically Computing Path Complexity of Programs. FSE ’15.
- **Bang**, Aydin, Phan, Pasareanu, Bultan: String Analysis for Side Channels with Segmented Oracles. FSE ’16.
- Phan, **Bang**, Pasareanu, Malacaria, Bultan: Synthesis of Adaptive Side-Channel Attacks. CSF ’17.

Timeline

Fall 2017:

- Unified theoretical model for side-channel techniques from my work.
- Incorporate feedback from committee.
- Improve prototype implementation.

Winter 2018:

- Finish implementation.
- Finish all experiments.

Spring 2018:

- Complete dissertaion draft by April.
- Defend dissertation in May.

Thanks!

Questions?

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