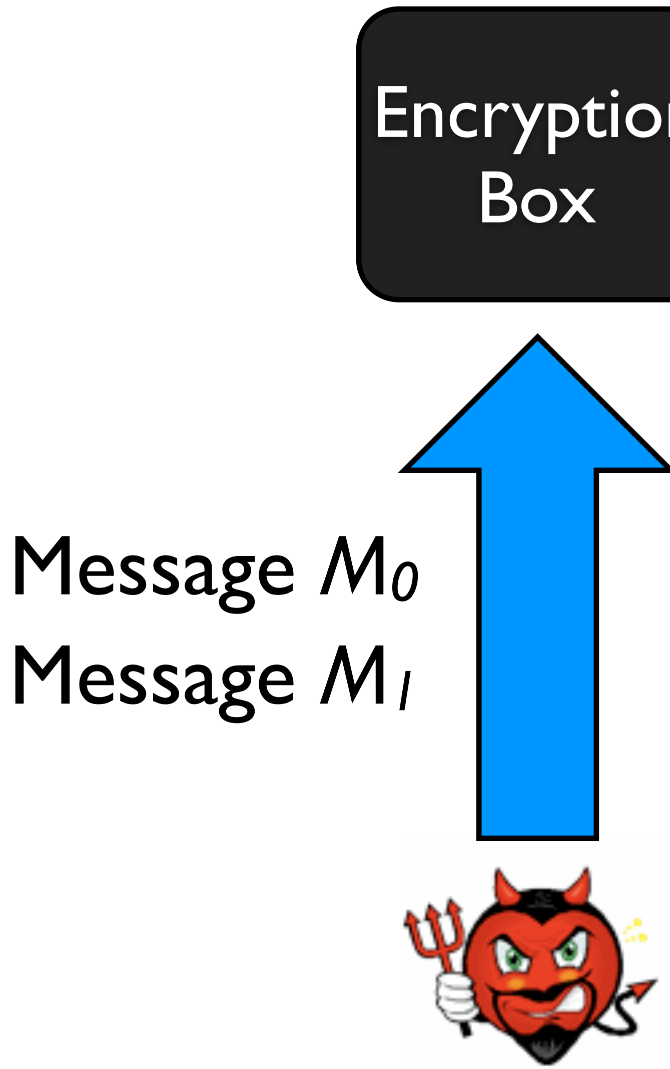
Leakage Resilient Computation

Yevgeniy Vahlis
joint work with Ali Juma, Charles Rackoff

Crypto

Encryption
Box

Crypto



Crypto

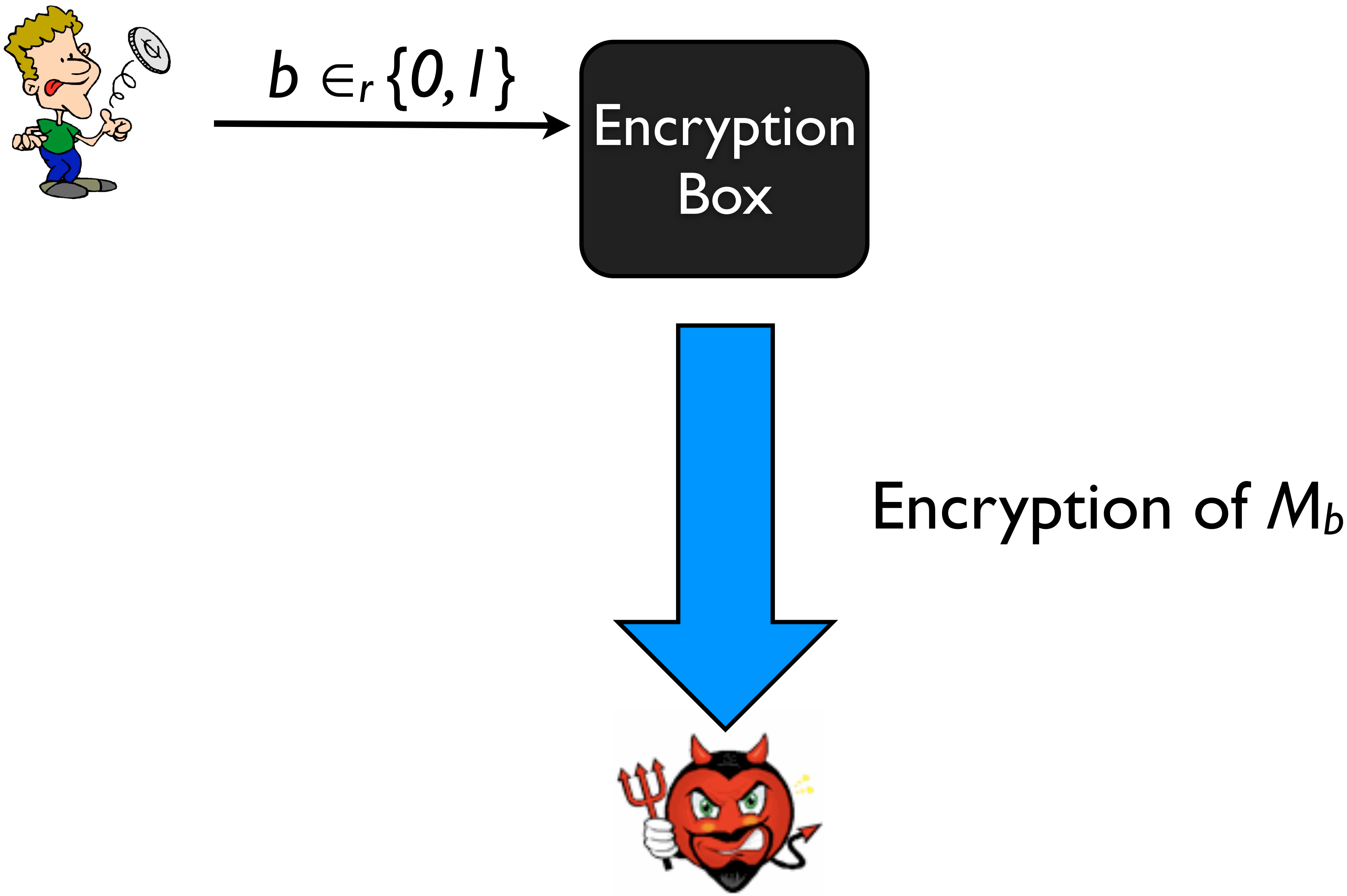
$b \in_r \{0,1\}$

Encryption Box

Message M_0

Message M_1

Crypto



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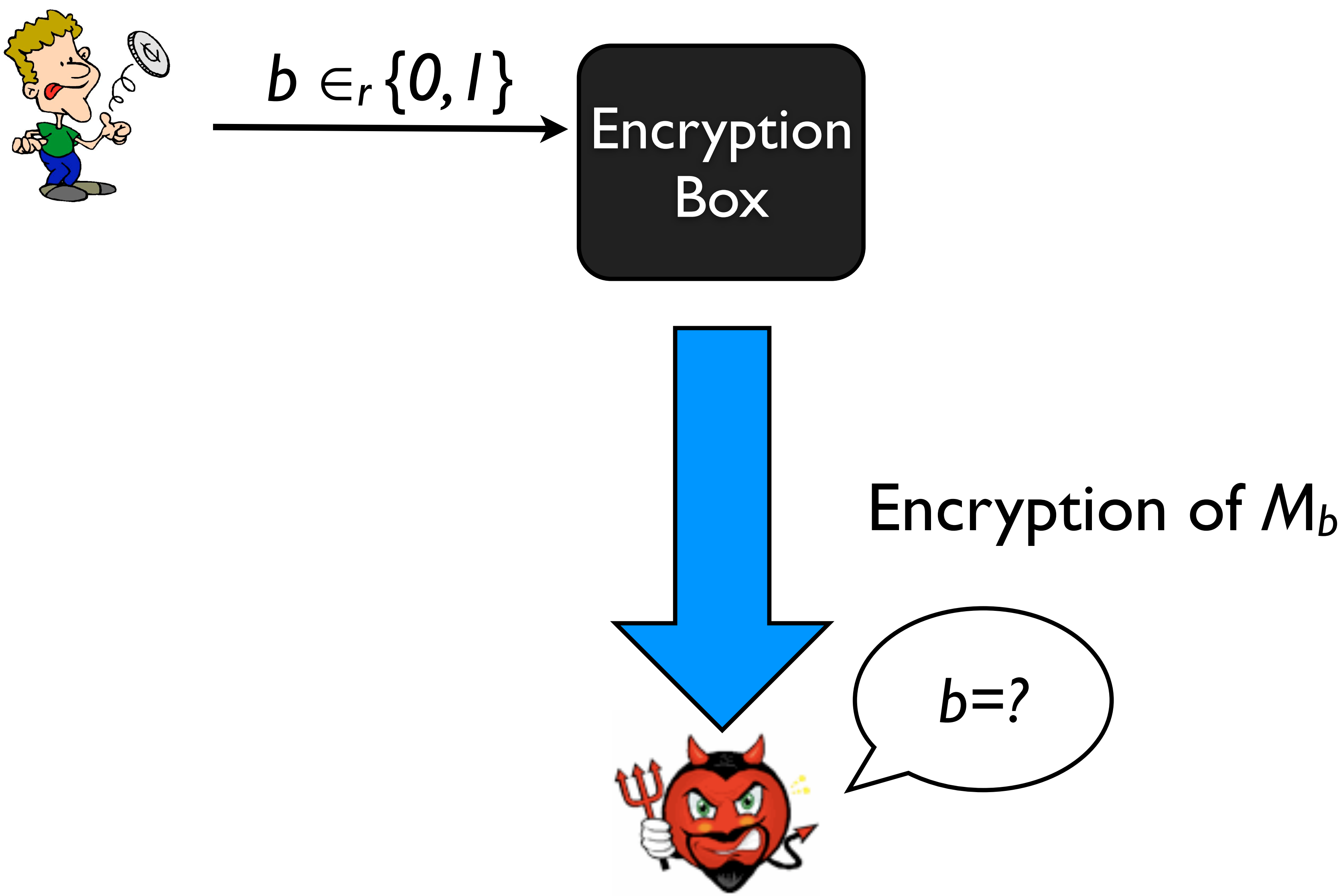
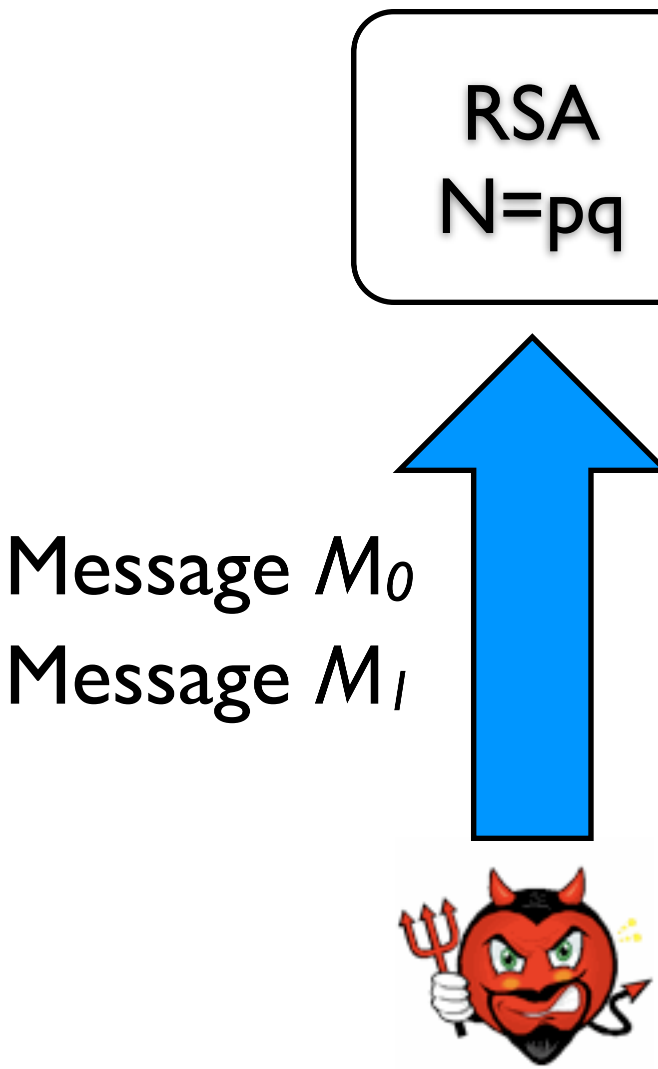


Crypto in Real Life

RSA
$N=pq$

Crypto in Real Life



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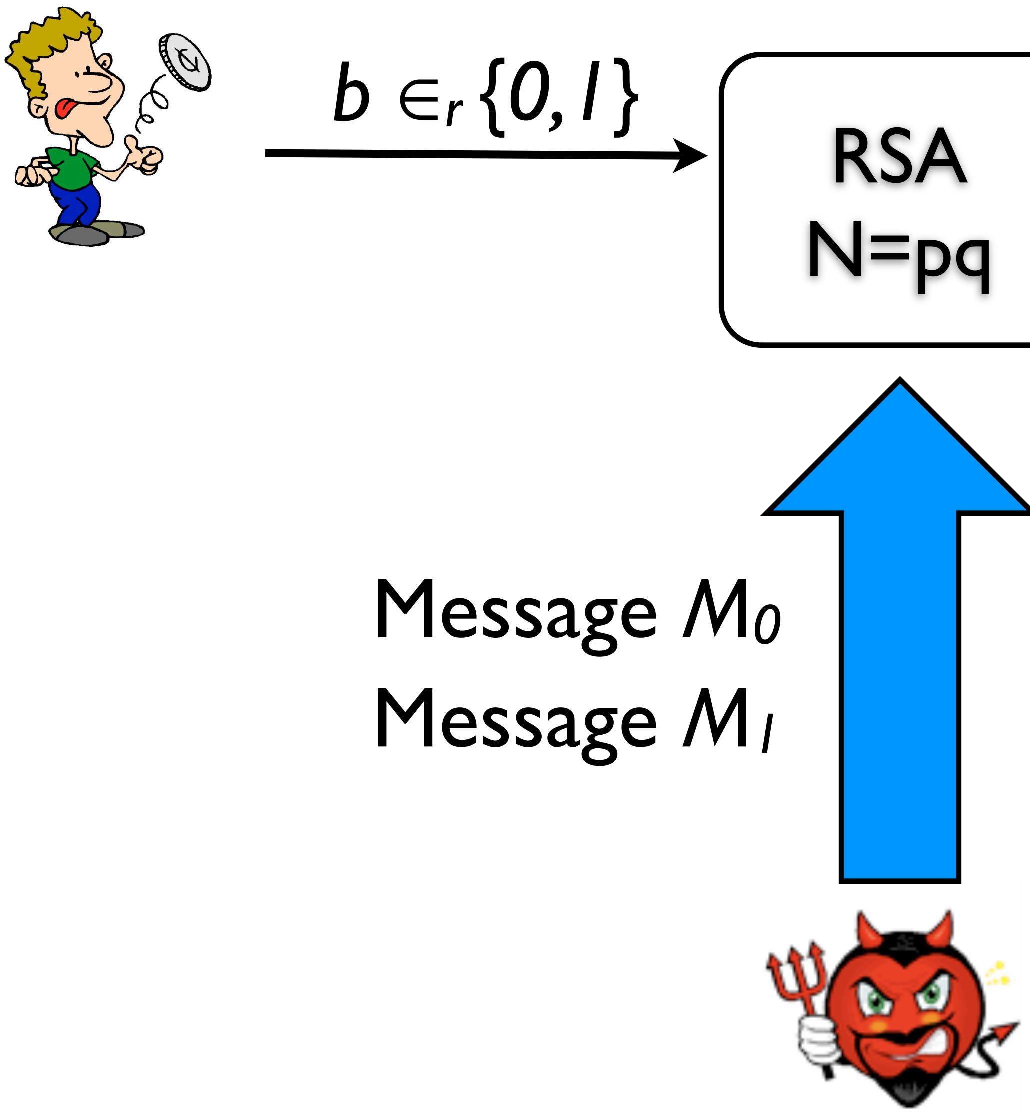

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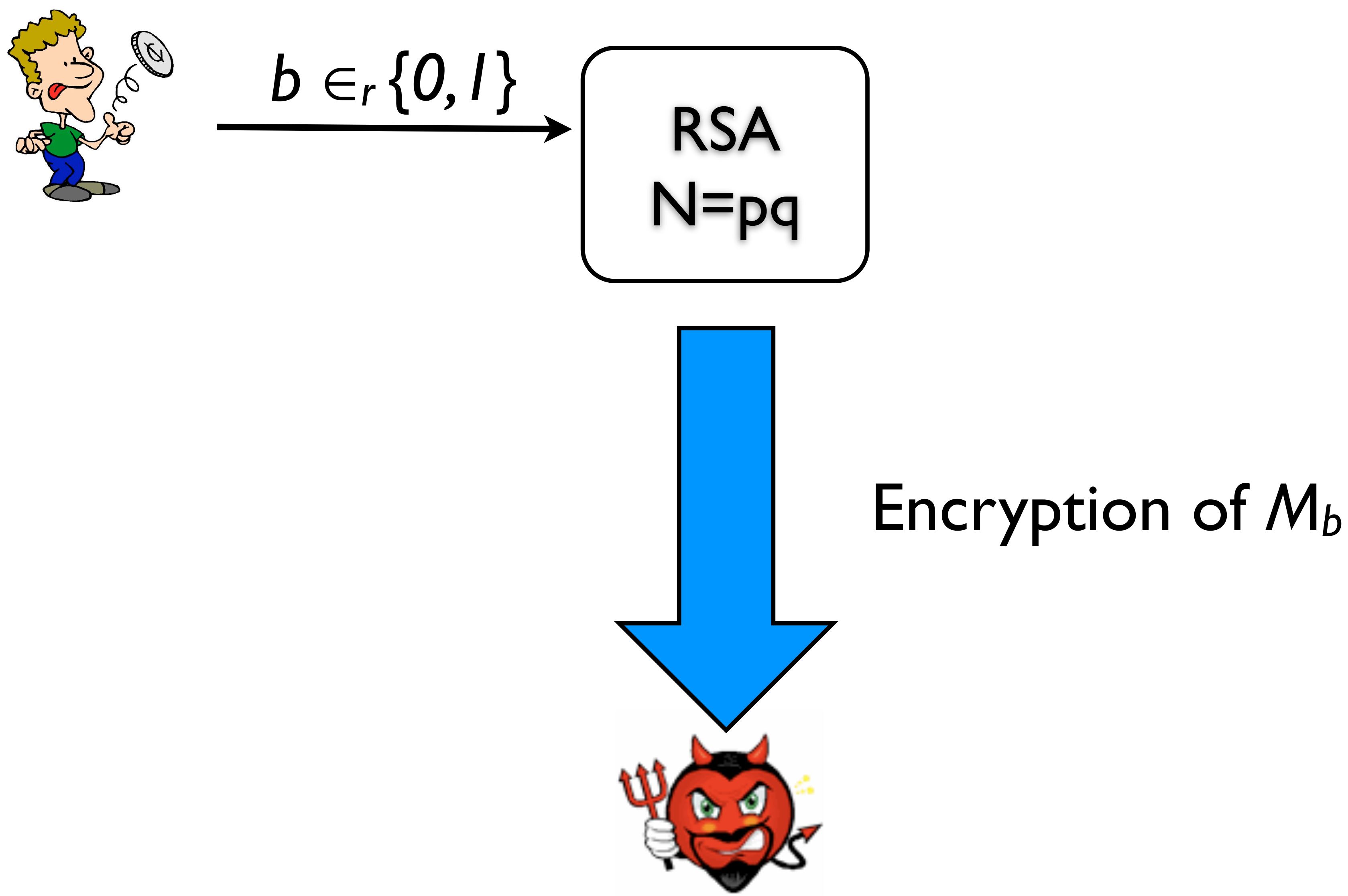

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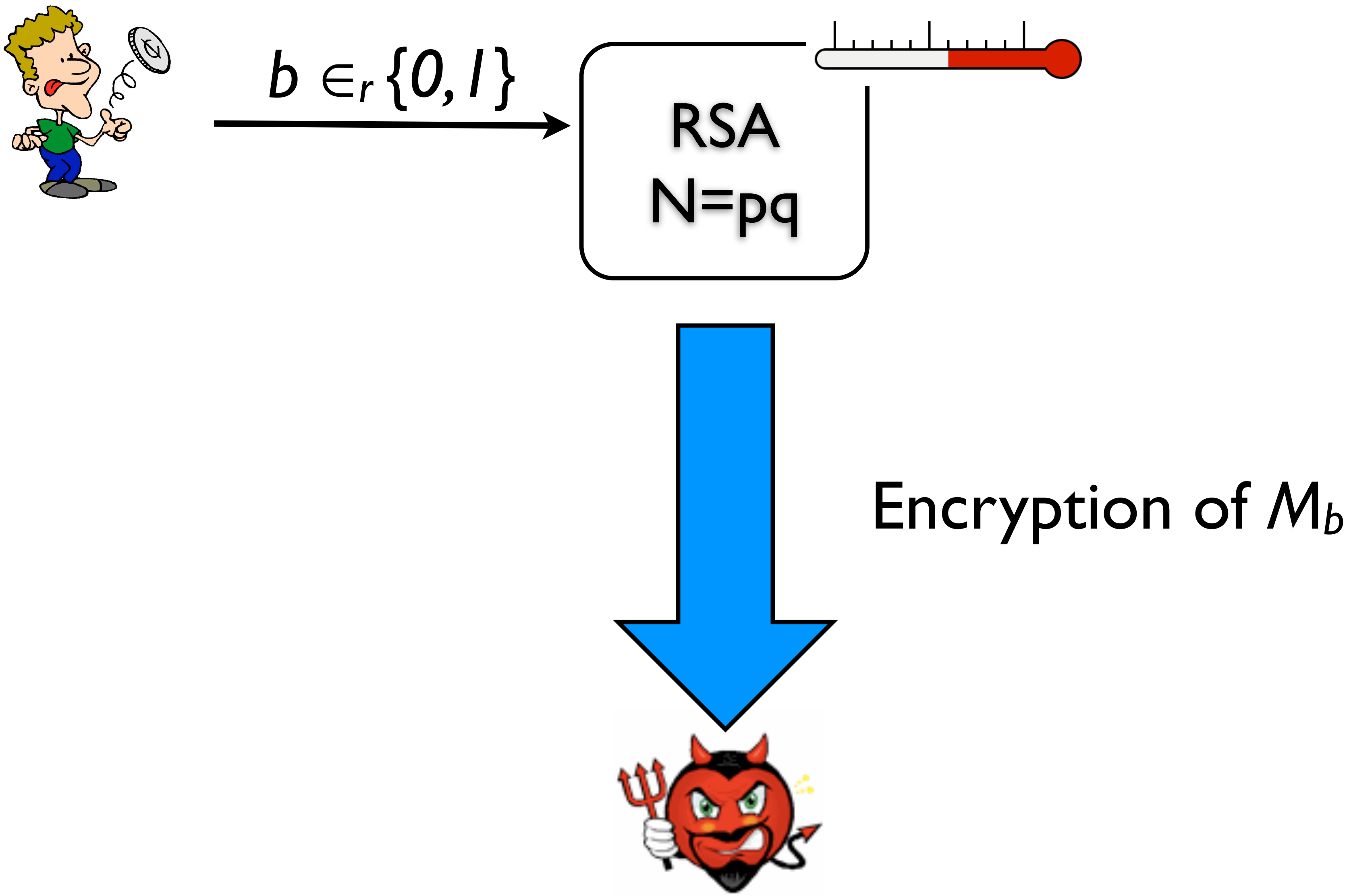

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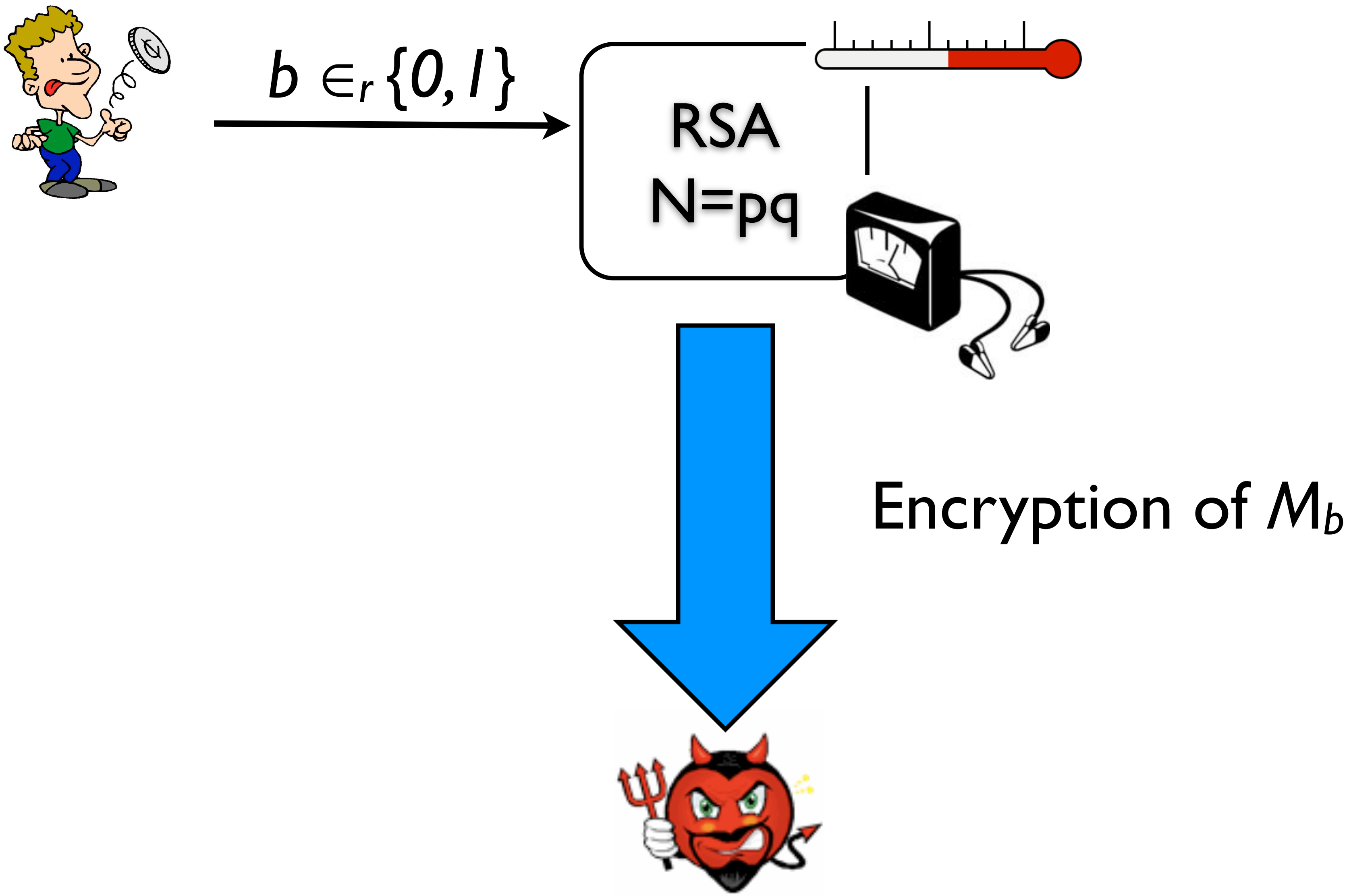

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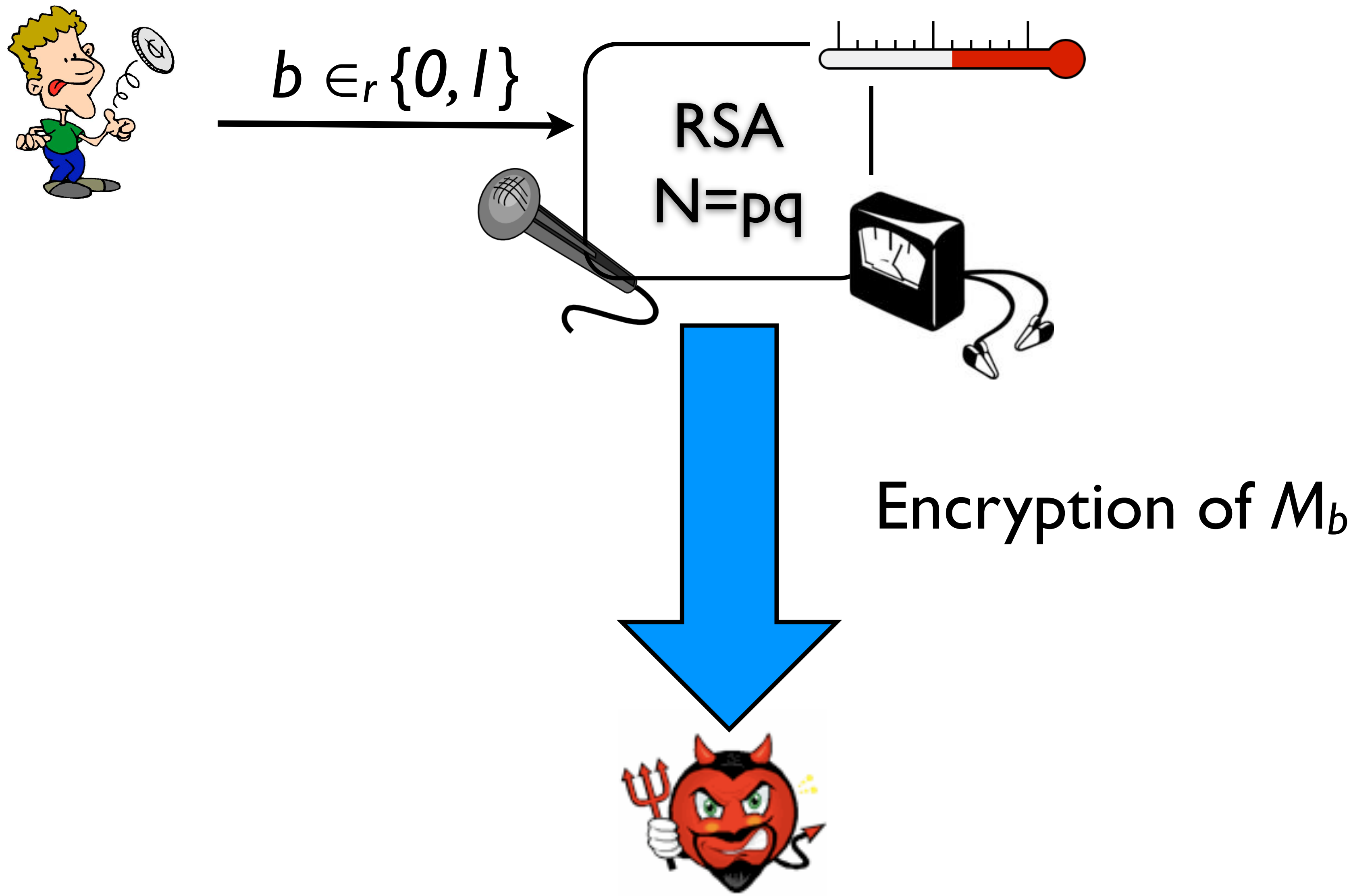

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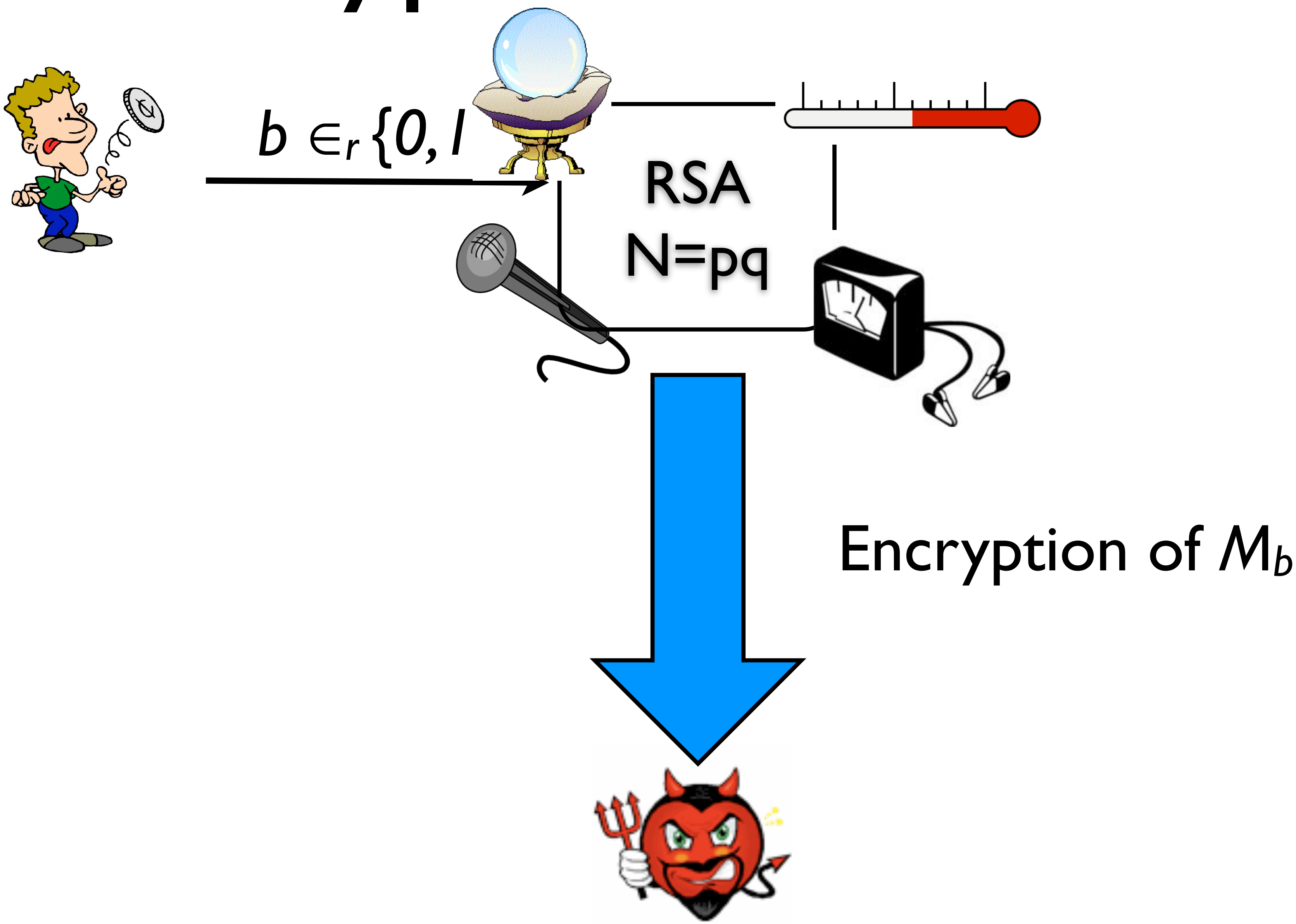

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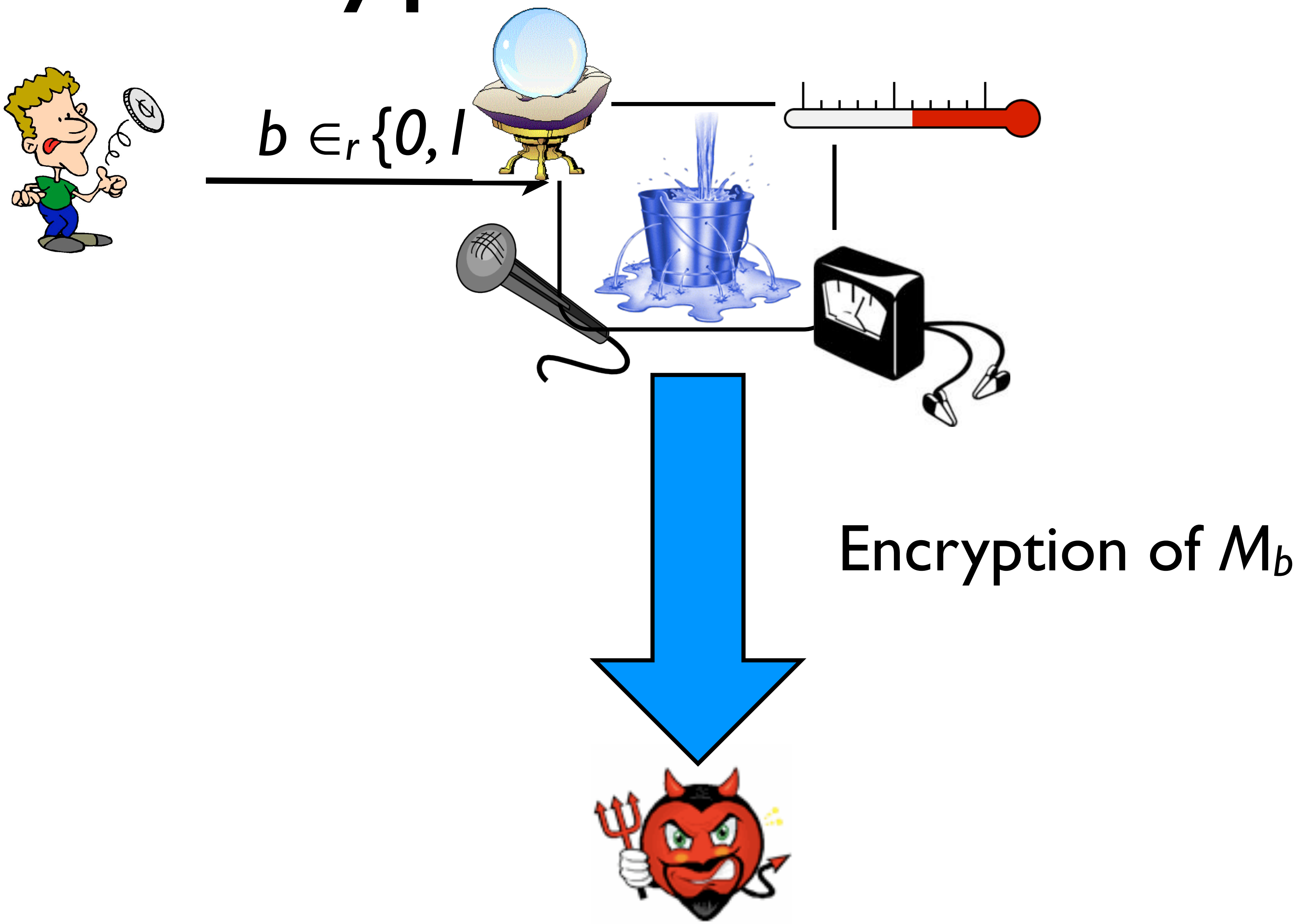

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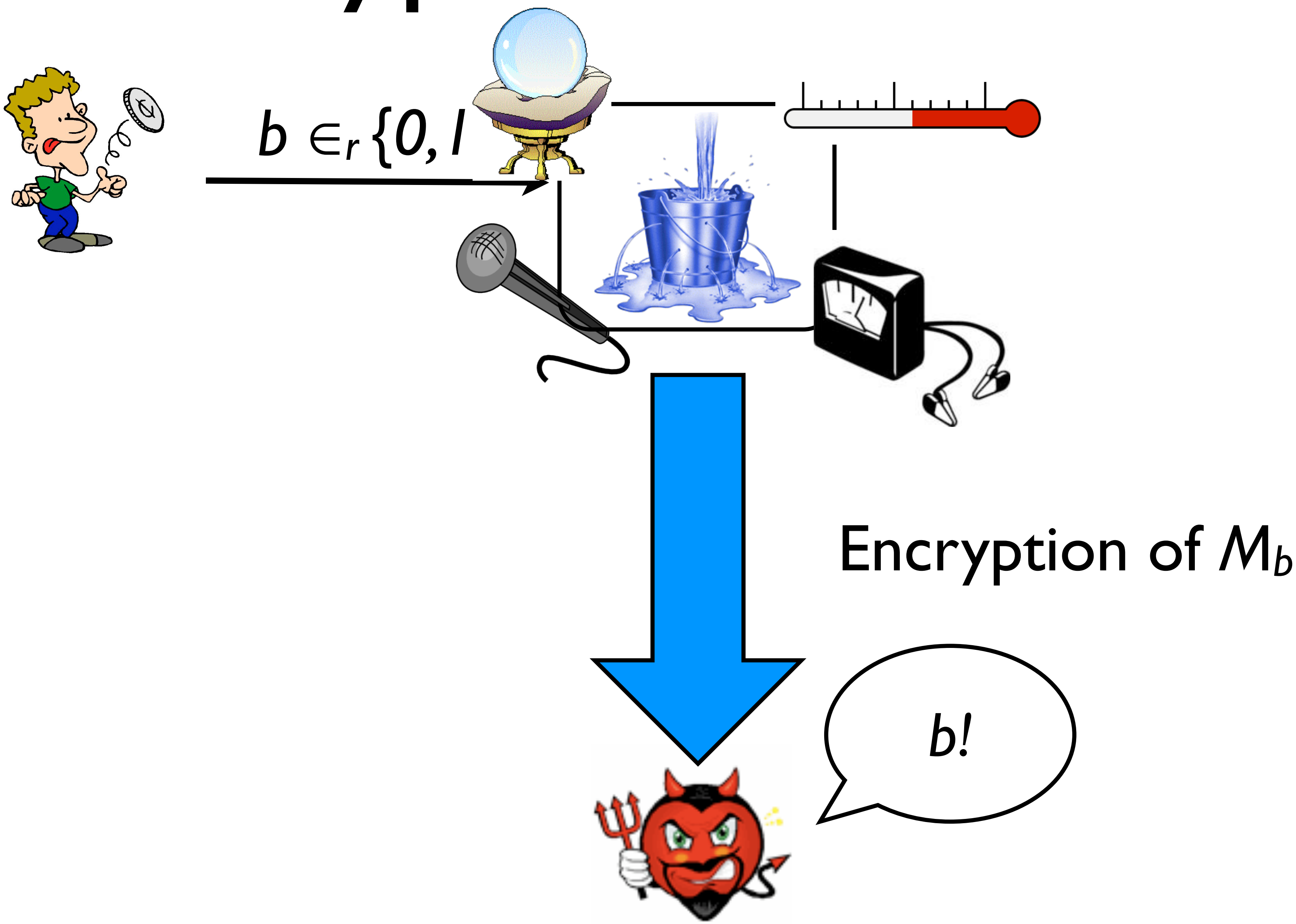

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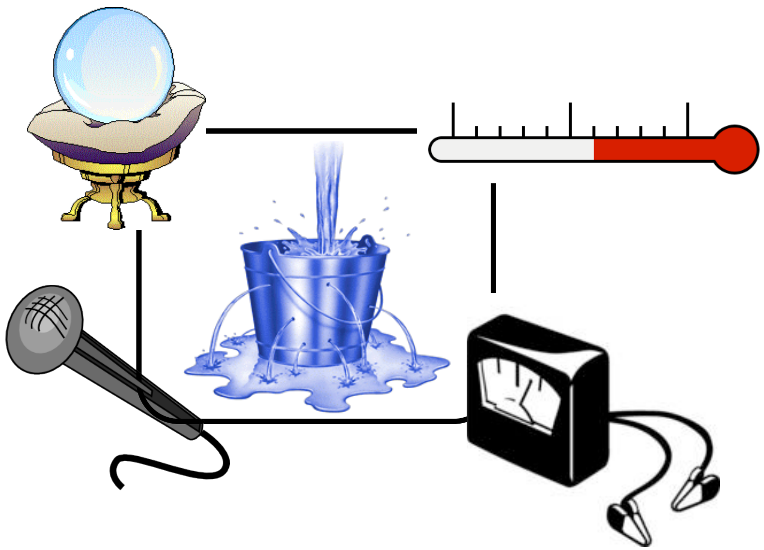

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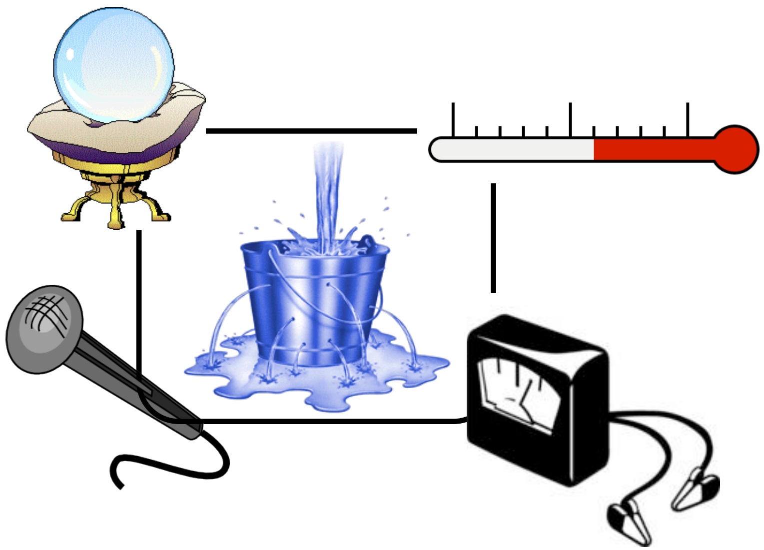
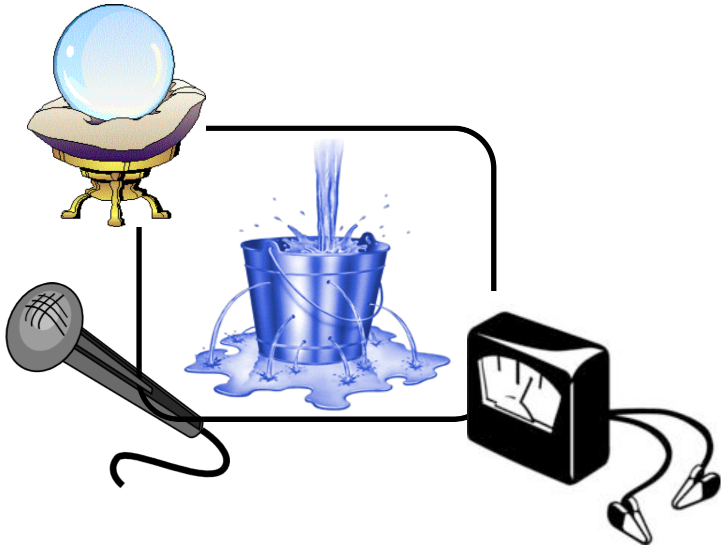


Solutions:

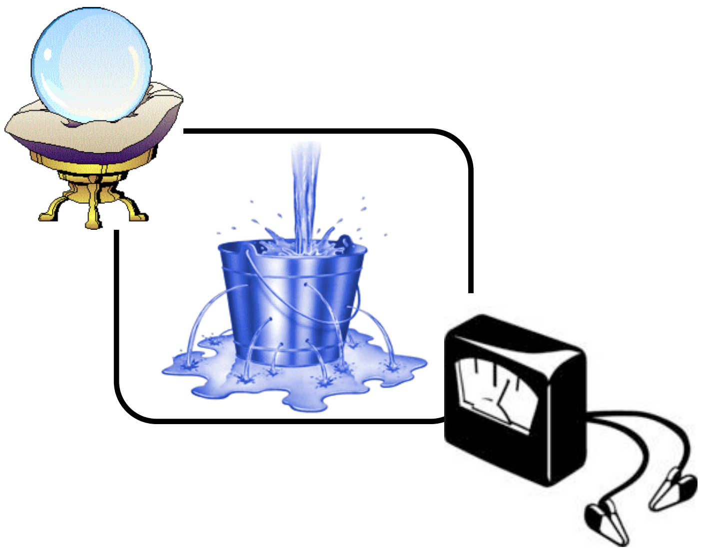
Crypto in Real Life



Solutions:

- Heat isolation

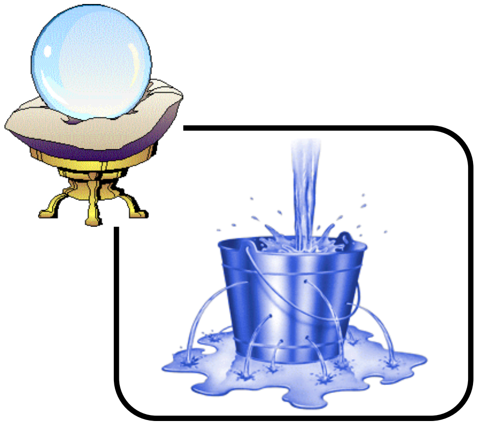
Crypto in Real Life



Solutions:

- Heat isolation
- Uniform cooling and quite fans

Crypto in Real Life



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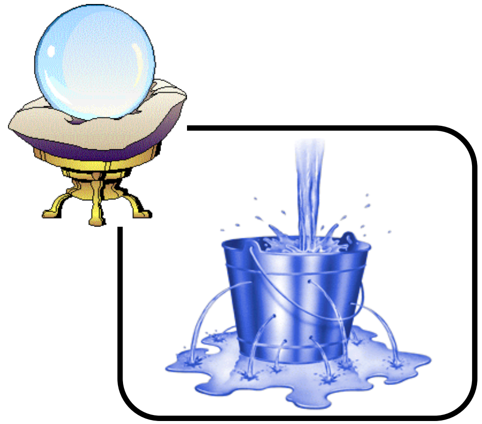
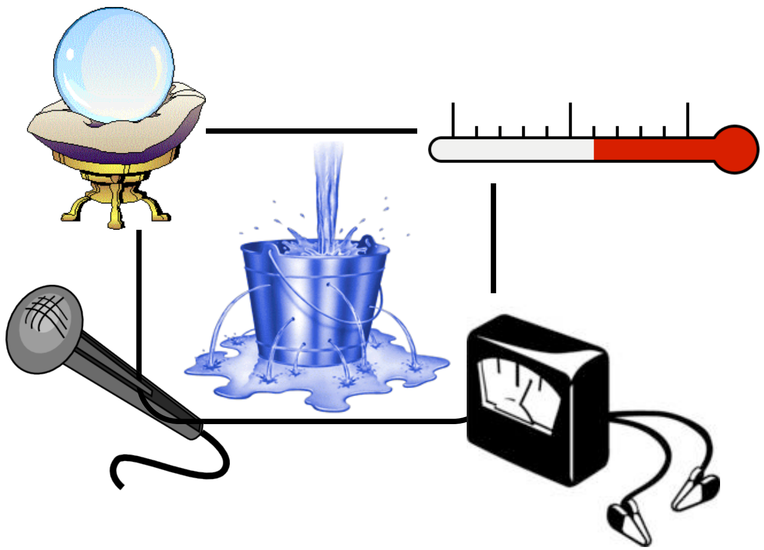


Solutions:

- Heat isolation
- Uniform cooling and quite fans
- Electromagnetic isolation
- **???**

Algorithmic Protection



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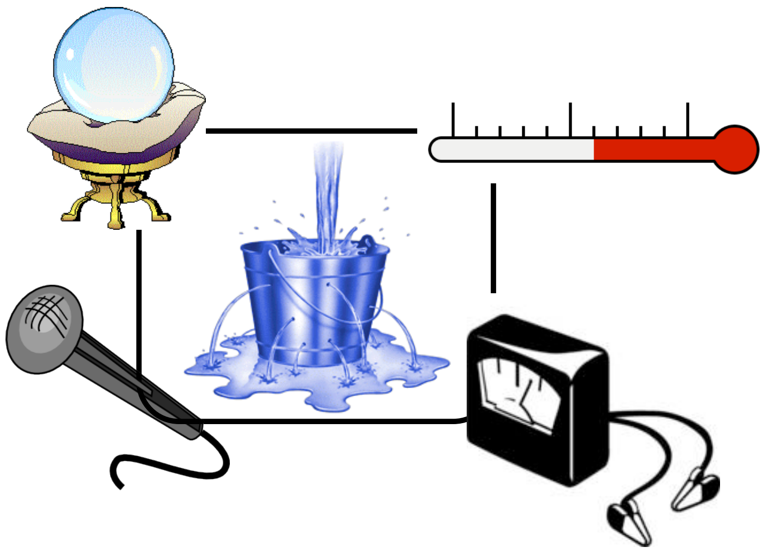
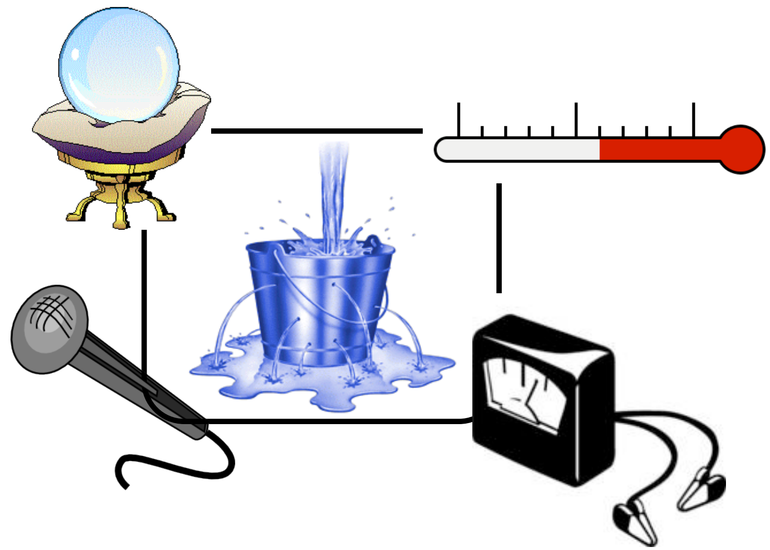


In recent years:

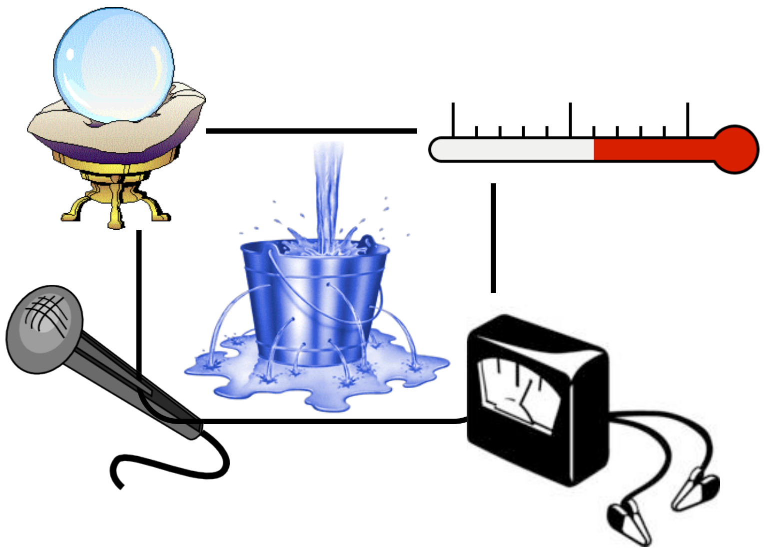
Algorithmic Protection



In recent years:

- Reduce assumptions about hardware

Algorithmic Protection



In recent years:

- Reduce assumptions about hardware
- Design algorithms that are secure under leakage

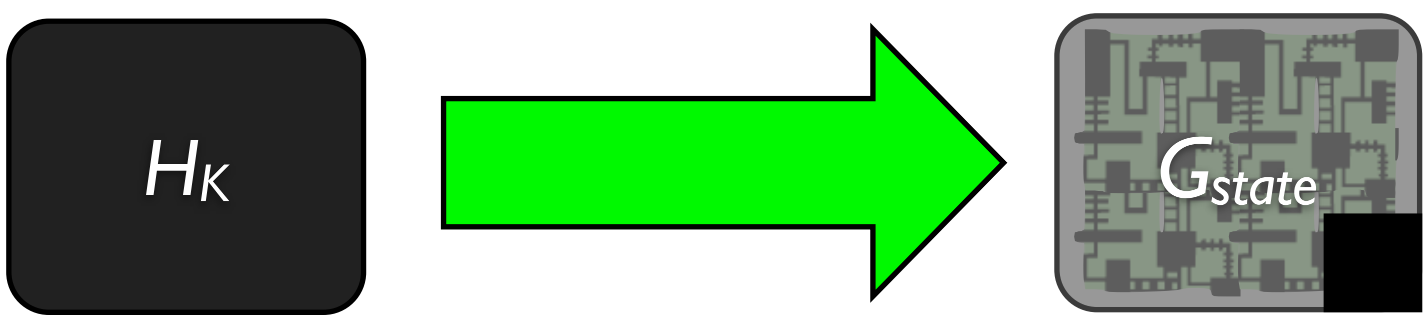
Previous Work

- [Goldreich & Ostrovsky 96] protect against complete leakage of memory when CPU is secure.
- [Ishai & Sahai & Wagner 2003] assume adversary leaks value of a fixed number of wires
- [Micali & Reyzin 04] introduce axioms and framework
- [Goldwasser & Kalai & Rothblum 2008] one-time programs
- [Dziembowski & Pietrzak 2008] Leakage resilient stream cipher in the split state model
- [Faust & Reyzin & Tromer 2009] protect against AC0 leakage functions (needs secure component)

Our Results

Our Results

- A compiler that transforms any keyed primitive H_K into a stateful algorithm G_{state}
- G_{state} is resilient against length bounded leakage in each invocation
- Need a fixed size, memory-less secure component



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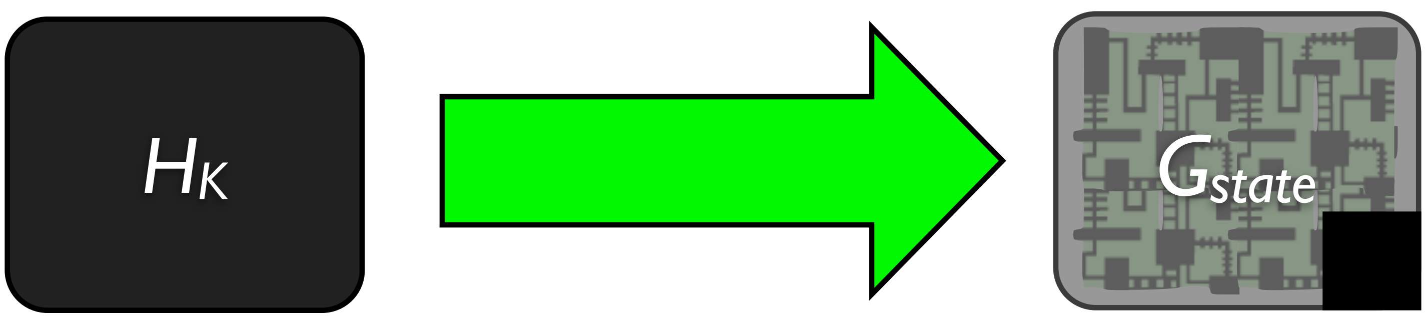
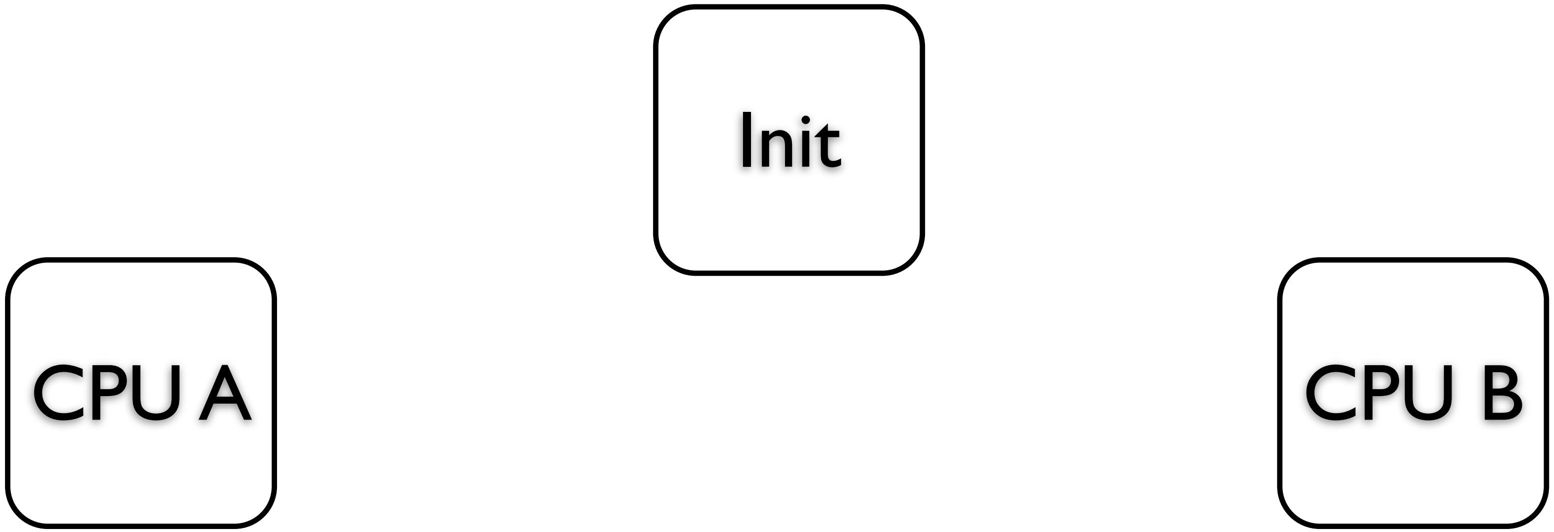


Achieve leak-resilience for arbitrary complexity from leak-resilience for fixed complexity

Model

Want to protect $H_K(x)$

Two computers that communicate over a *public* channel. Initialization is secure.



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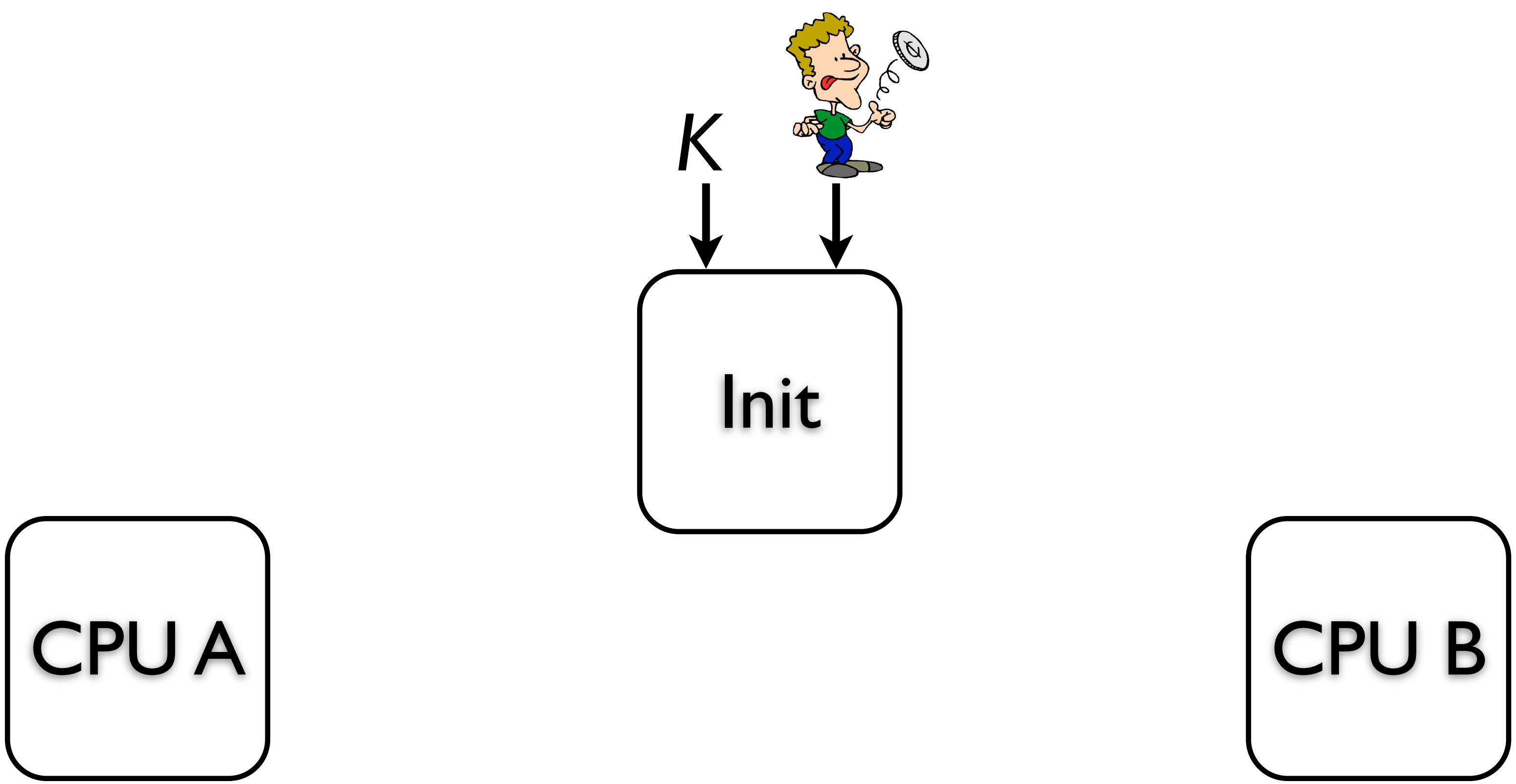

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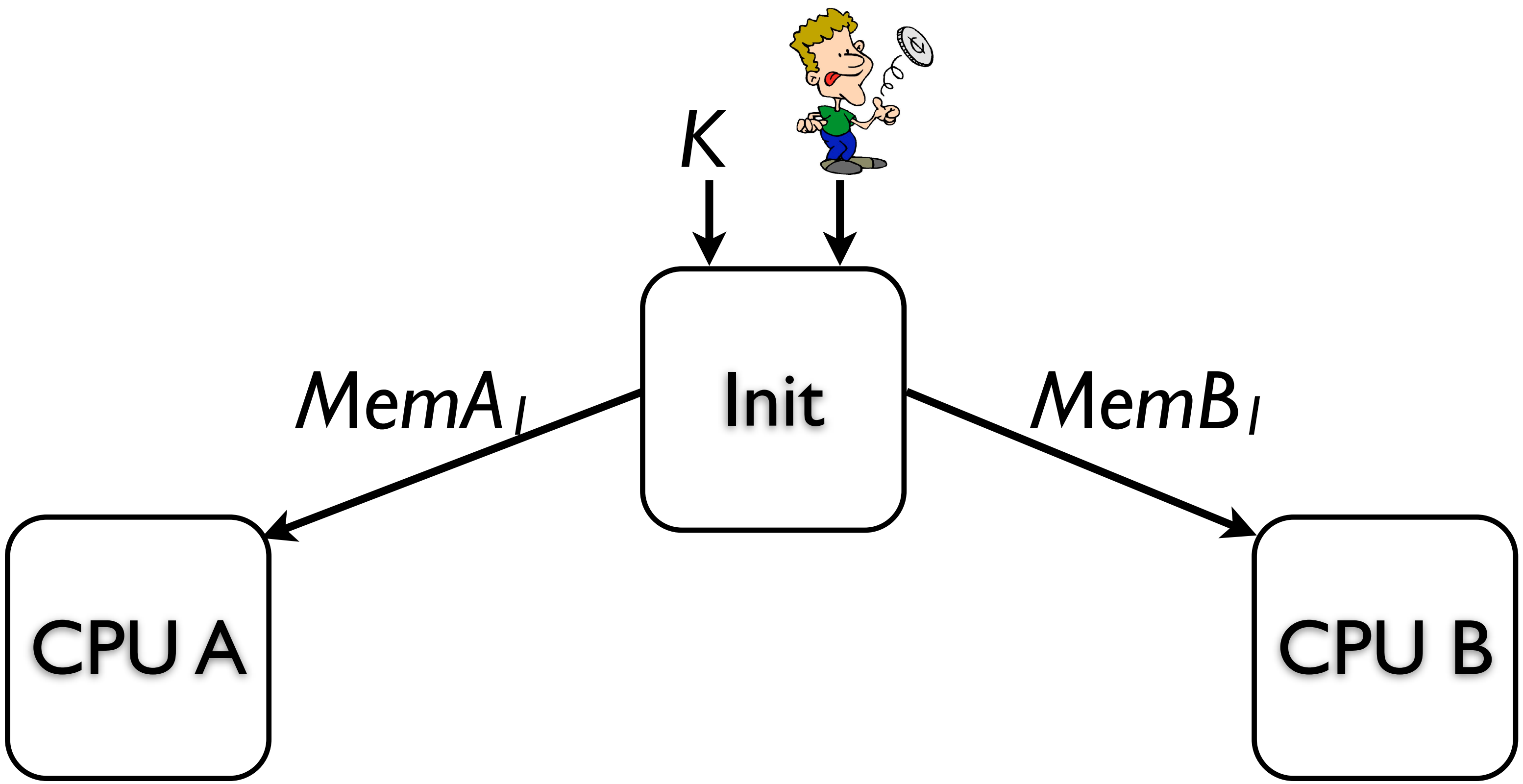

Model

Evaluating $H_K(x)$

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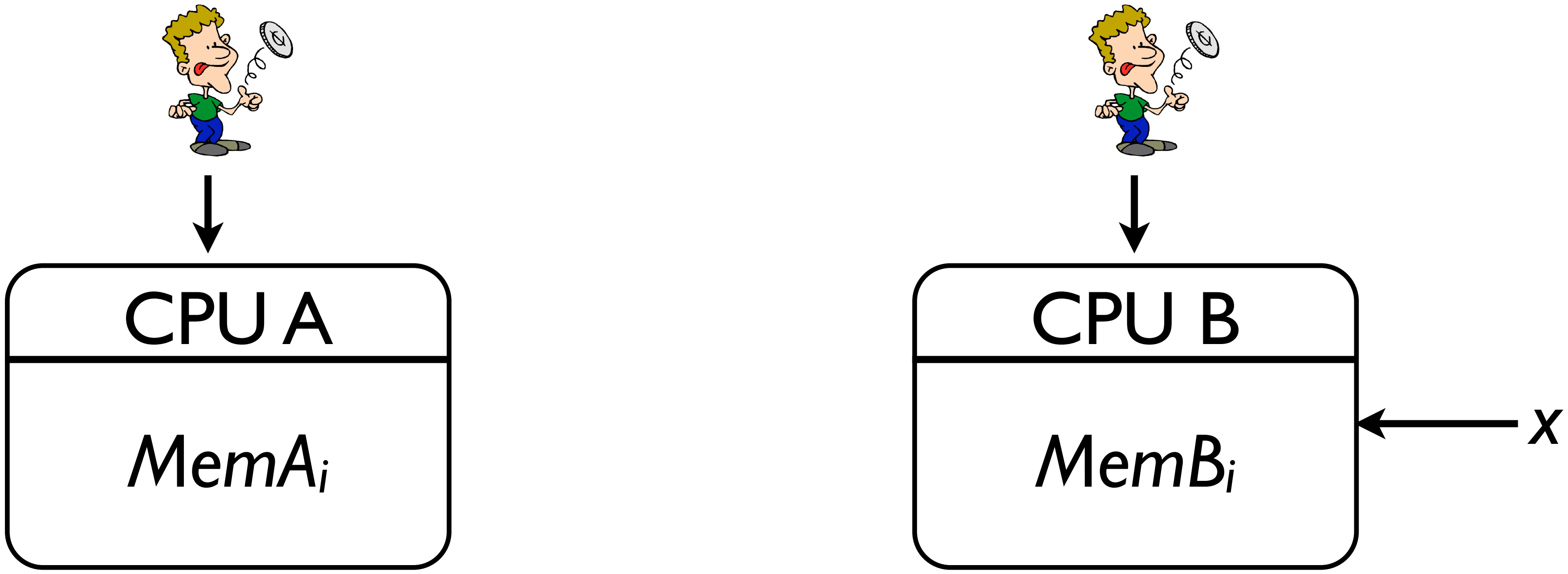

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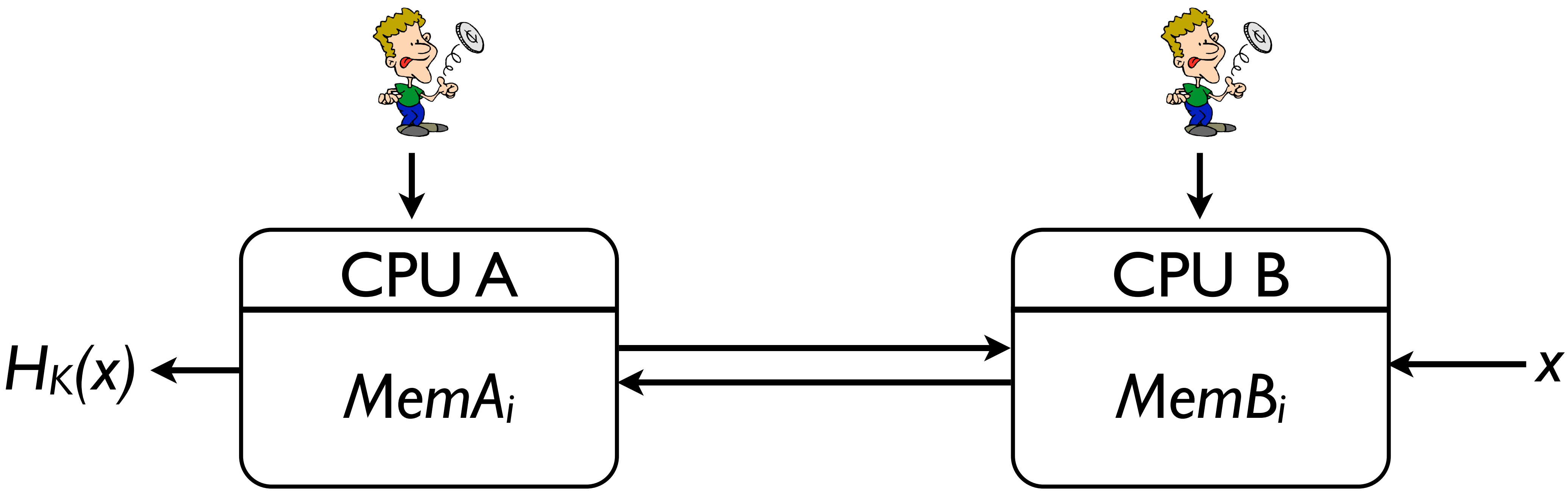

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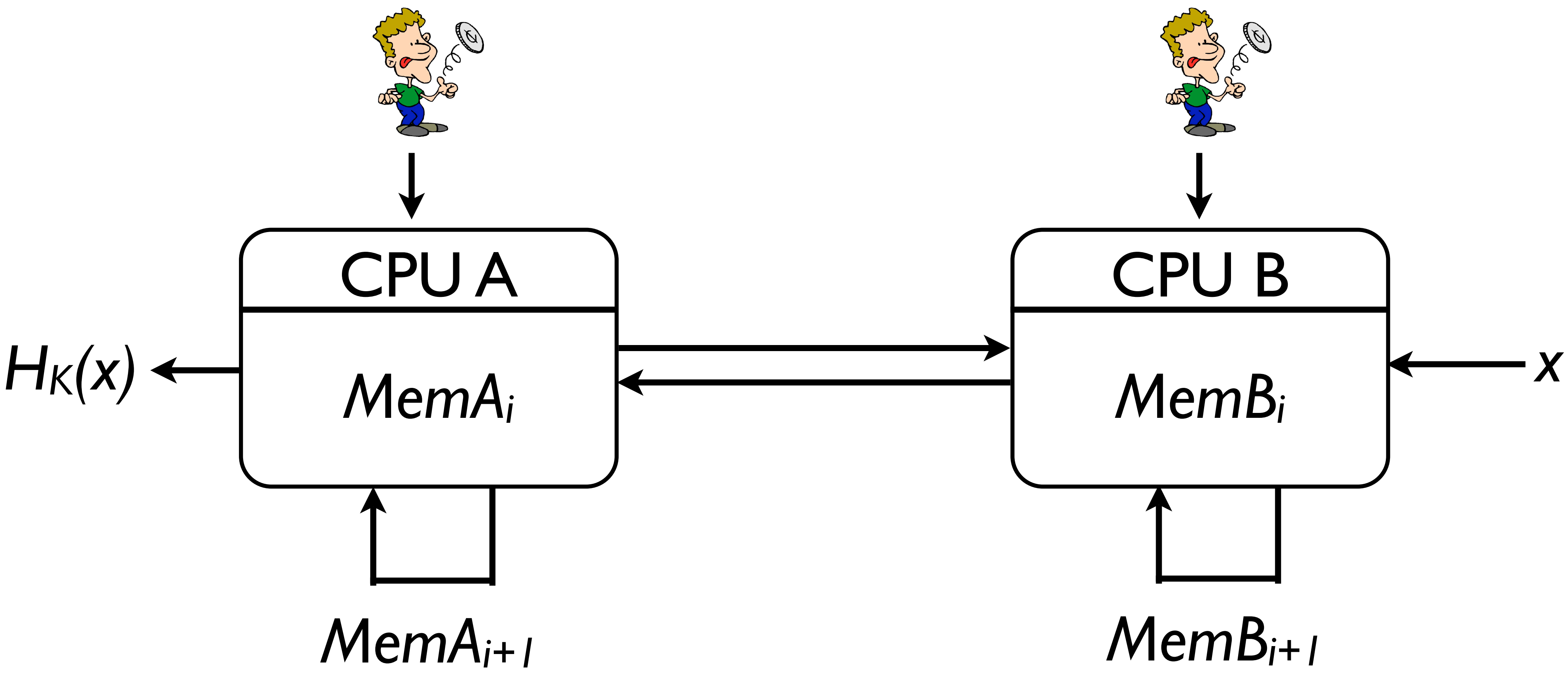
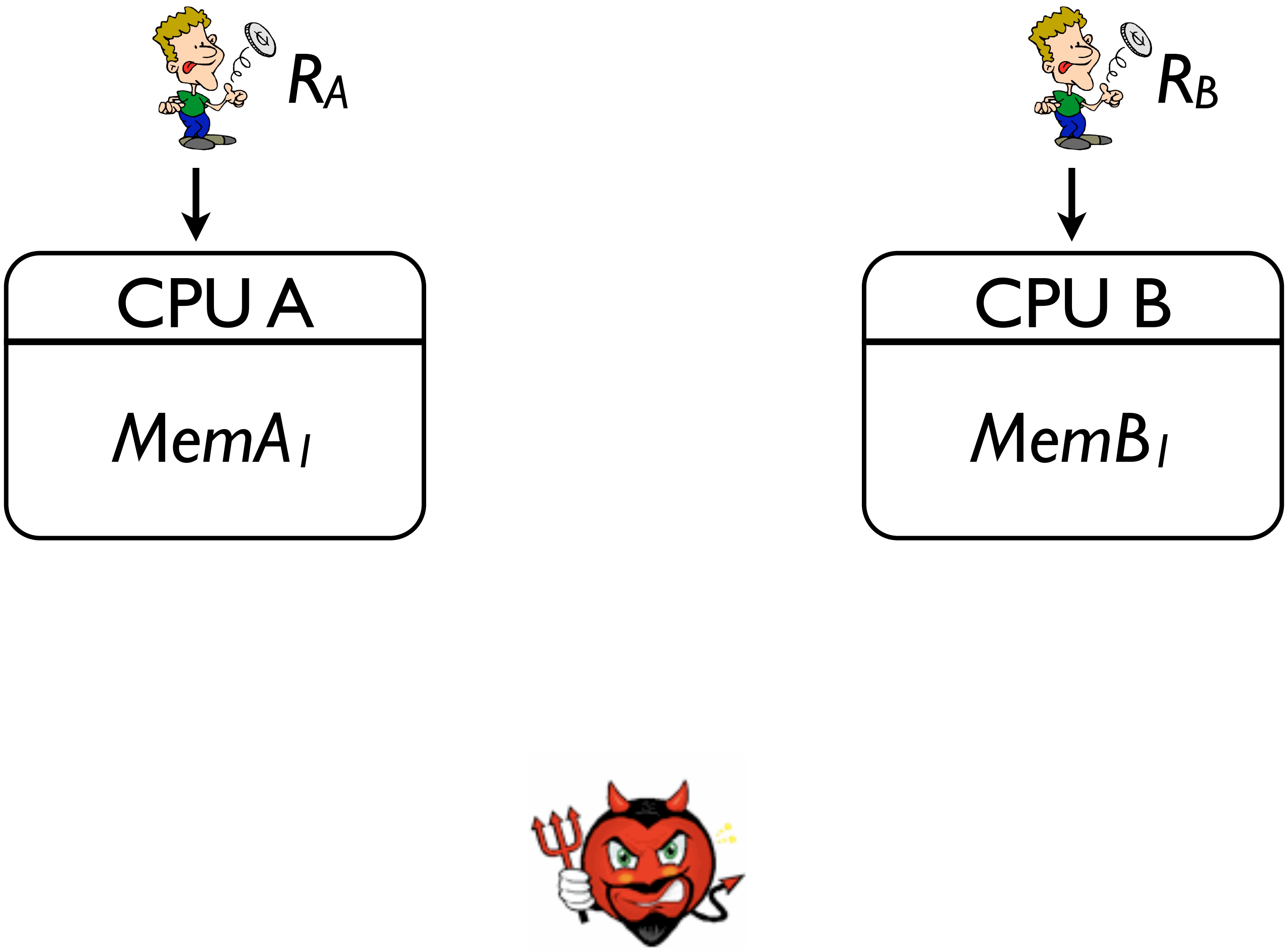


Leakage



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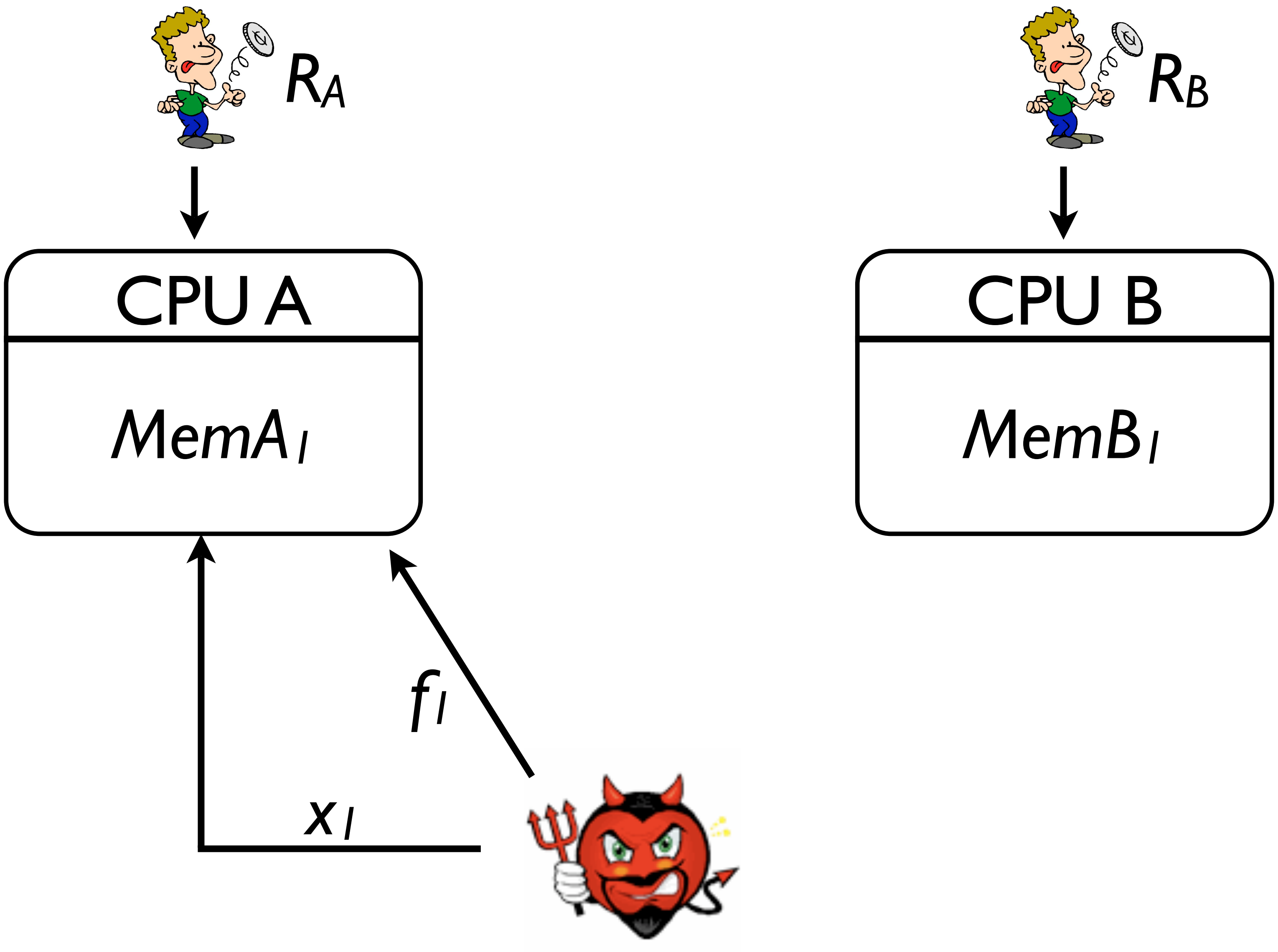

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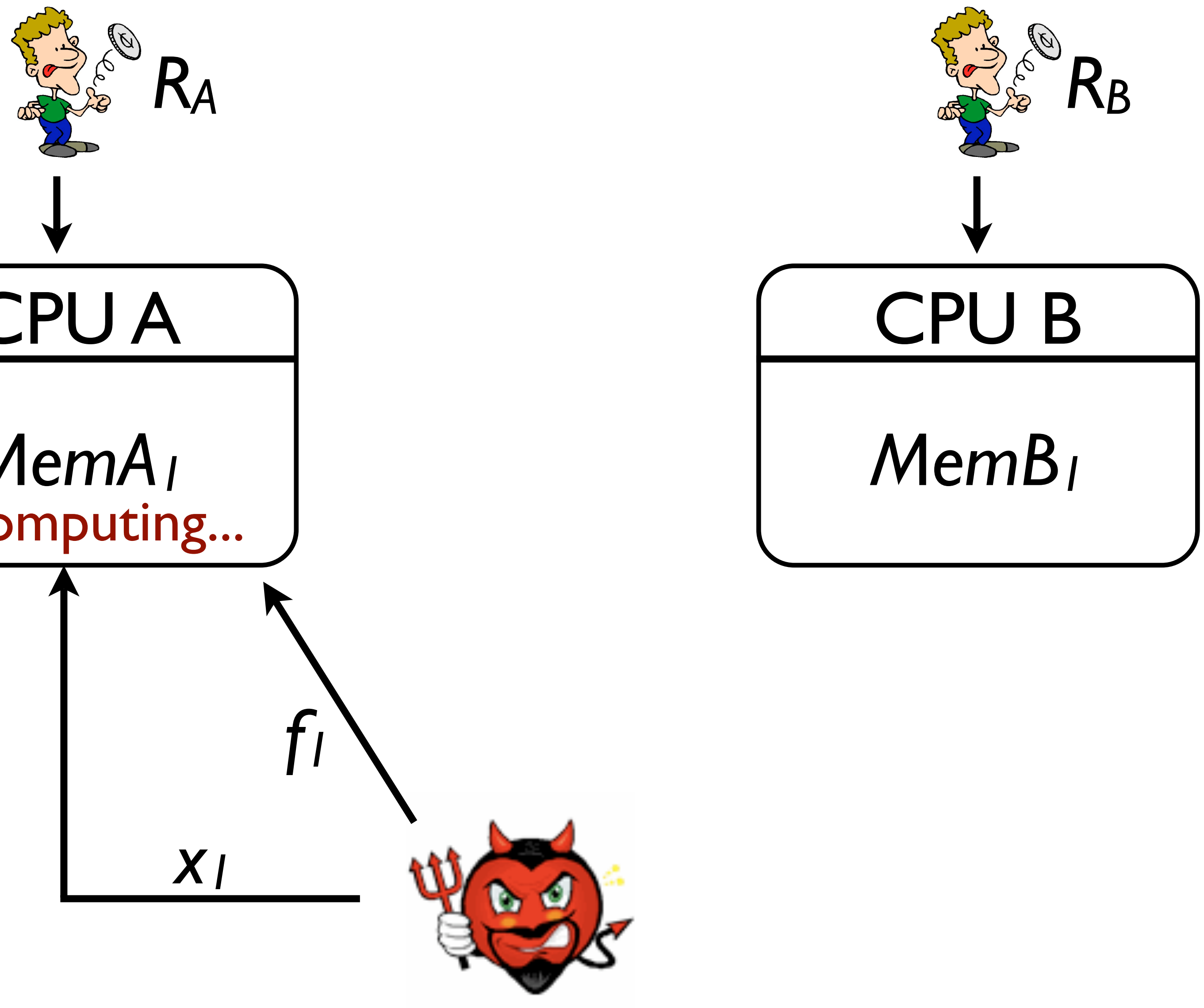

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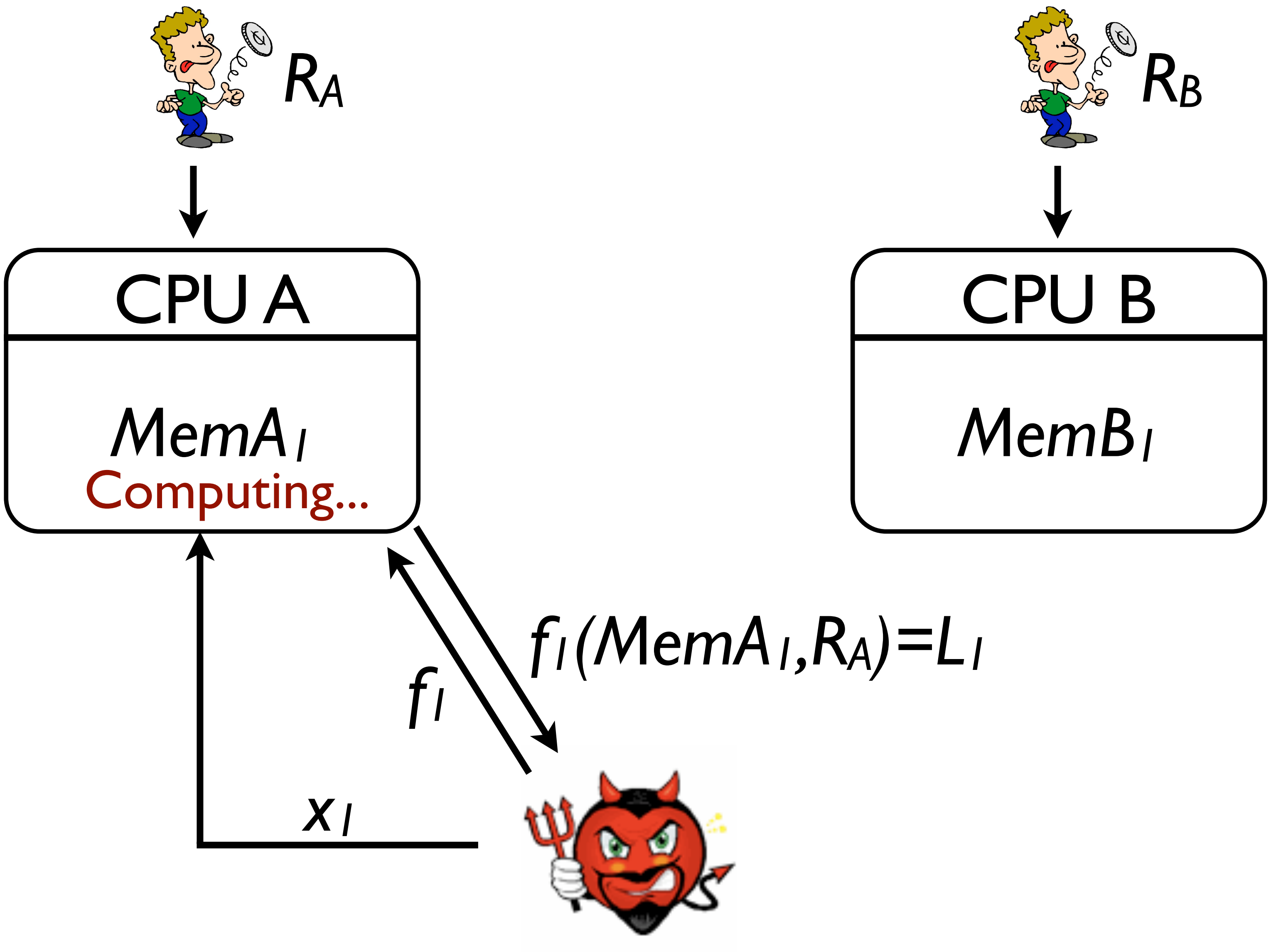

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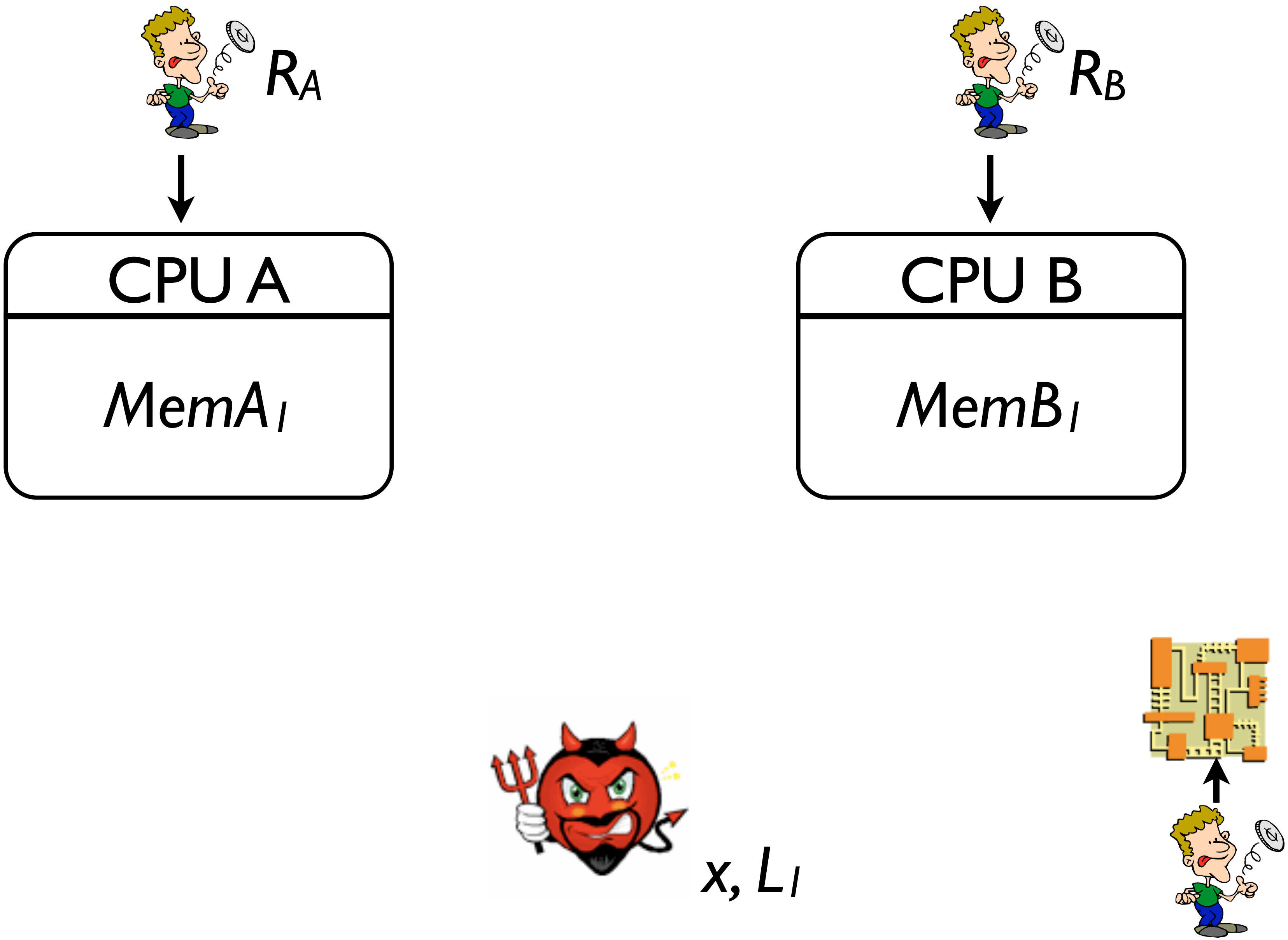

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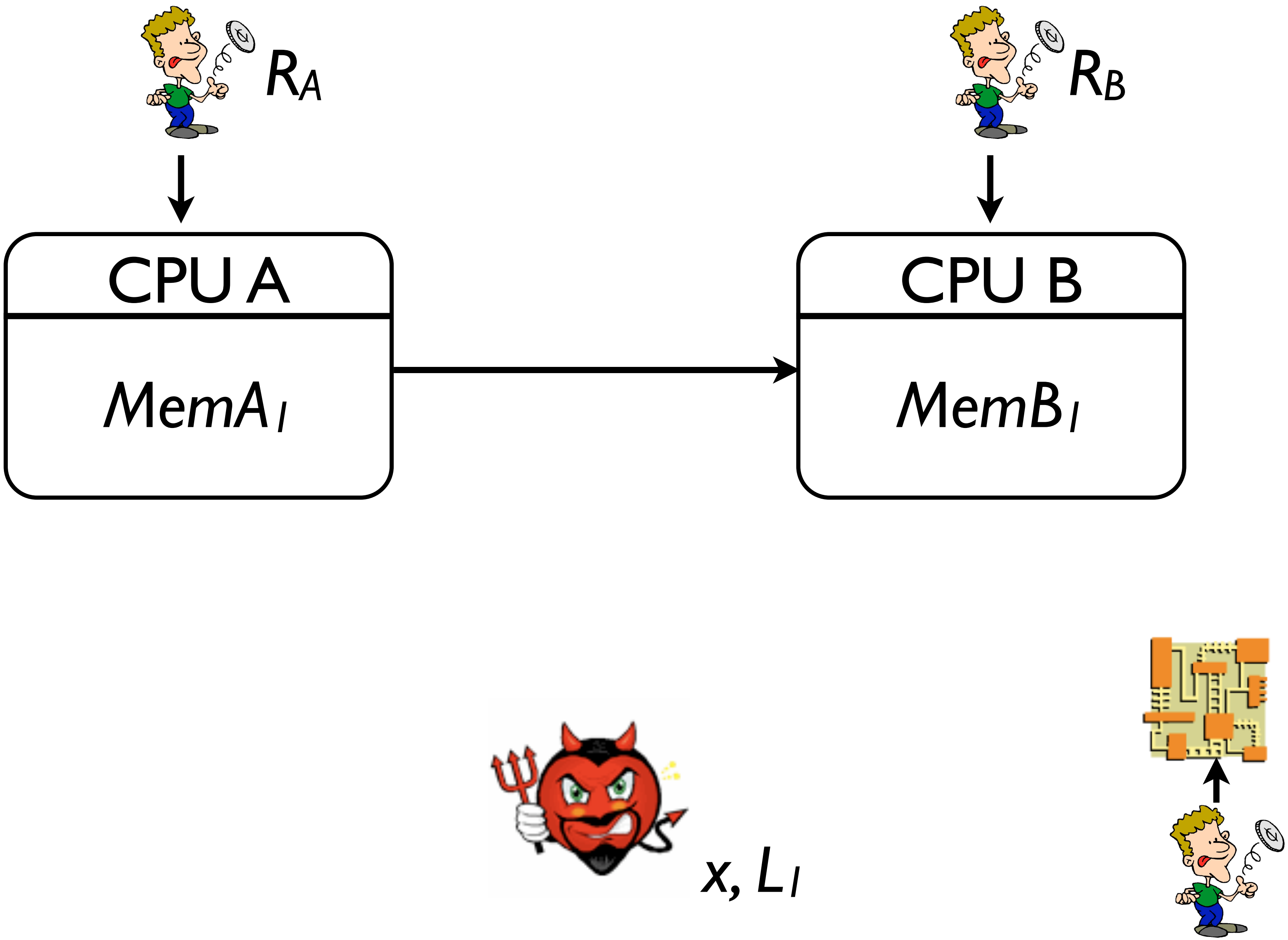

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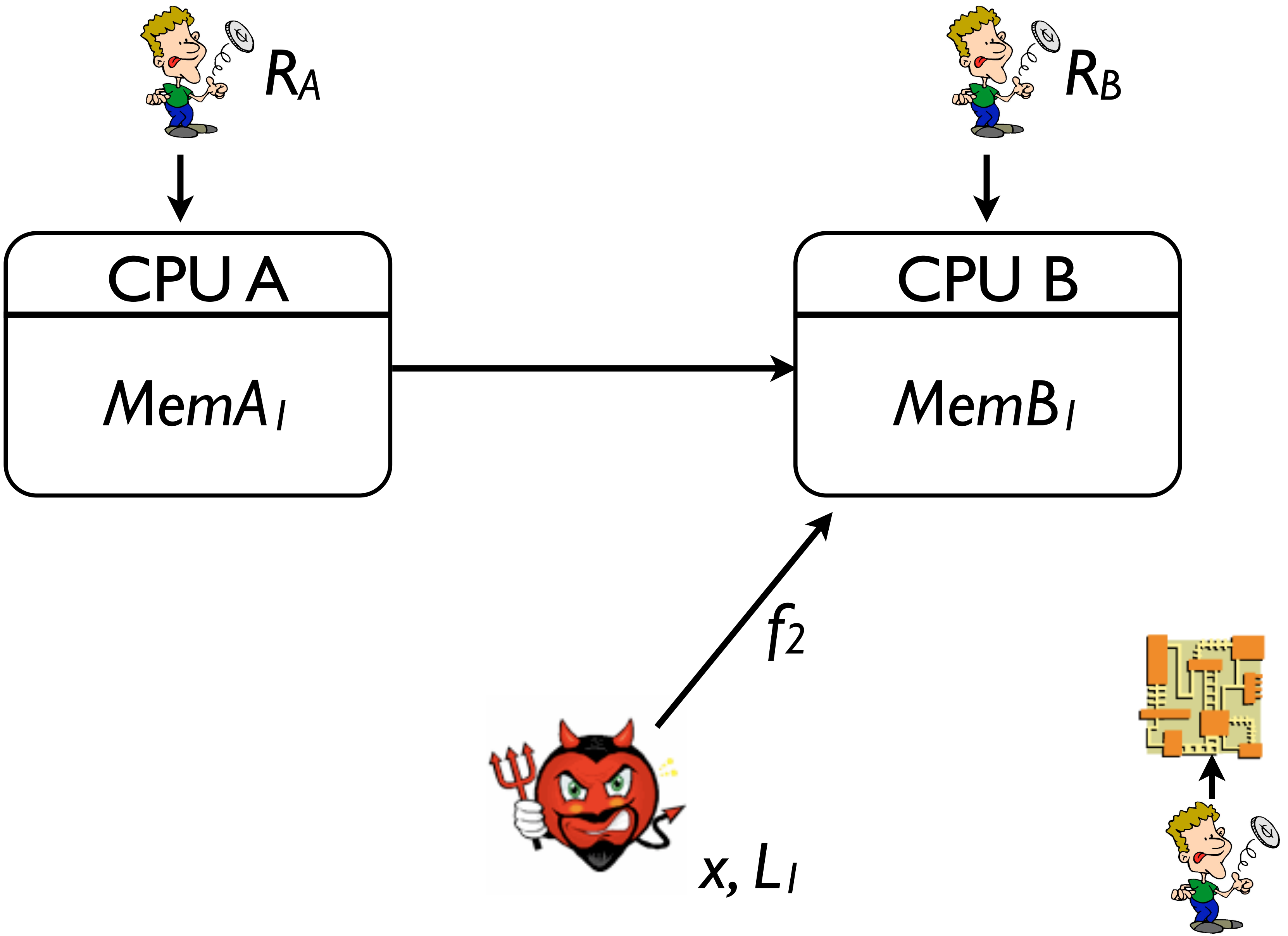

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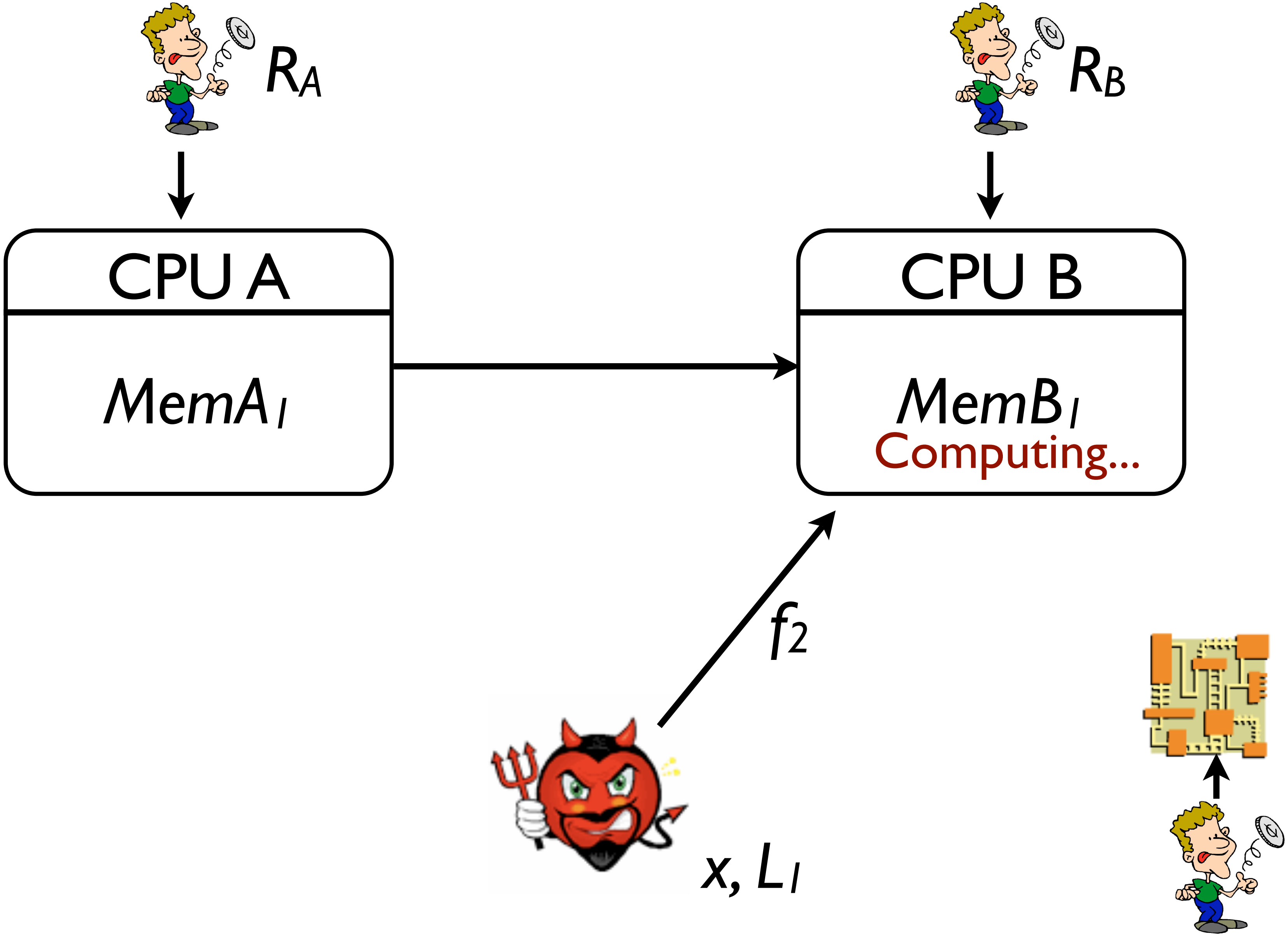

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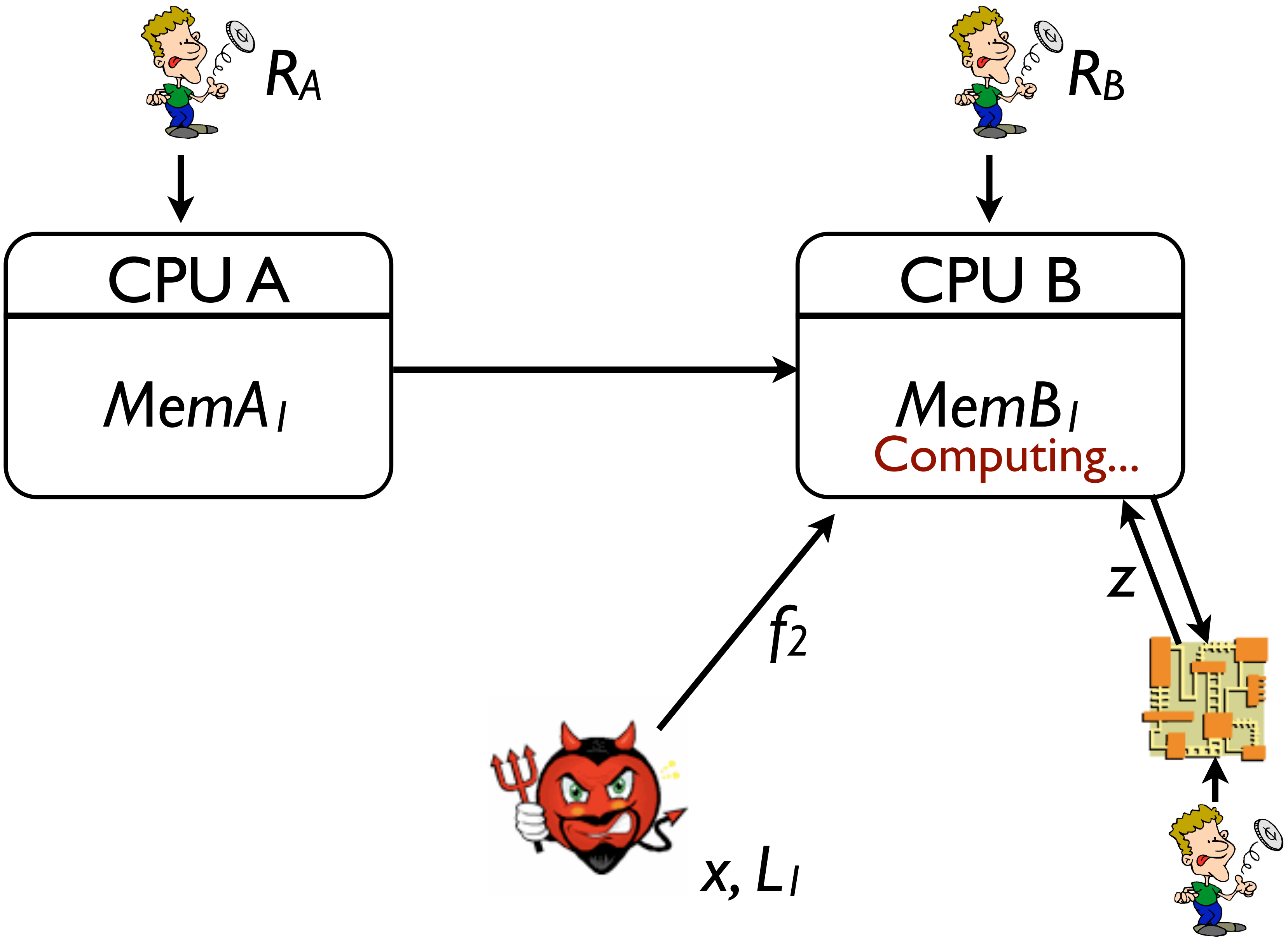

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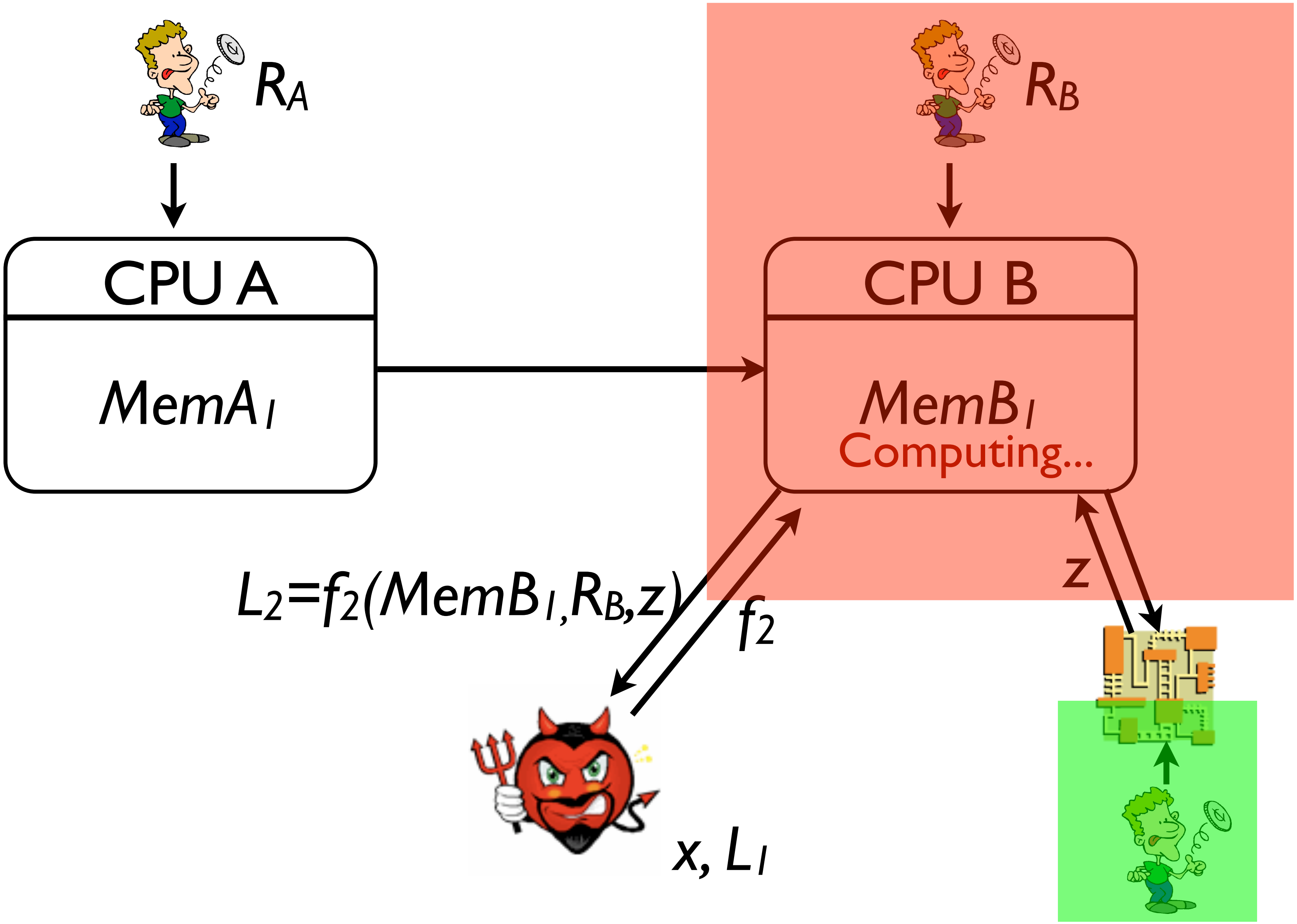

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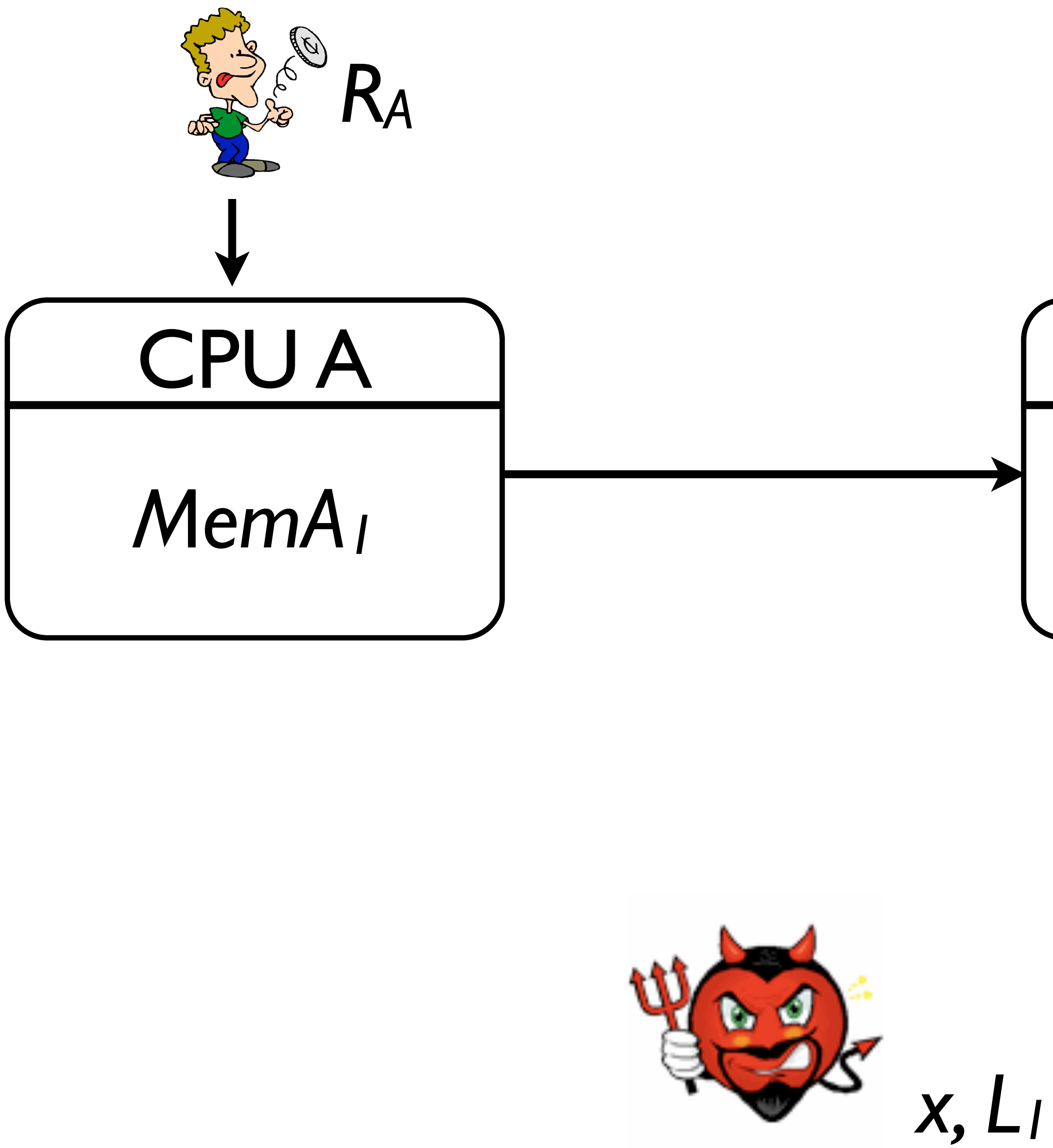
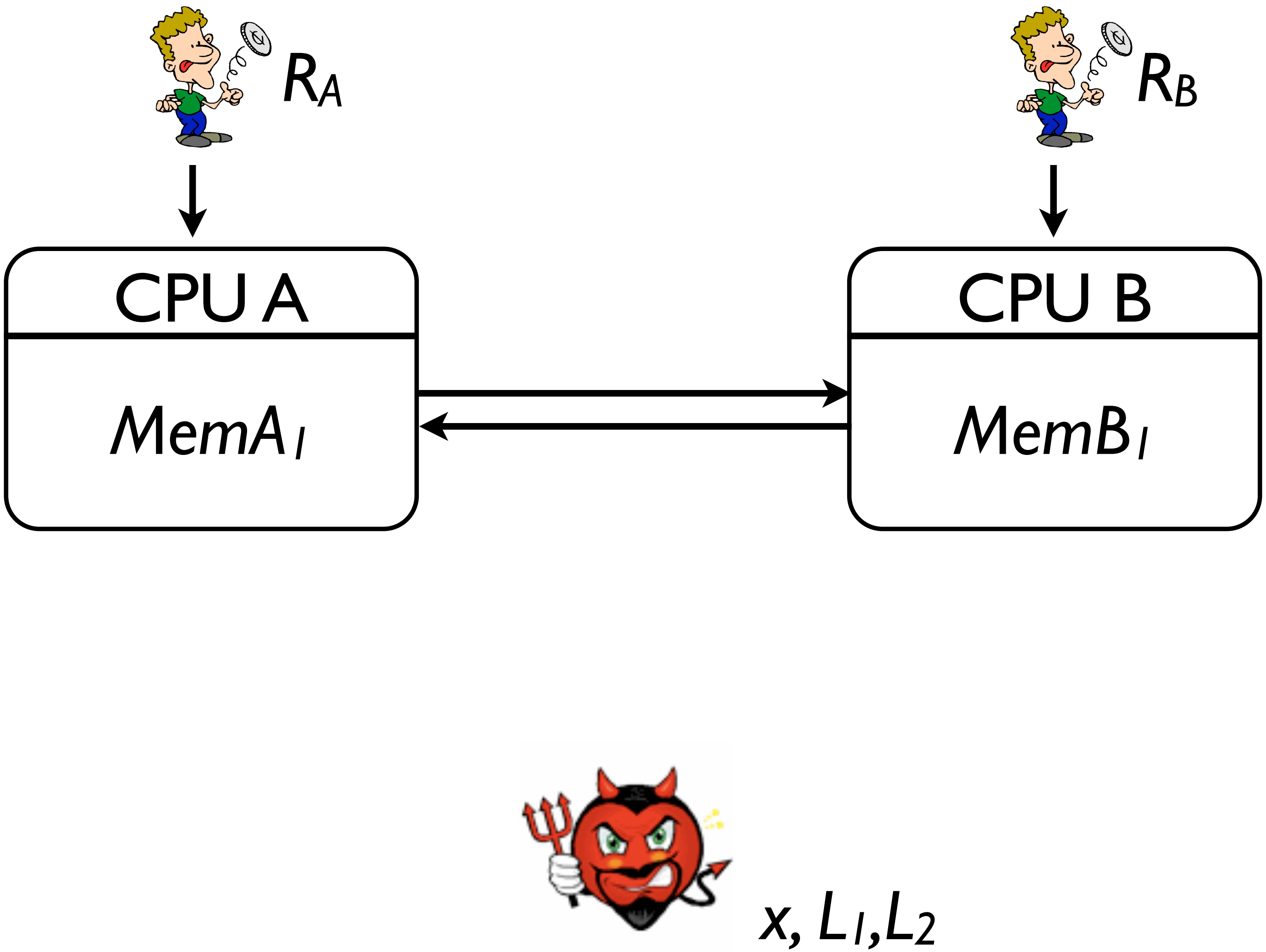


help

Leakage



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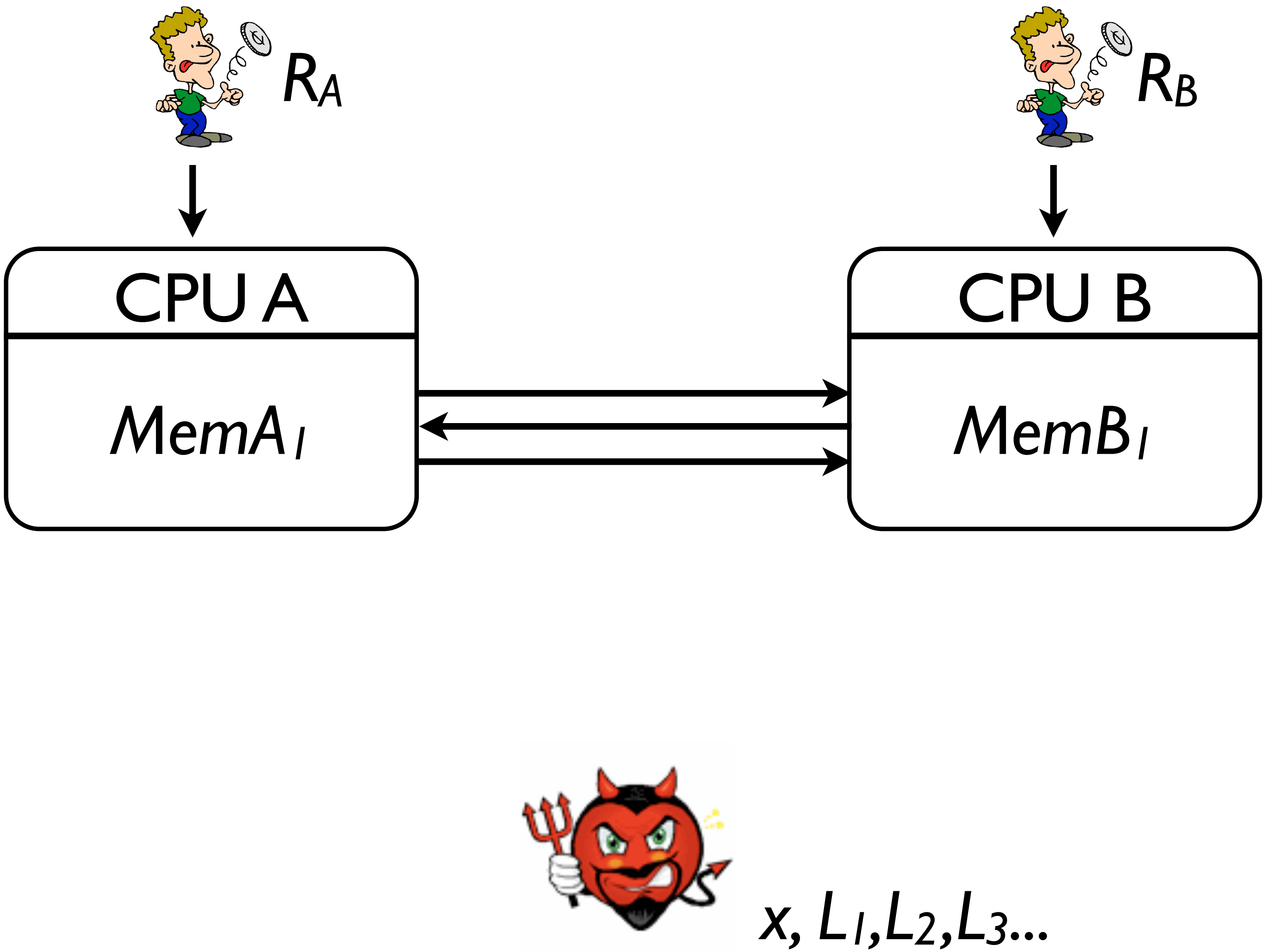

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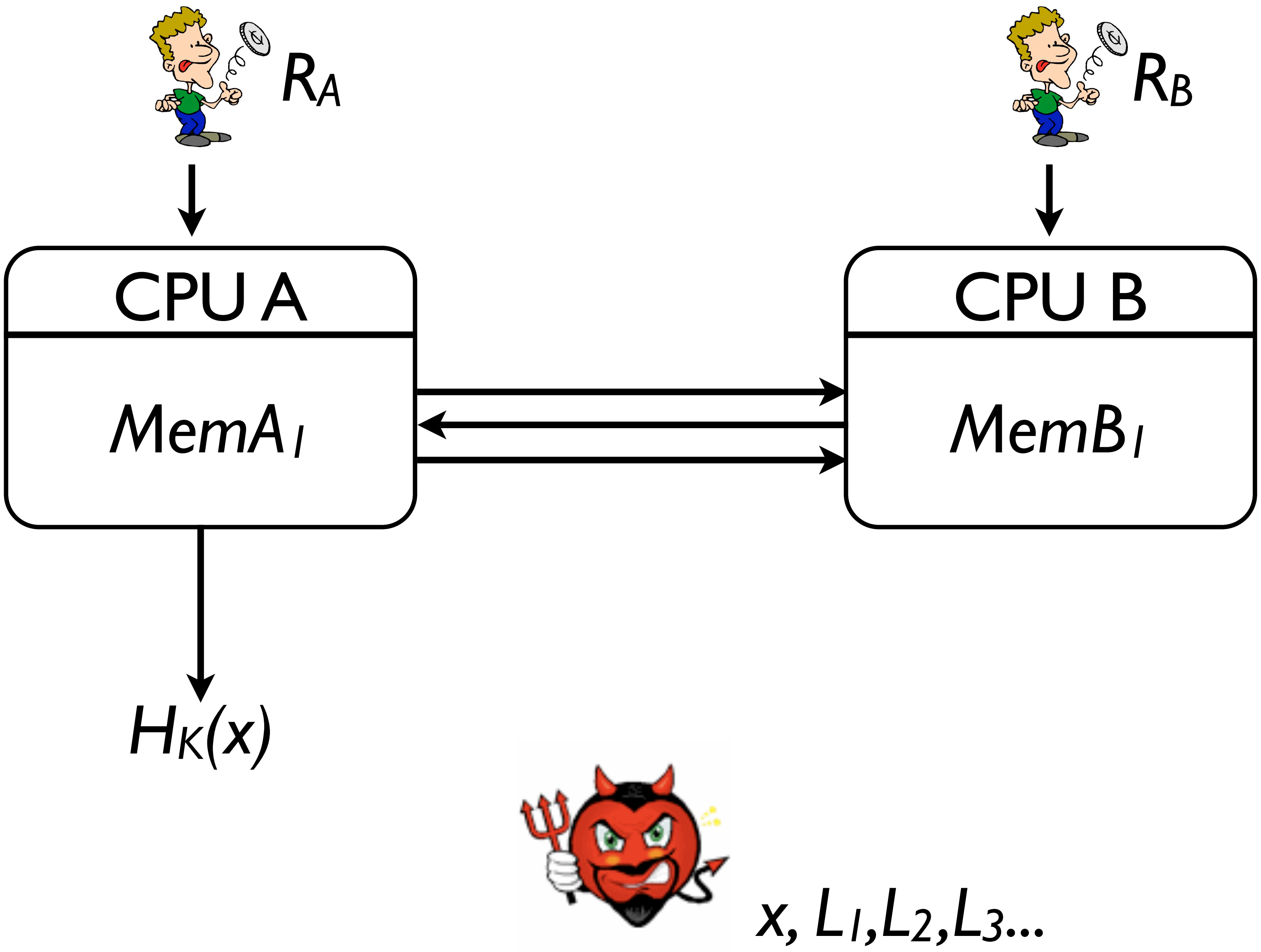

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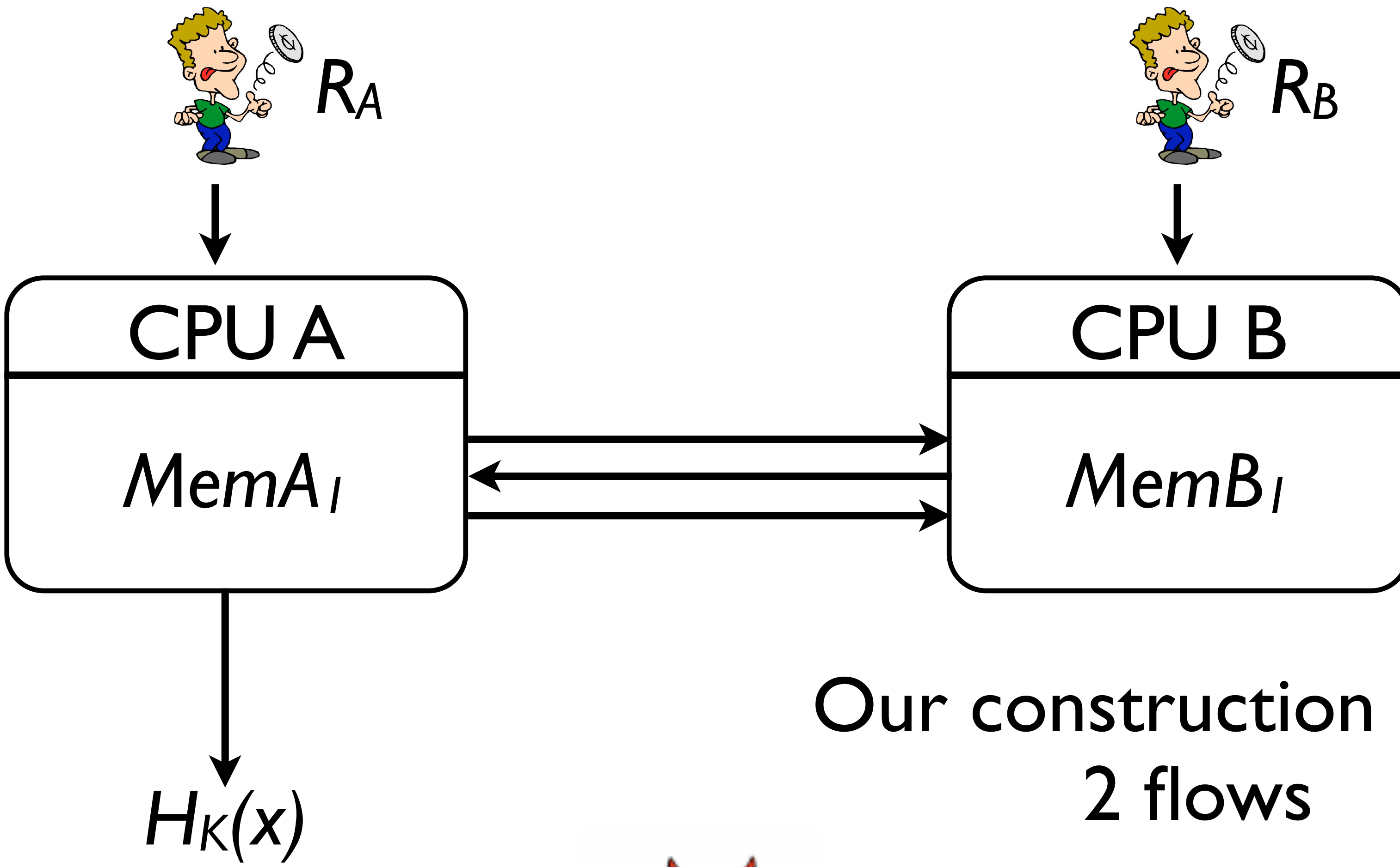


Our construction needs
2 flows

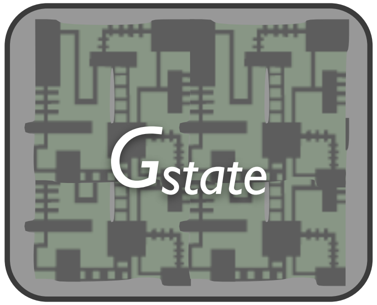
$x, L_1, L_2, L_3...$

help

Definition of Security

Definition of Security

Real World



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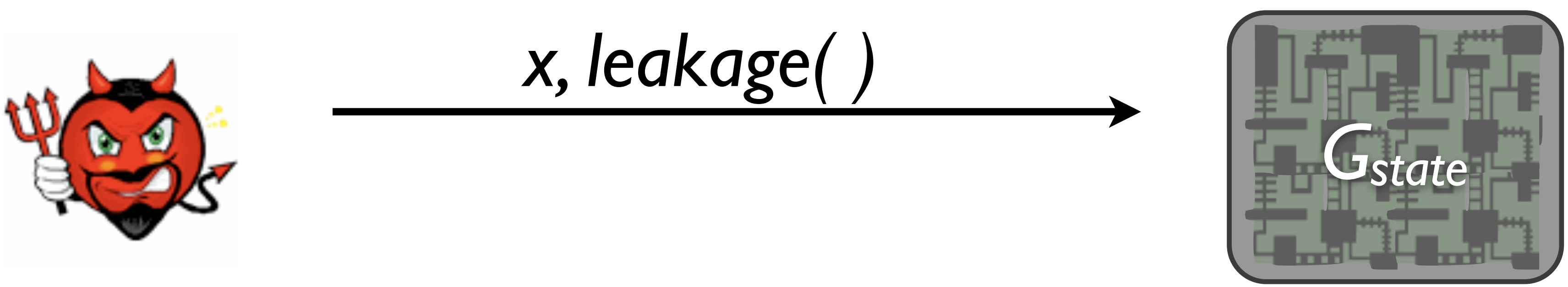
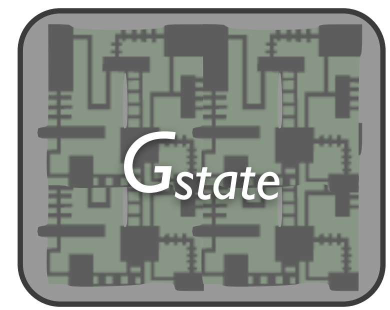


Definition of Security

Real World

x, leakage( )

$H_K(x)$, *leakage(state)*



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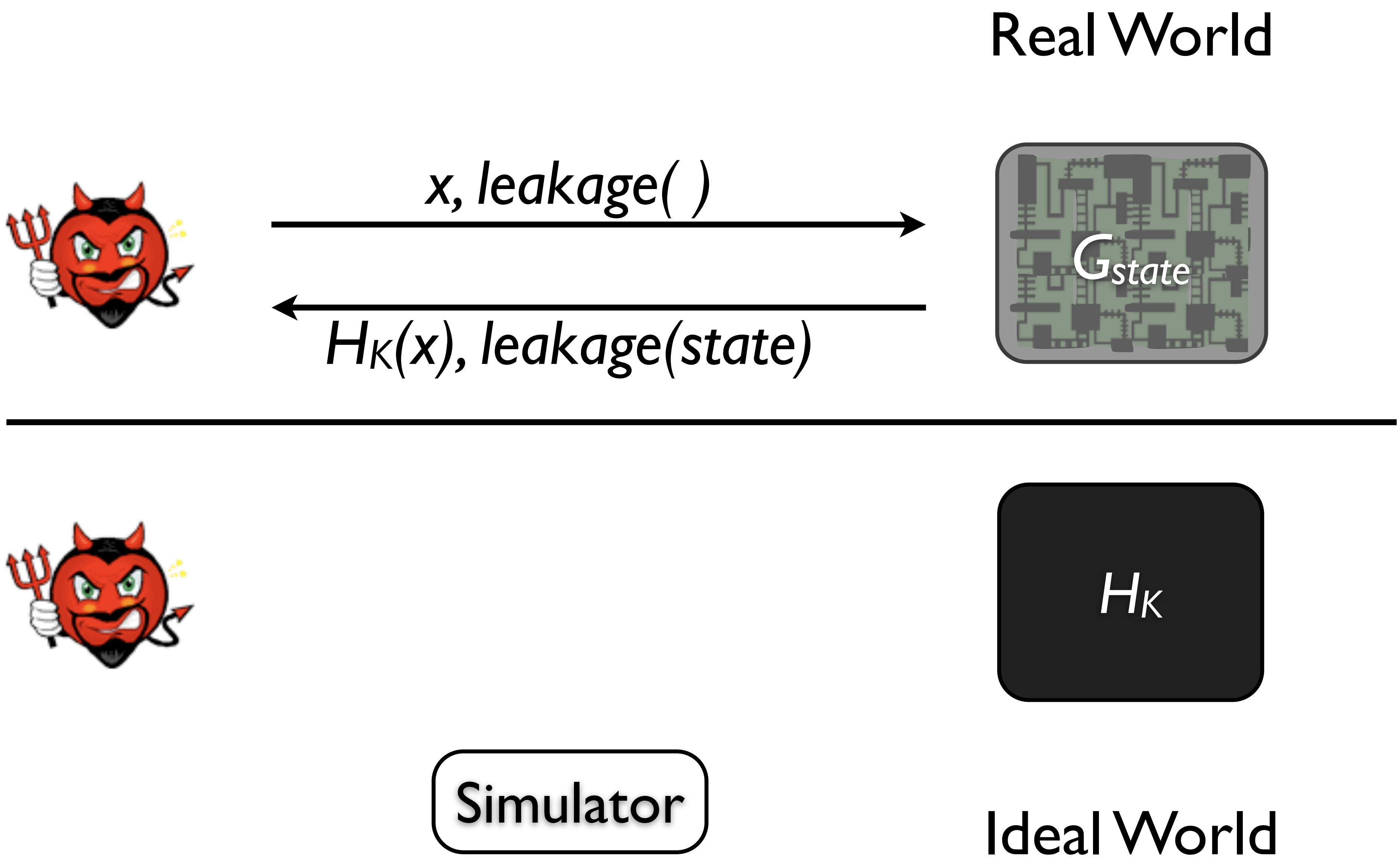

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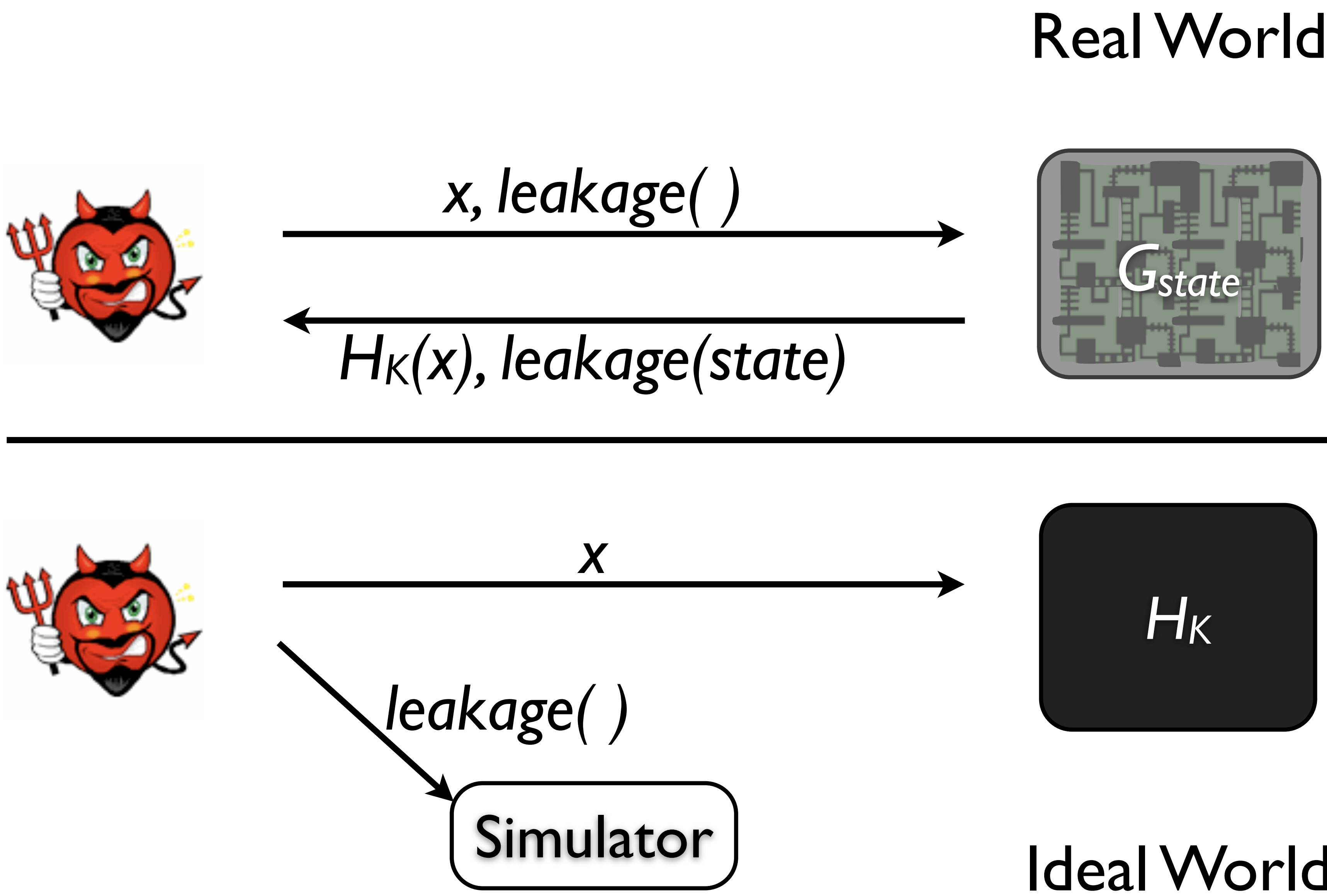

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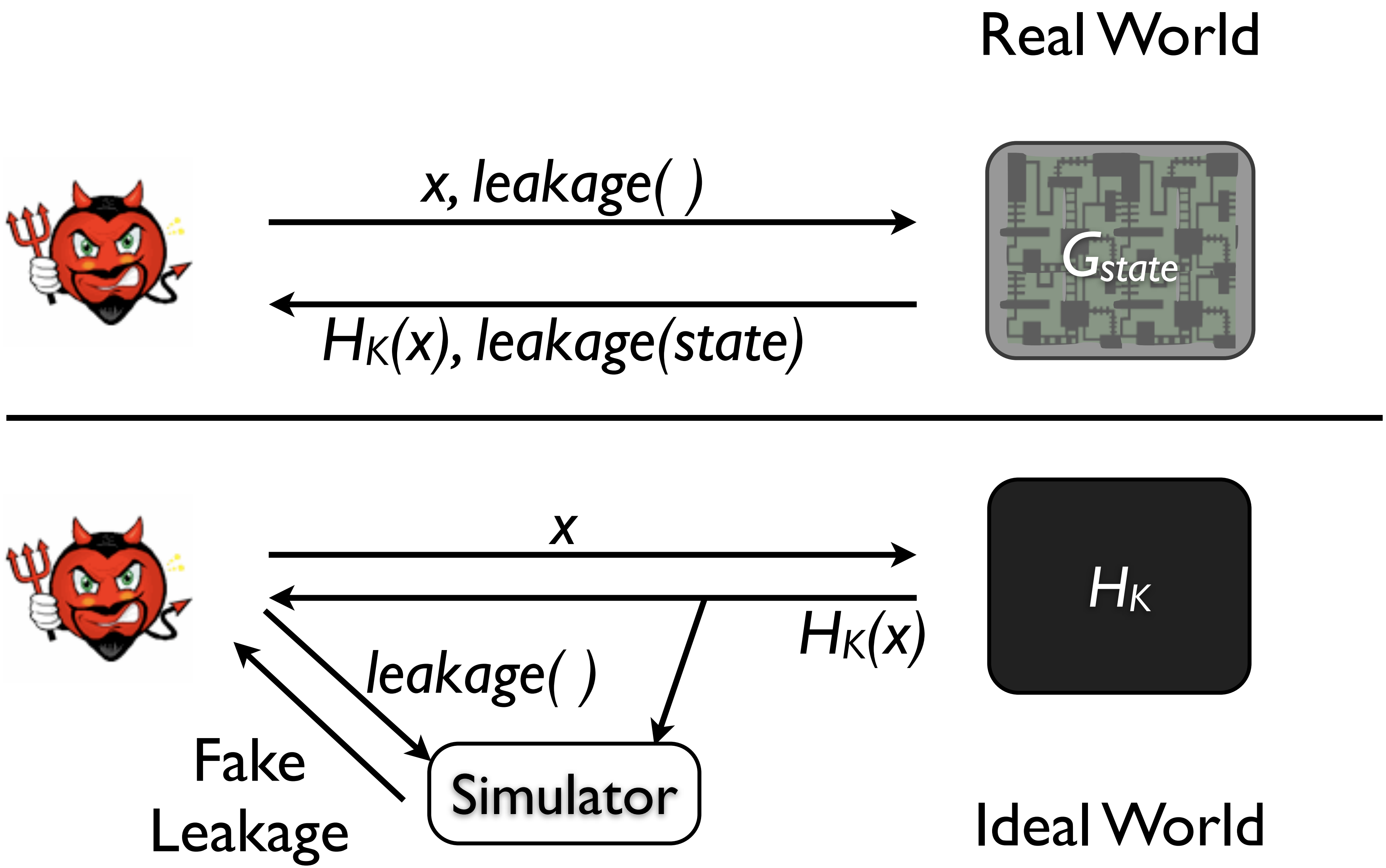


Main Tool

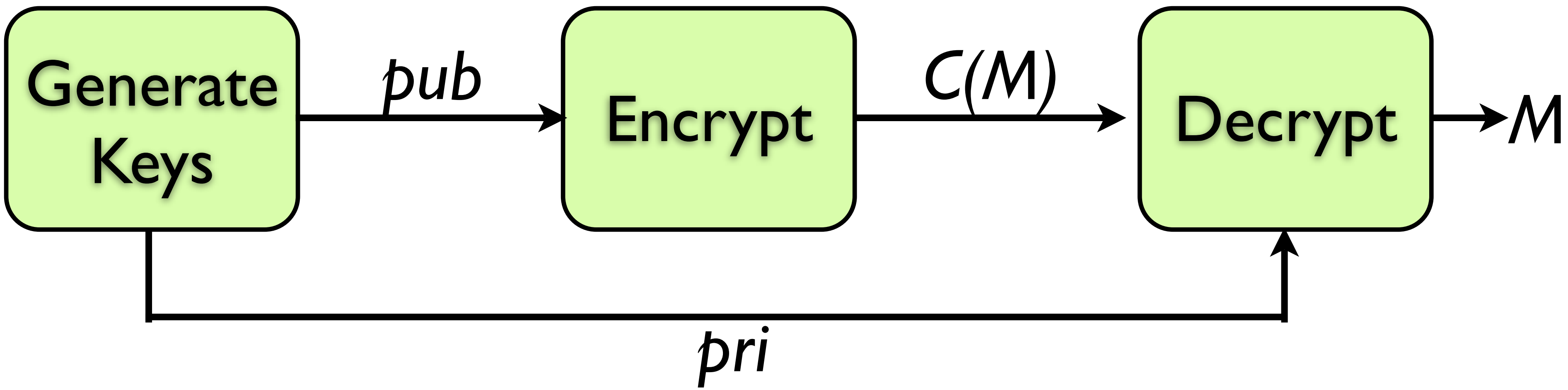
Fully Homomorphic Encryption (FHE)

First construction by Gentry at STOC 09
Based on Ideal Lattices

Other restricted constructions are known
[Boneh Goh Nissim 2005]
[Melchor Gaborit Herranz 2008]

Homomorphic Encryption

Regular Public Key Encryption



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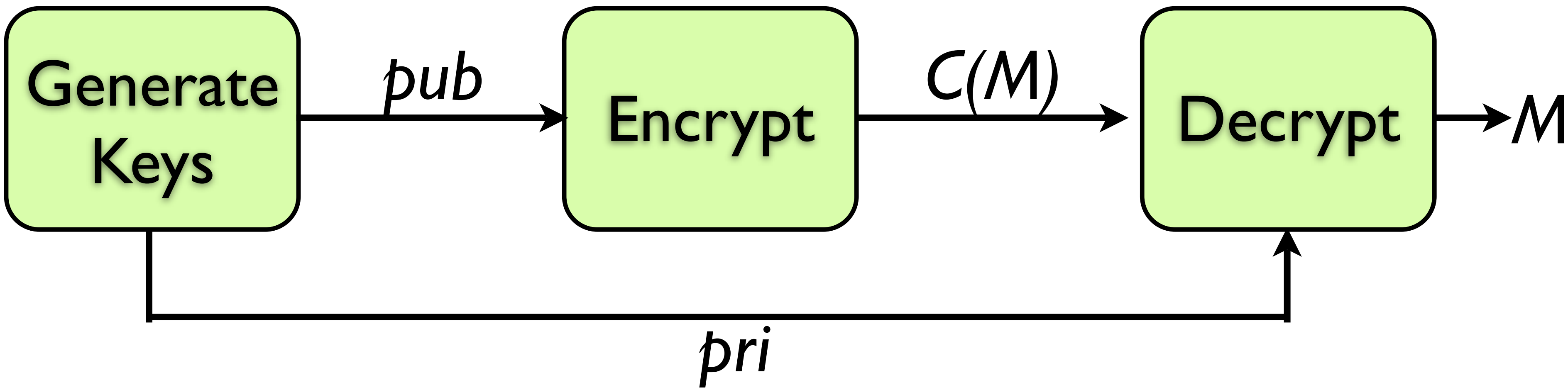

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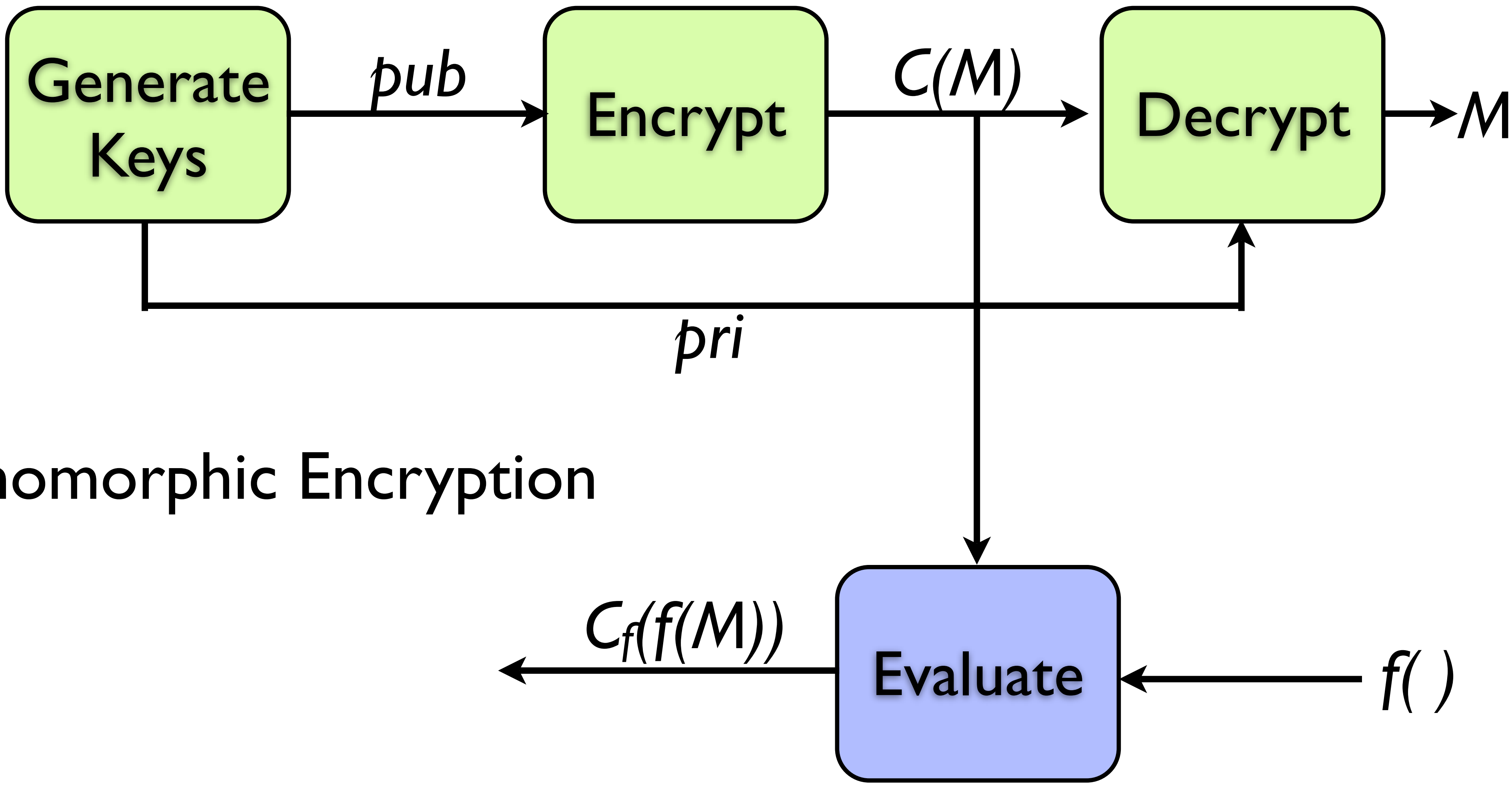

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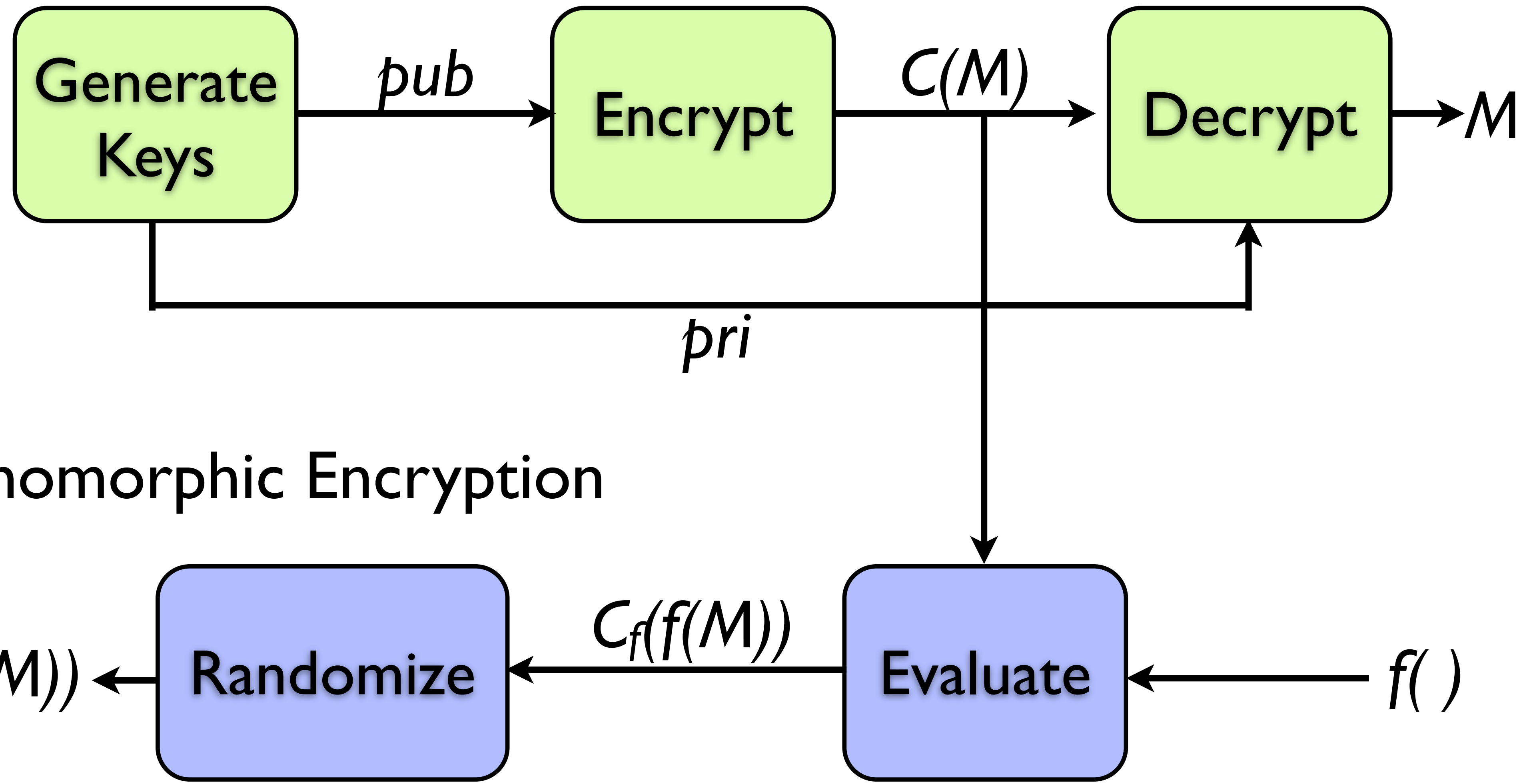

Homomorphic Encryption

Our Construction

Initialization(K):

Generate keys *pri*,*pub*

$C(K) = Enc_{pub}(K)$

Our Construction

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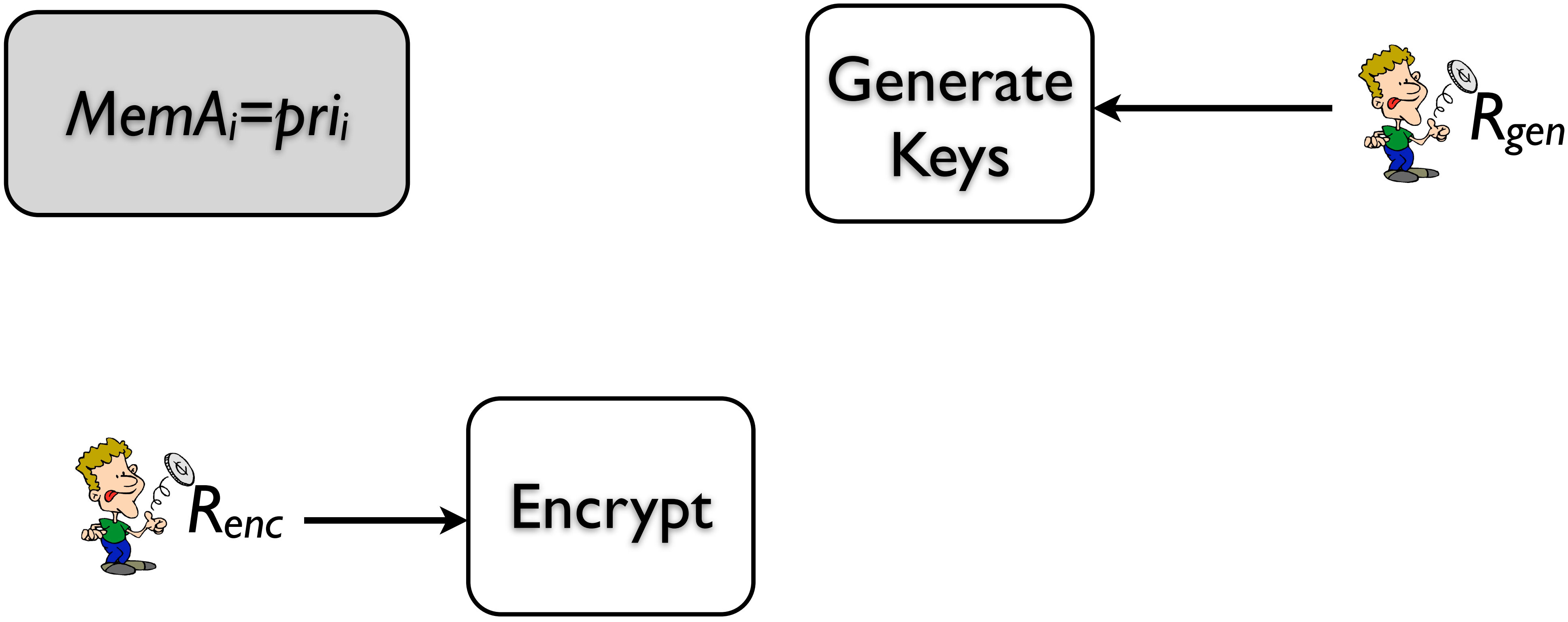
Generate keys pri,pub

$C(K) = Enc_{pub}(K)$

First Attempt

Step 1: CPU A



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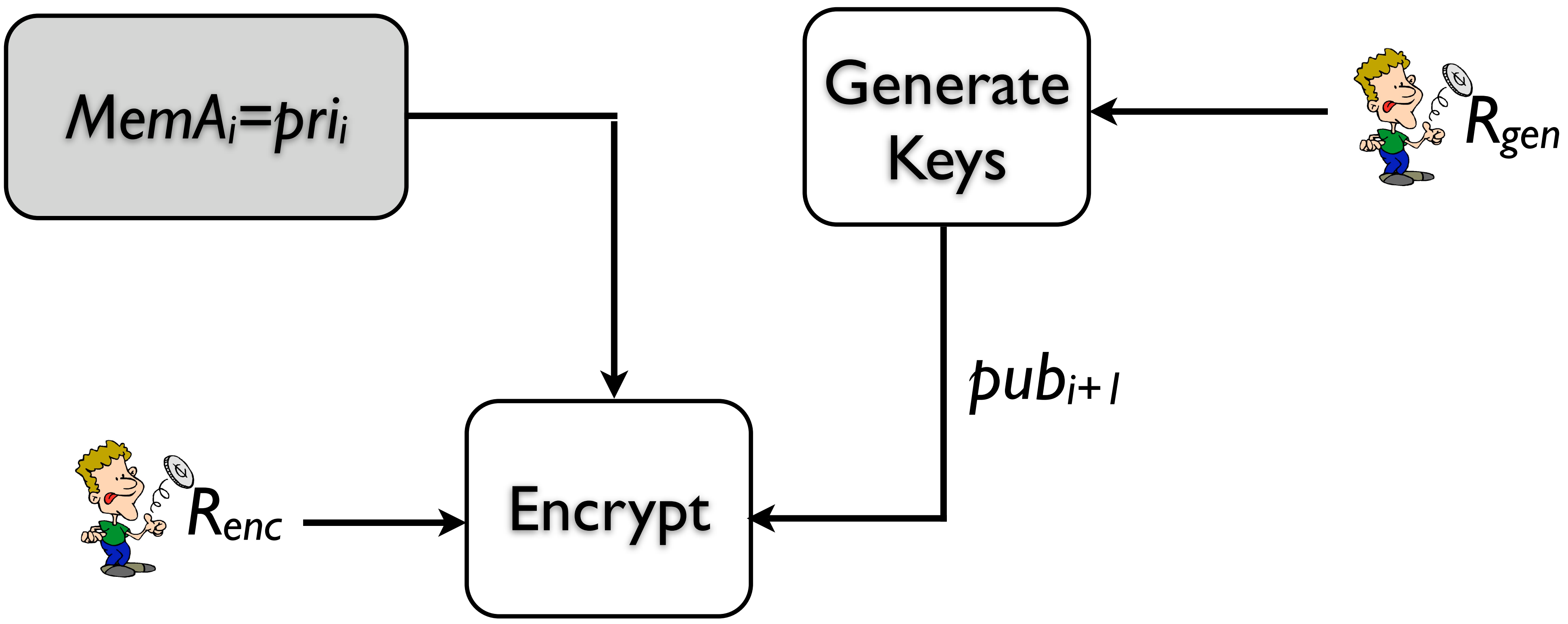

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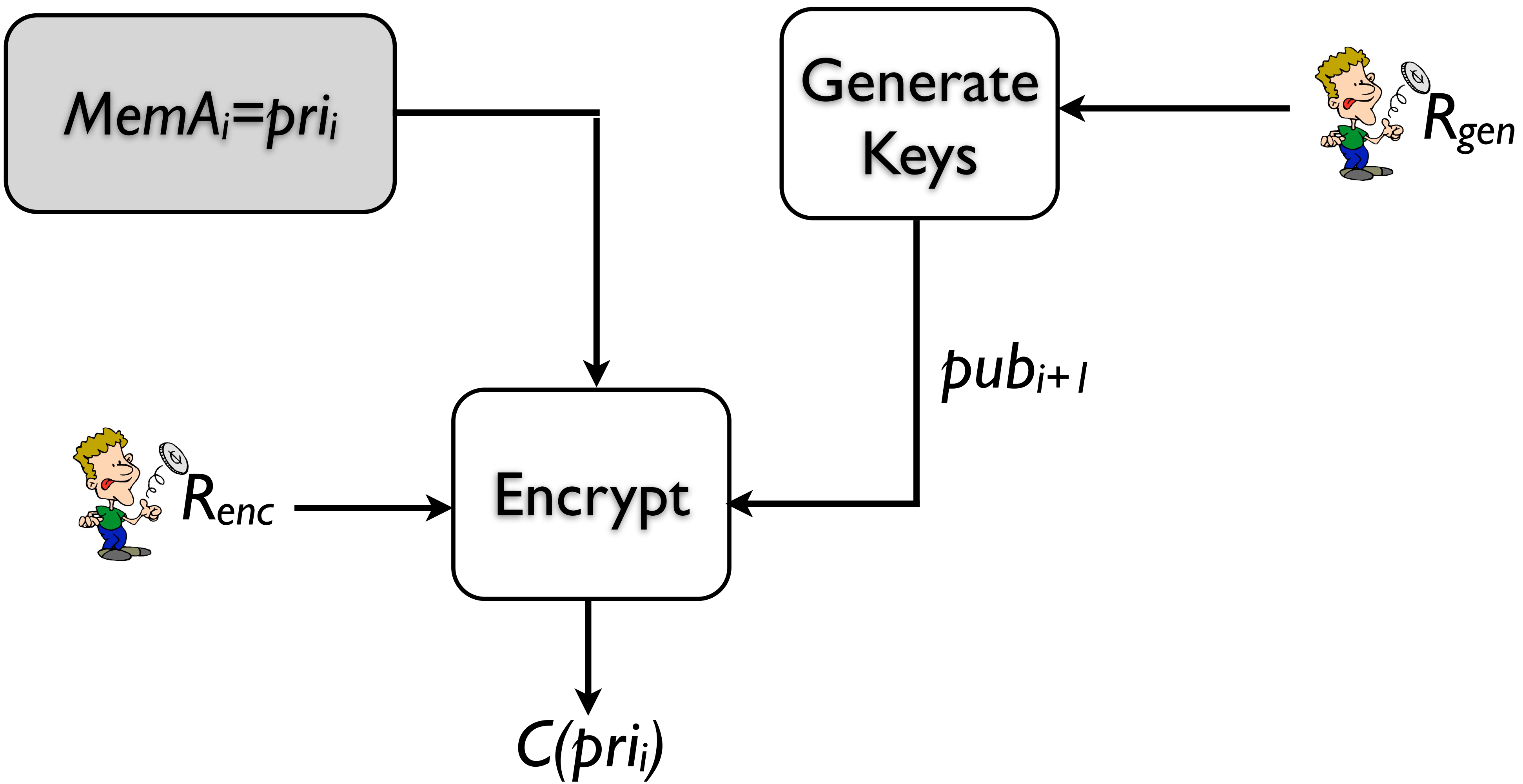

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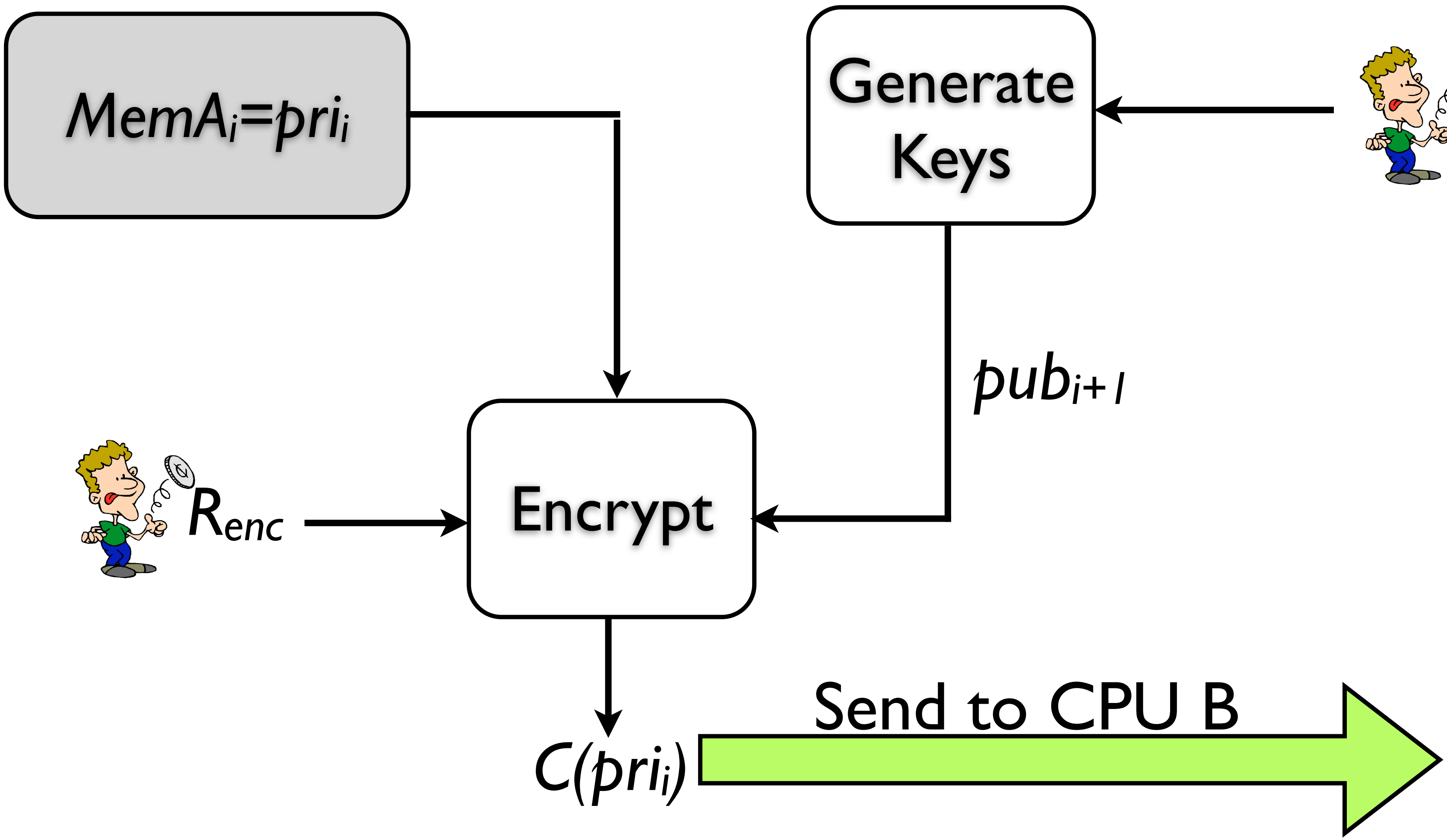

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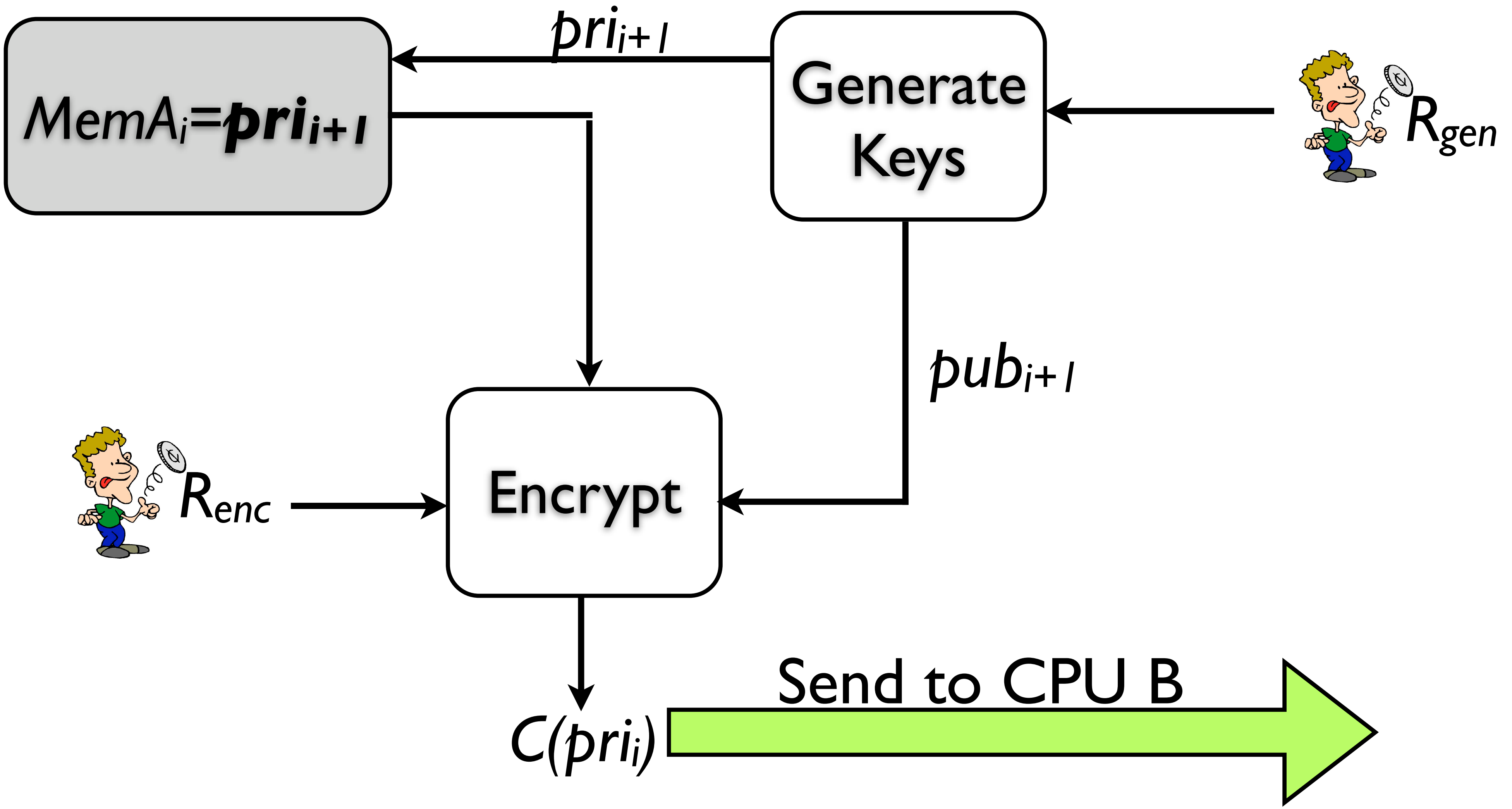

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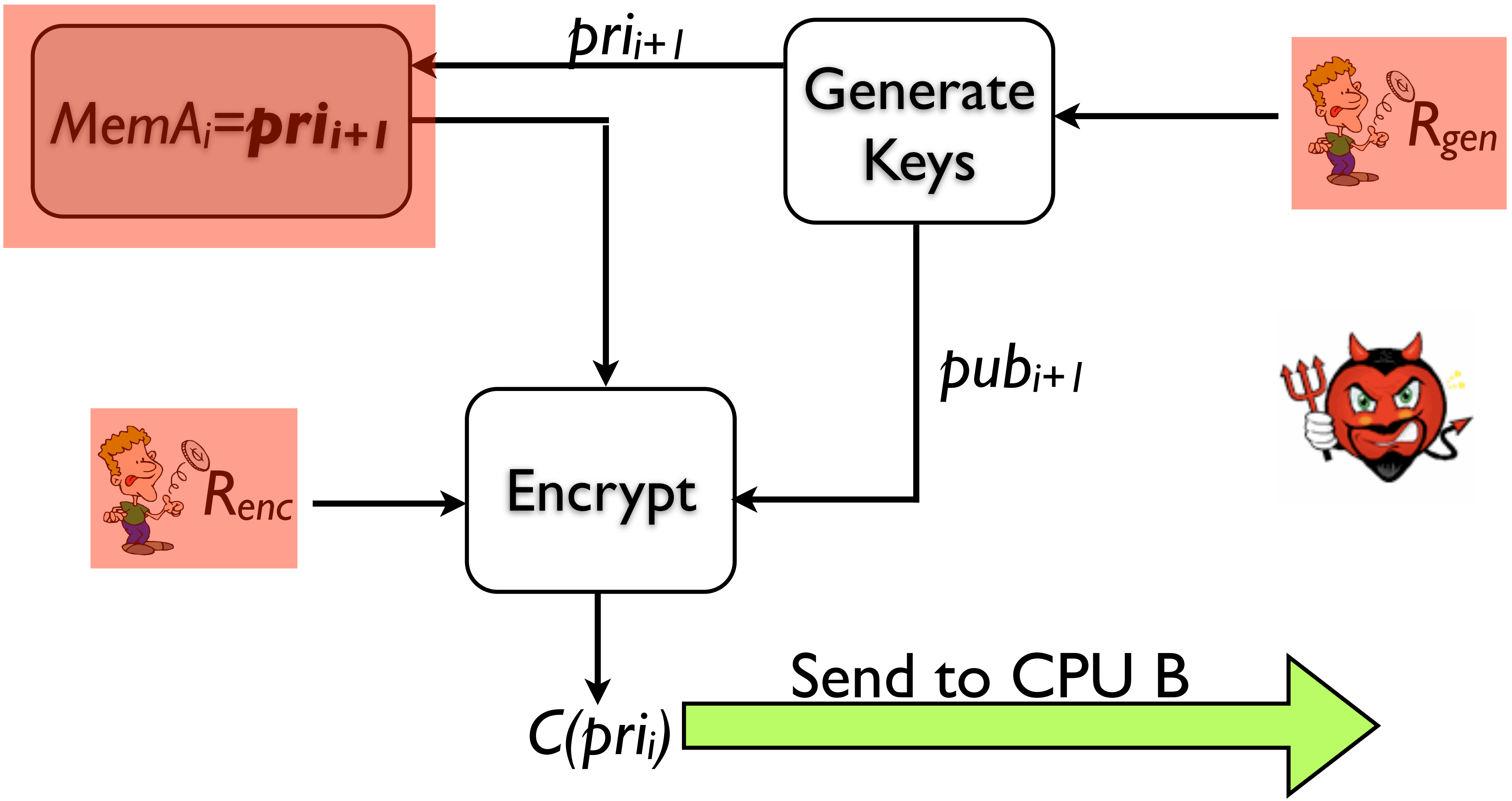


First Attempt

Step 2: CPU B

Input: *x*

$C_{i+1}(pri_i)$

Evaluate relative to pub_{i+1}

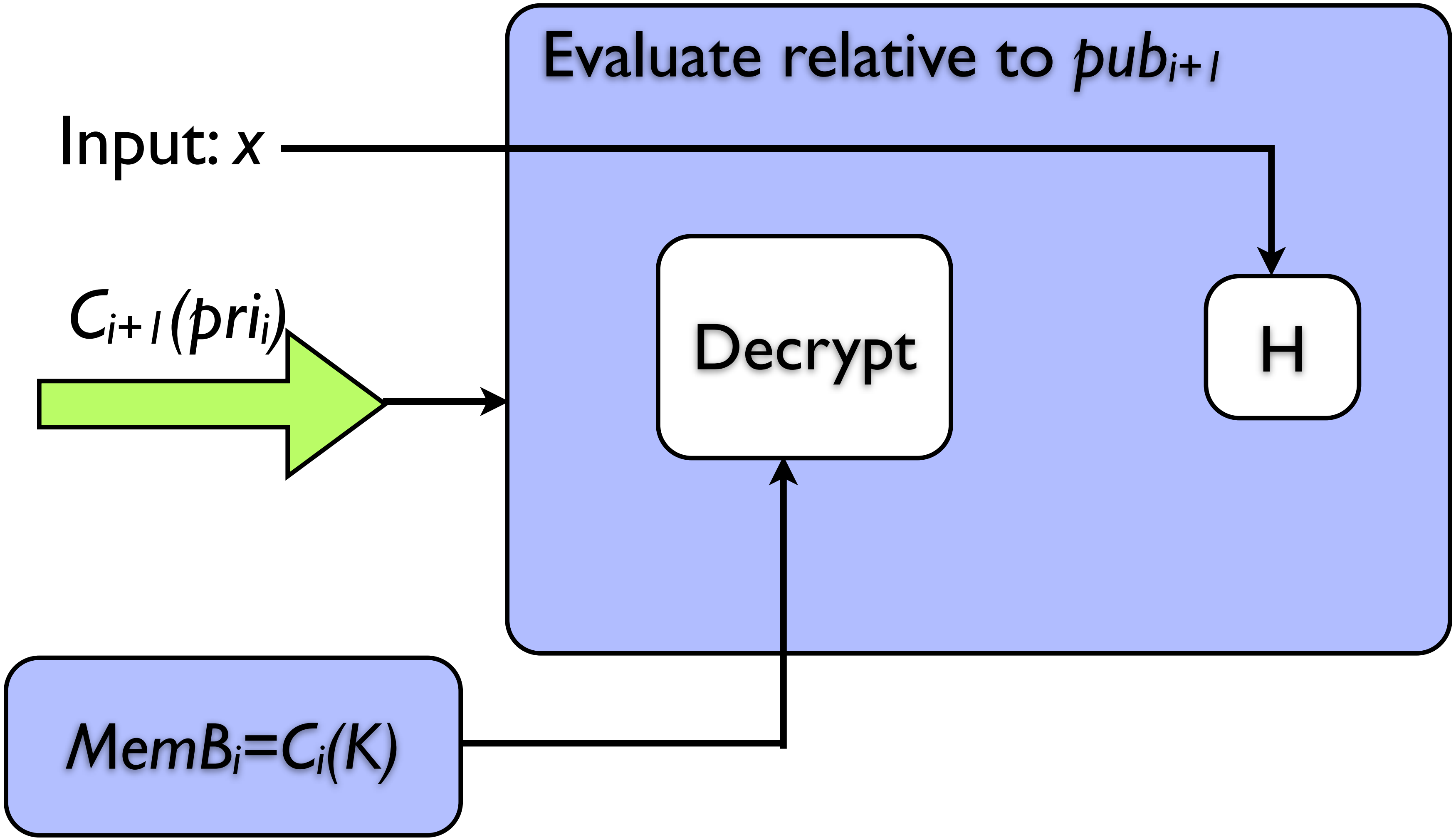
Decrypt

H

$MemB_i=C_i(K)$

First Attempt

Step 2: CPU B



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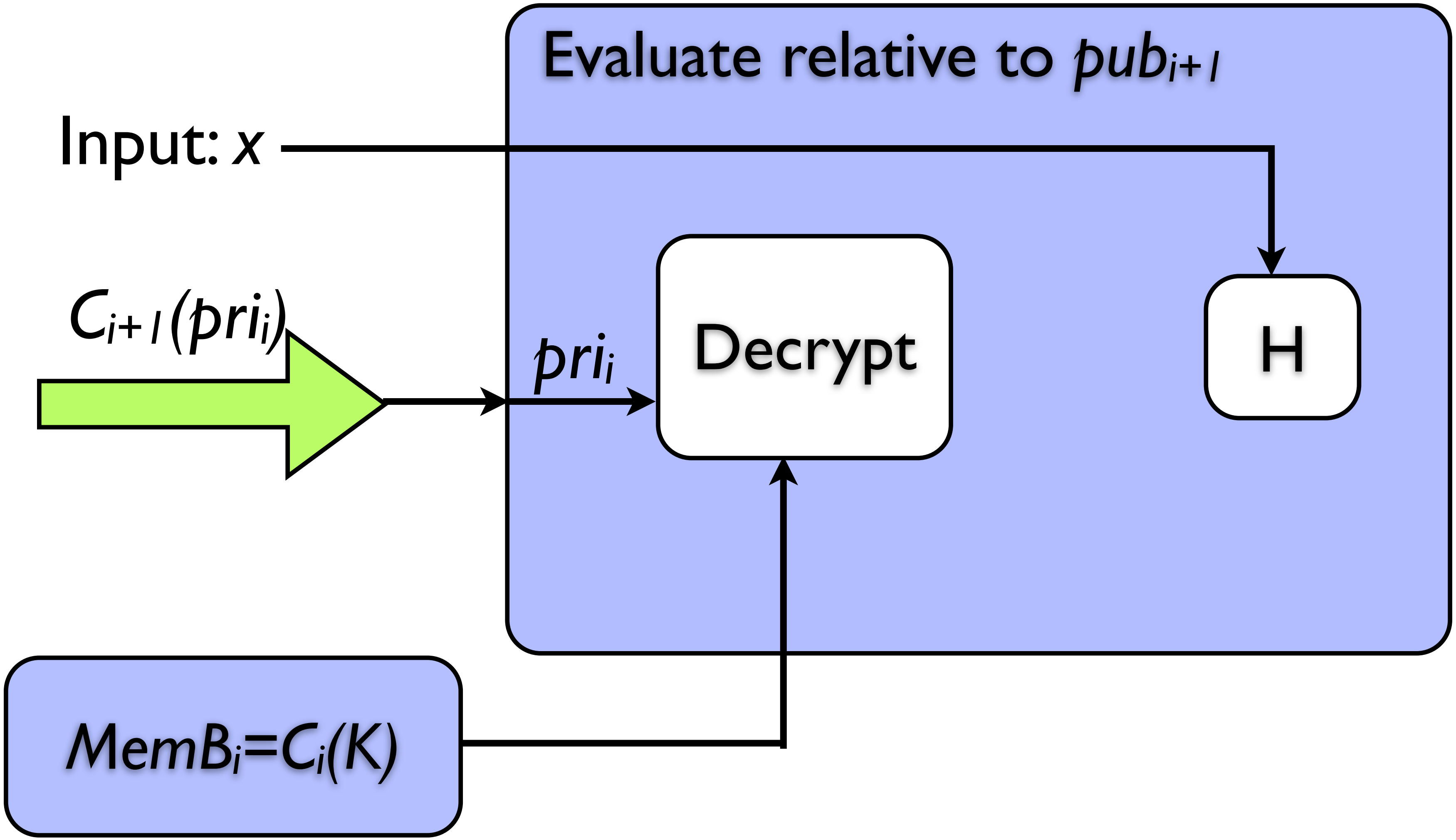

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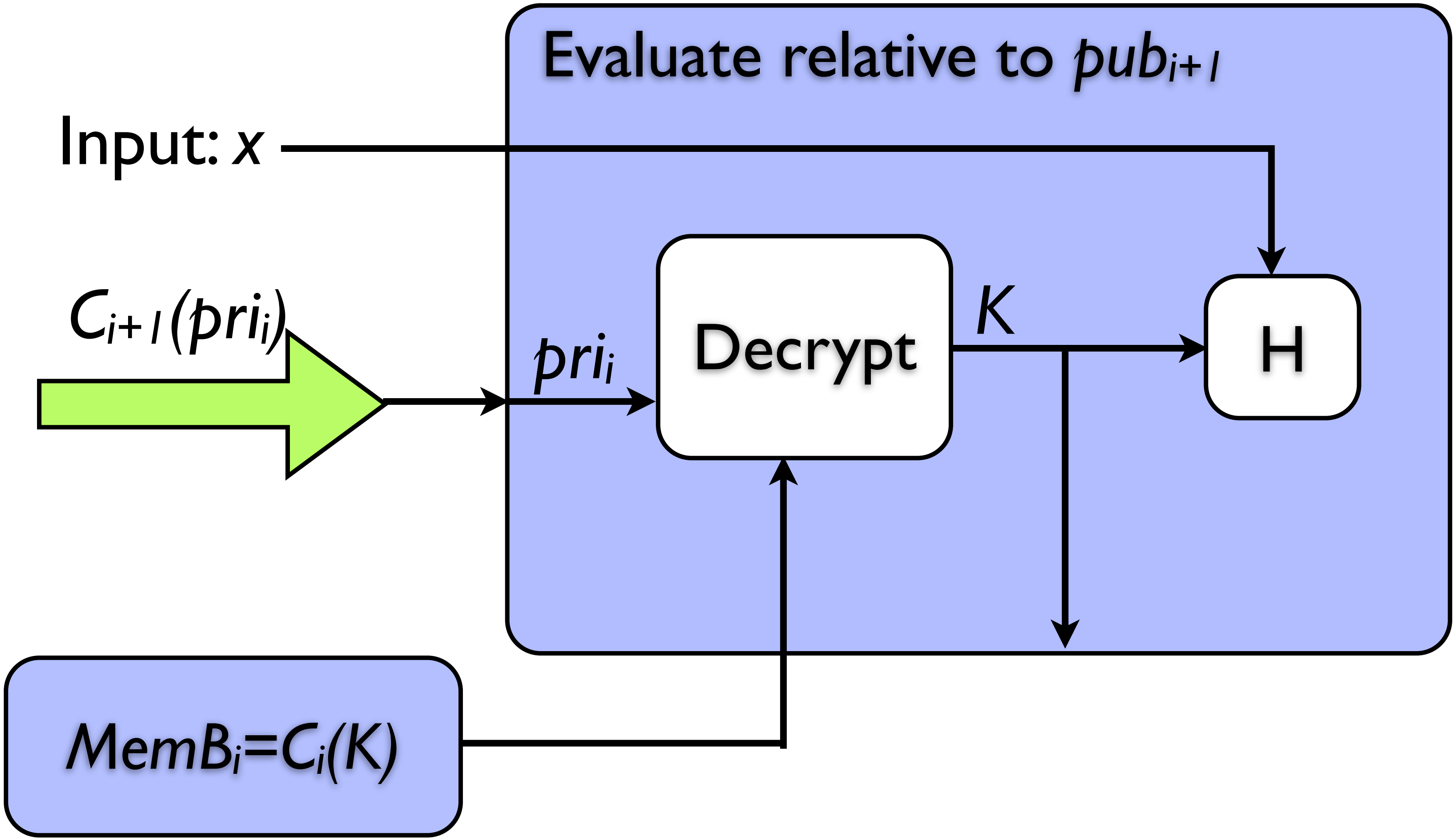

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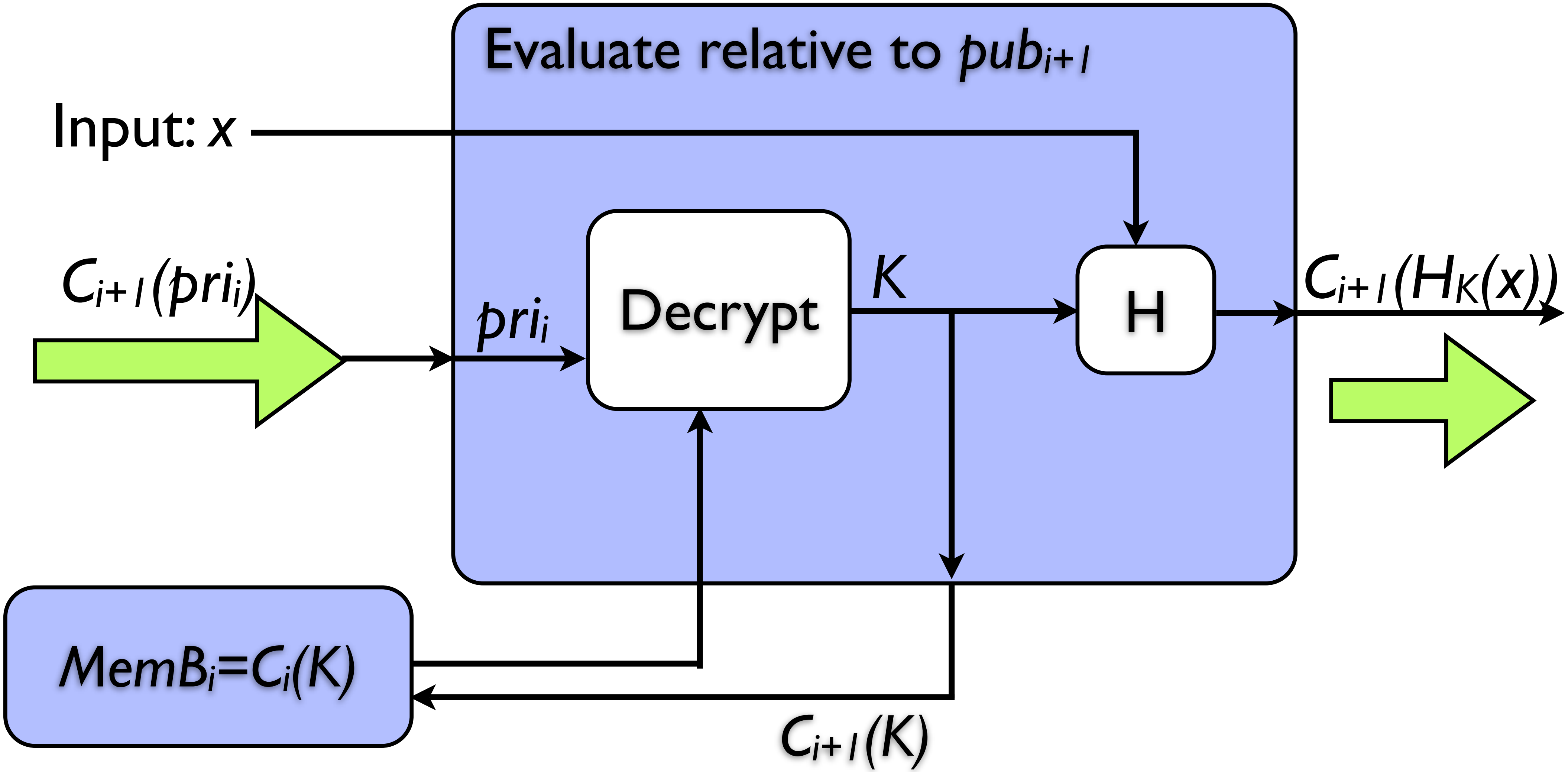
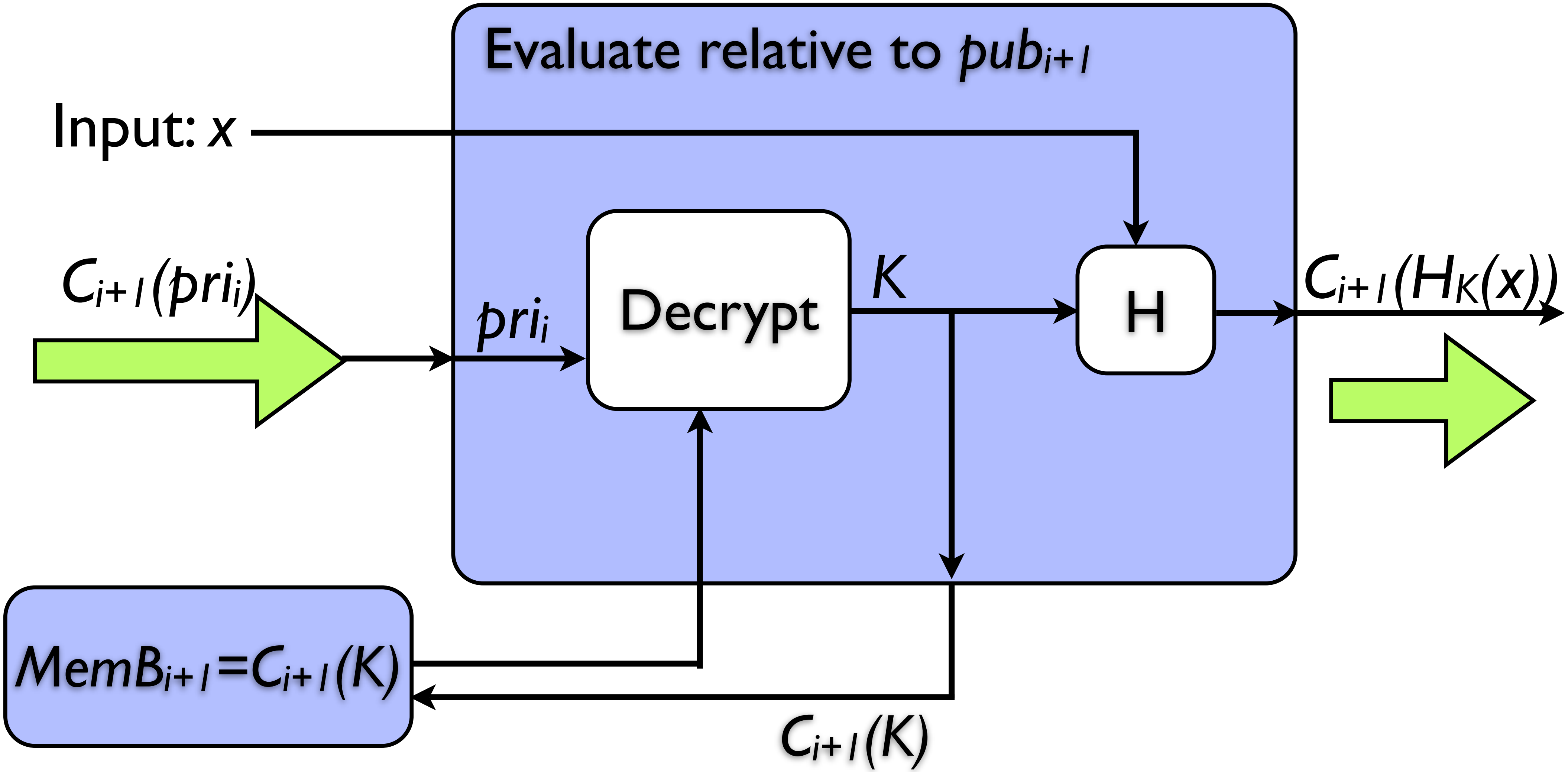
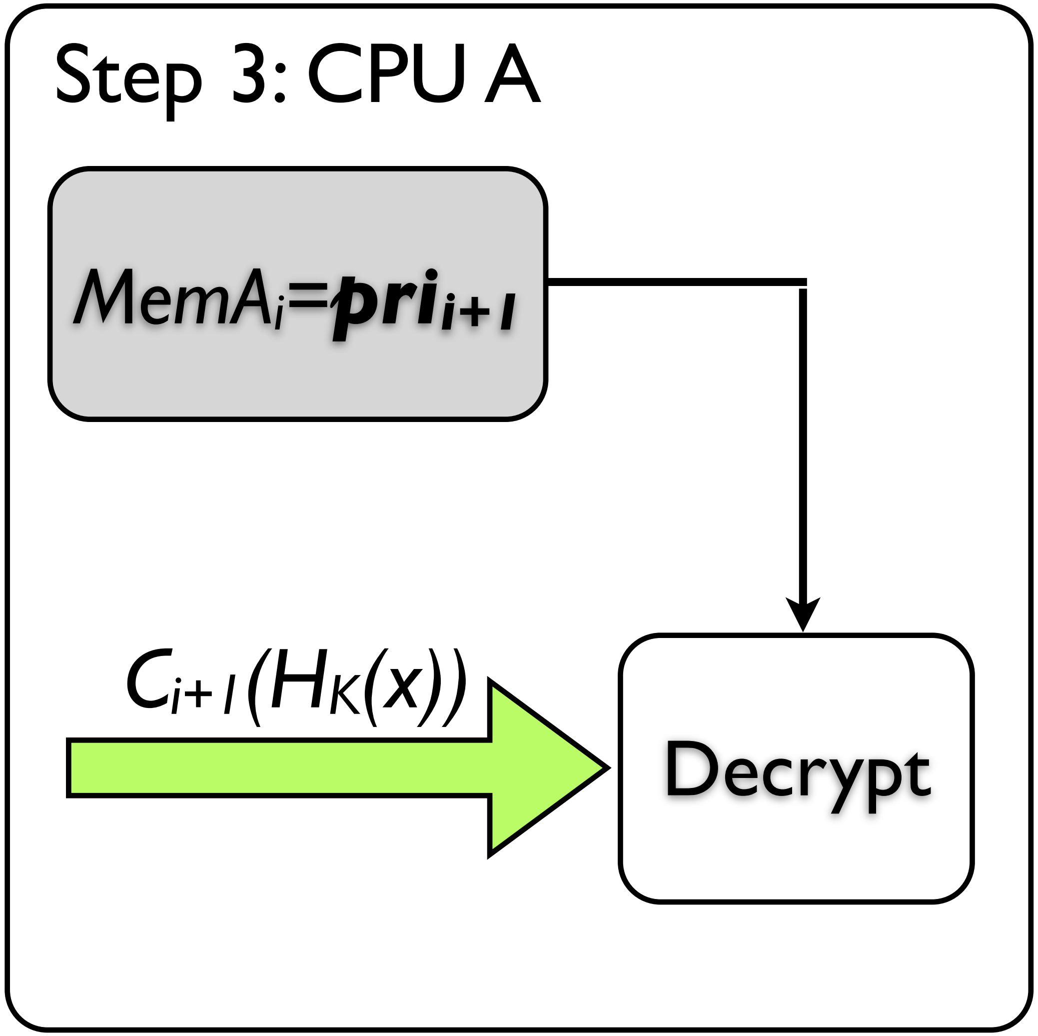


First Attempt

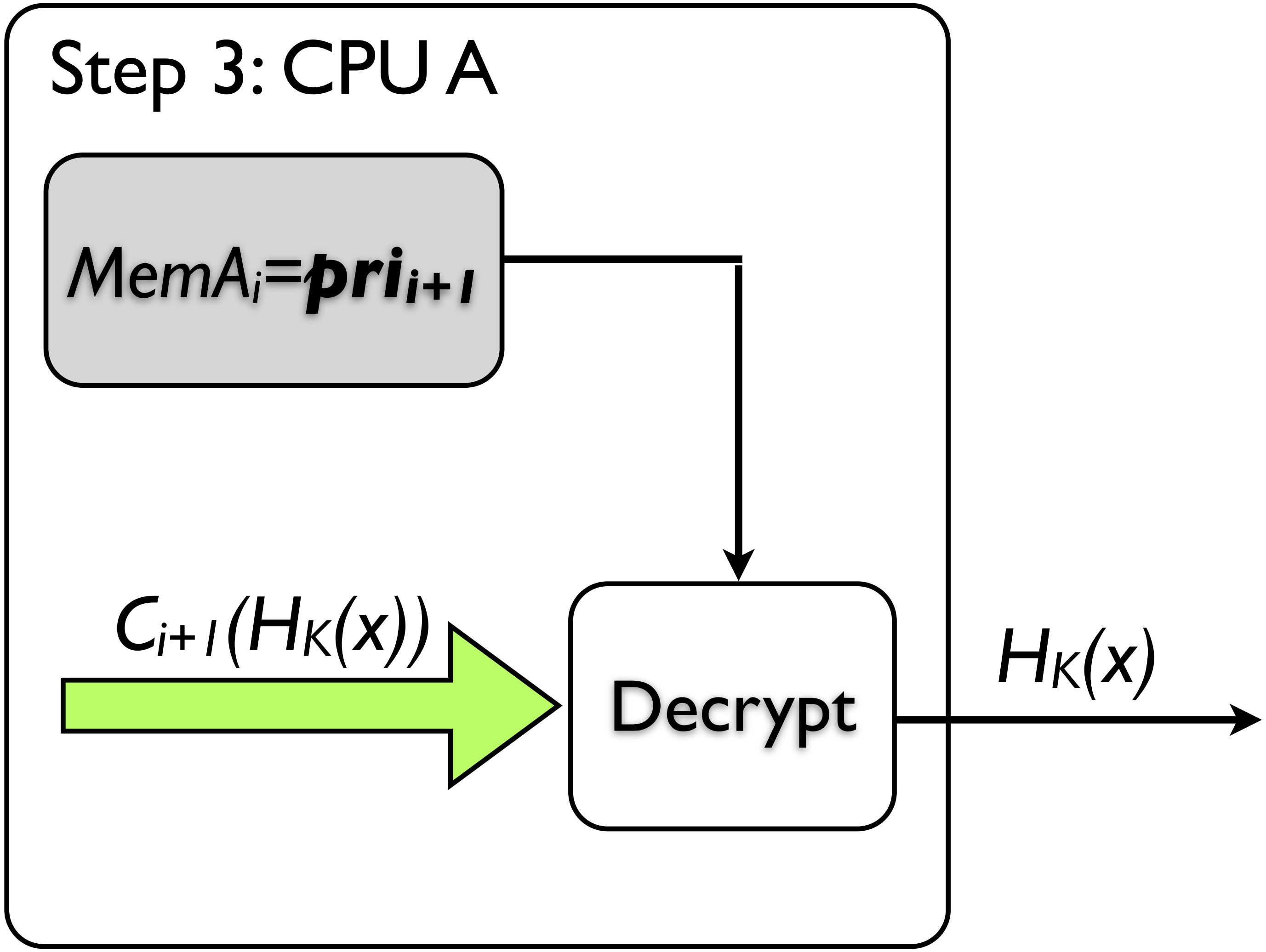
Step 2: CPU B



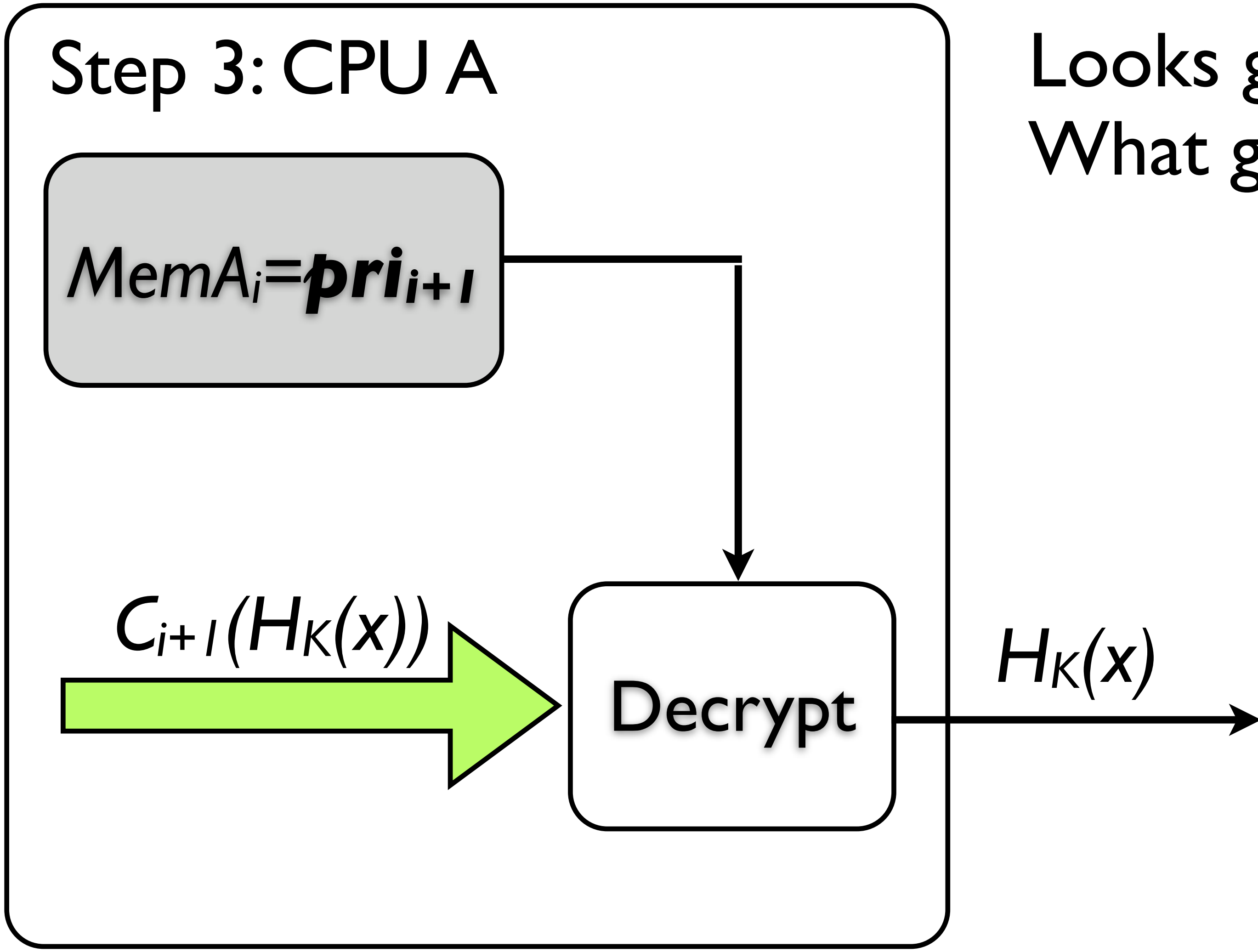
First Attempt



First Attempt

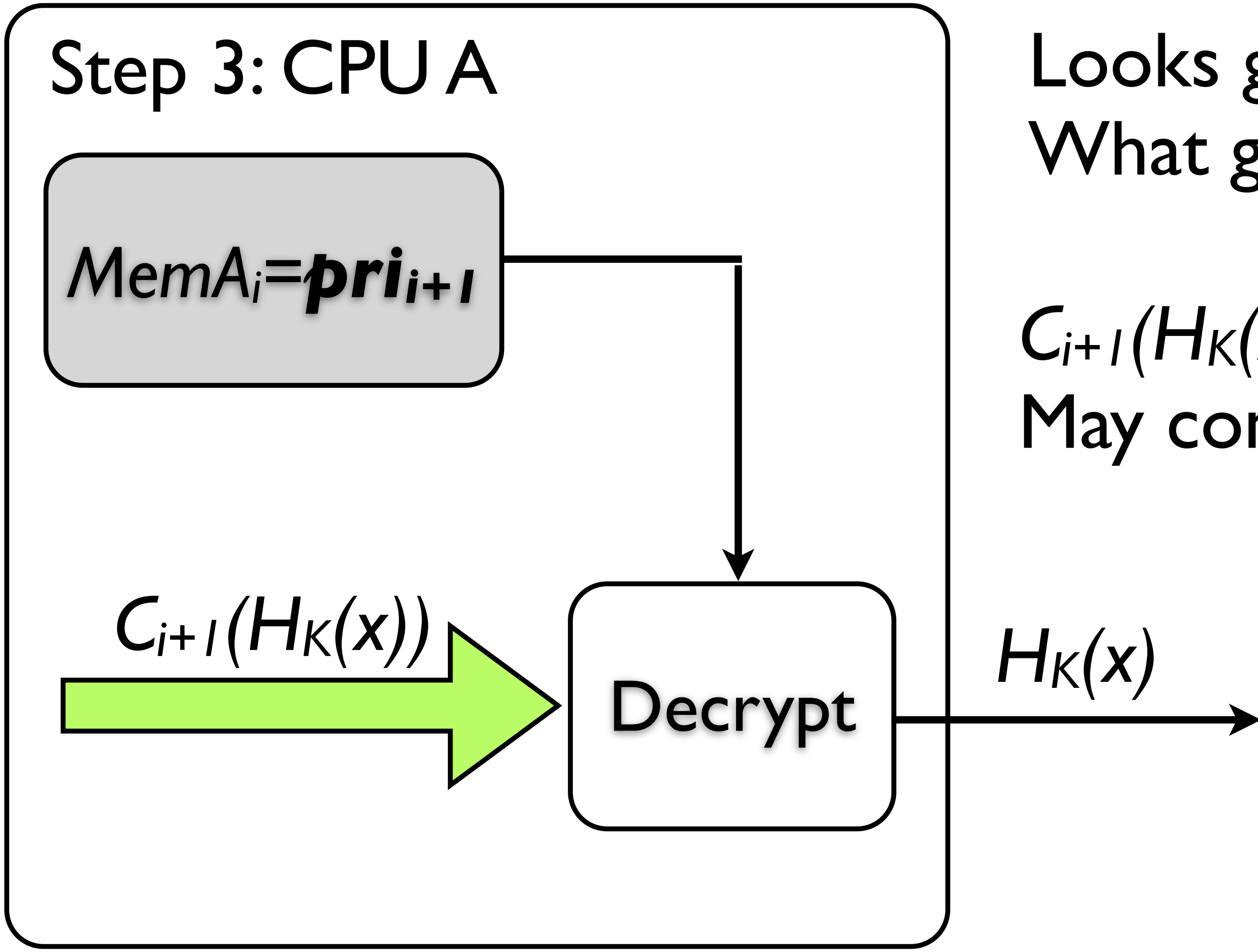


First Attempt



Looks great!
What goes wrong?

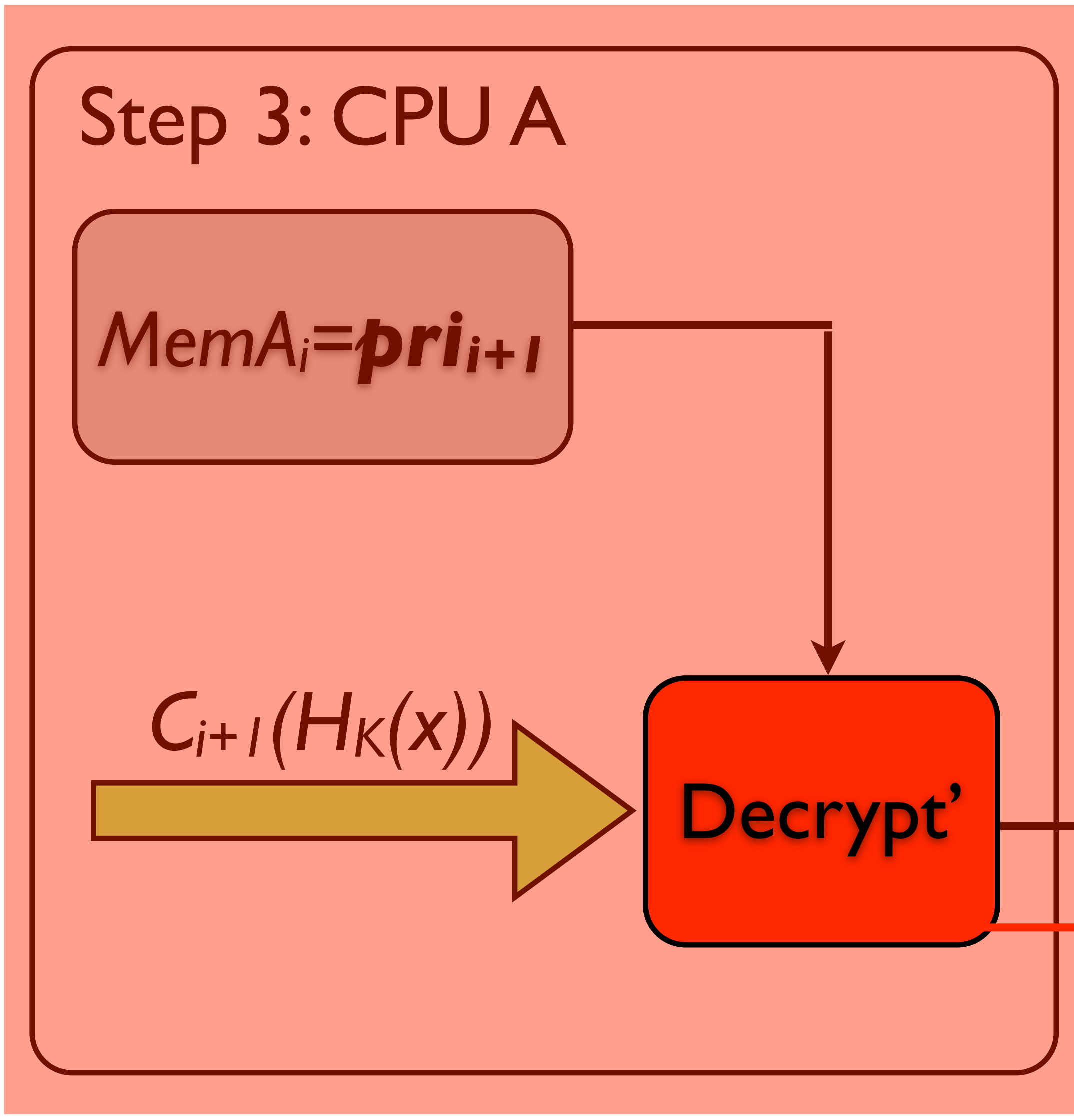
First Attempt



Looks great!
What goes wrong?

$C_{i+1}(H_K(x))$ carries history
May contain K

First Attempt

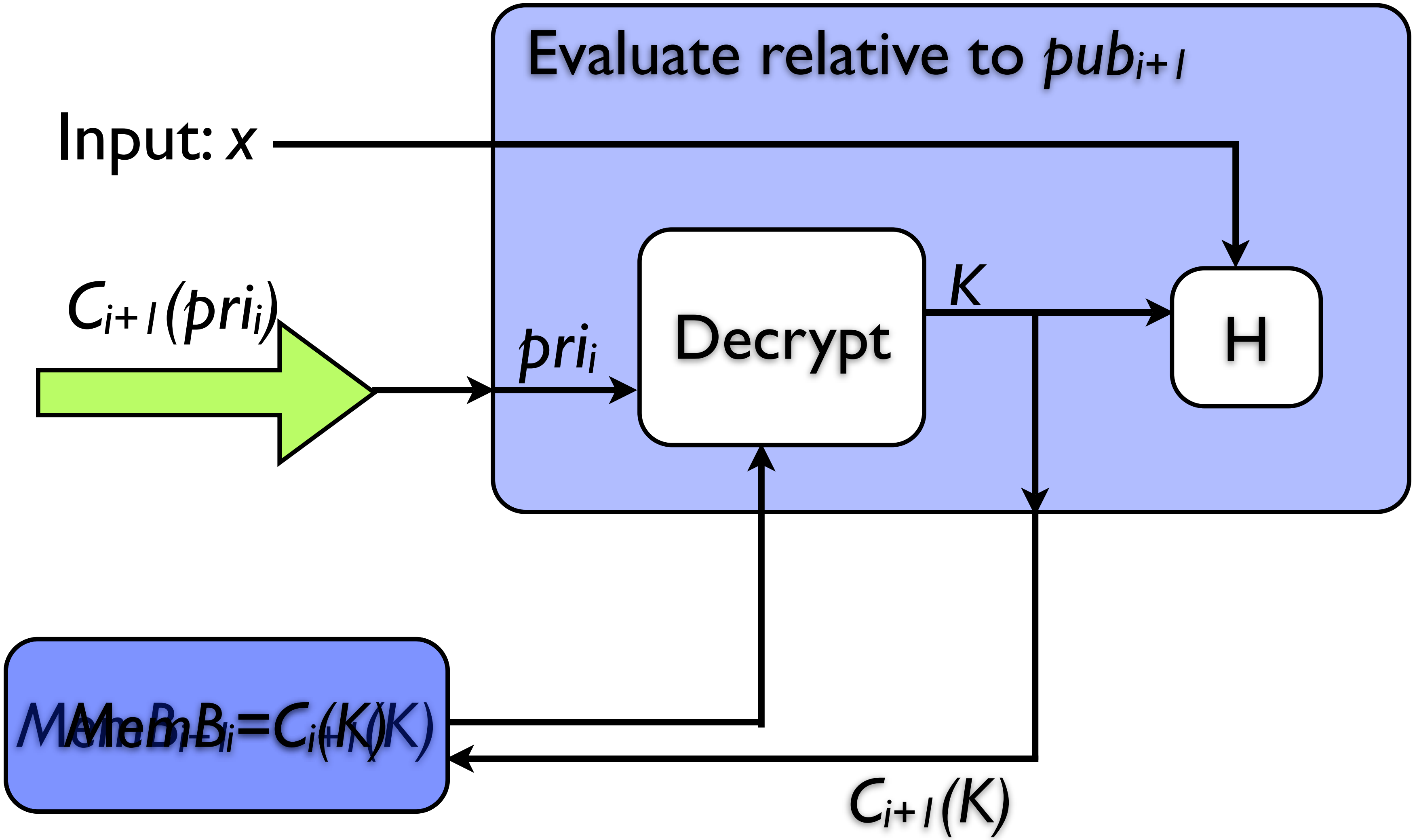


Looks great!
What goes wrong?

$C_{i+1}(H_K(x))$ carries history
May contain K

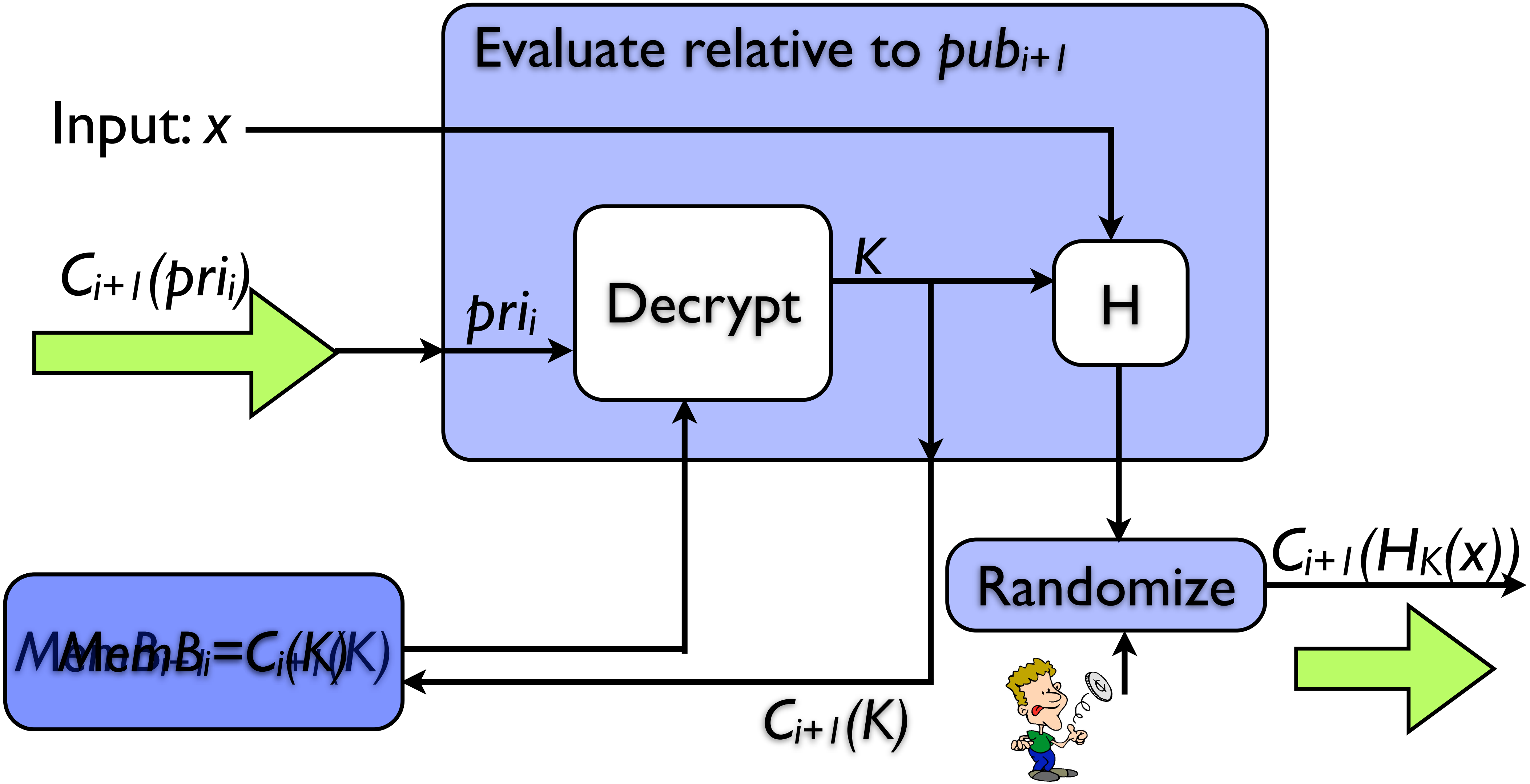
Second Attempt

Step 2’: CPU B



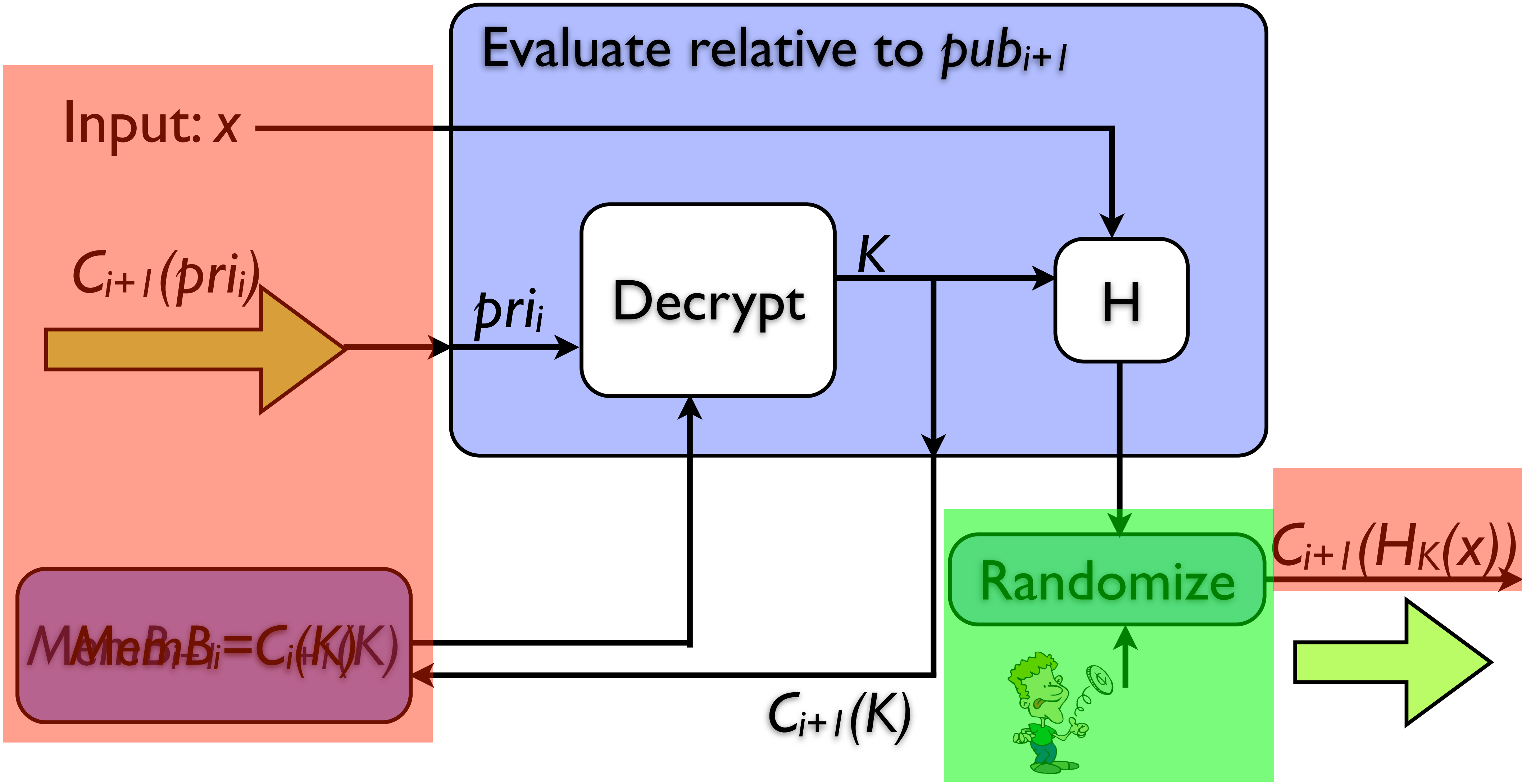
Second Attempt

Step 2': CPU B

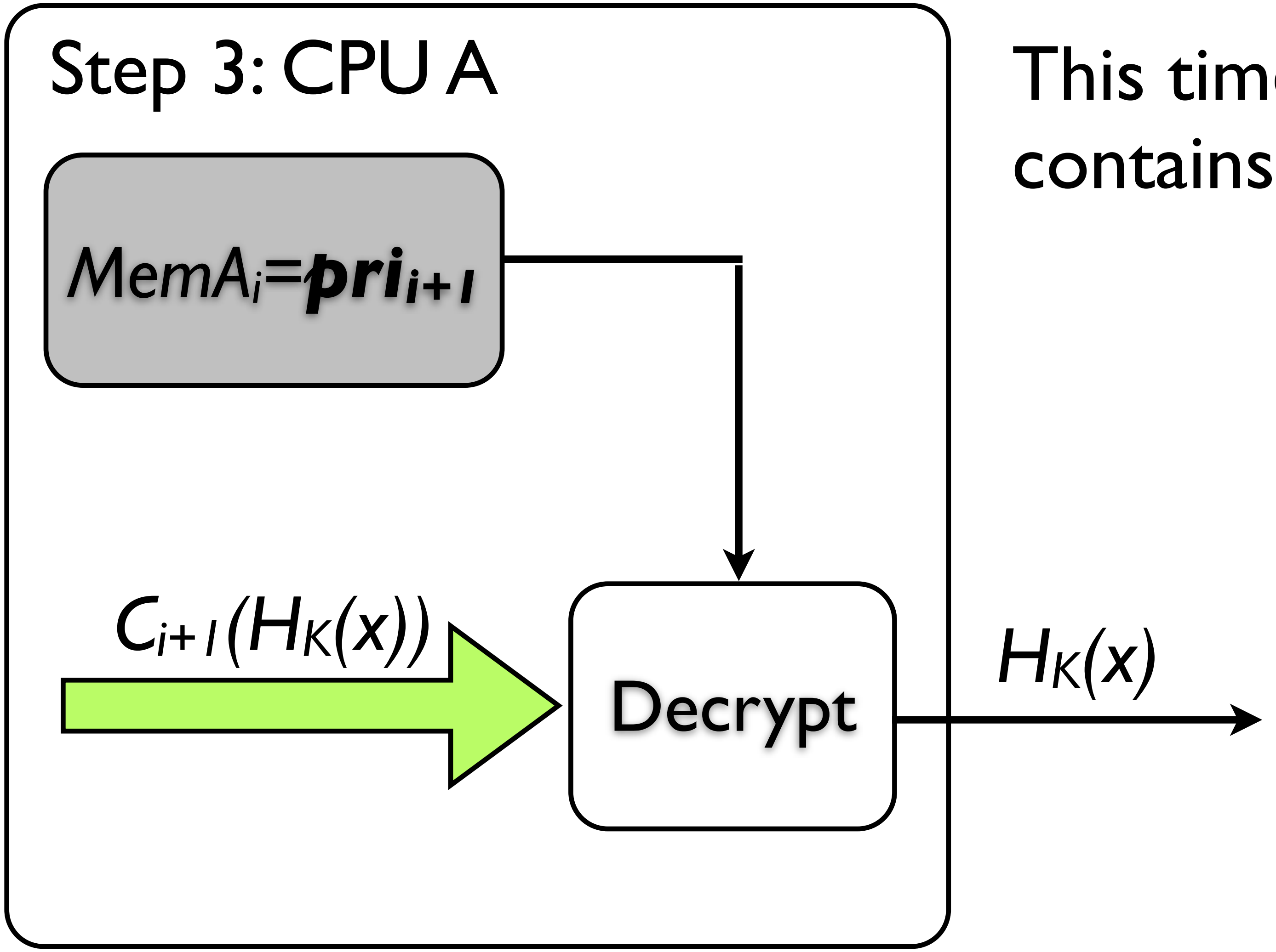


Second Attempt

Step 2': CPU B

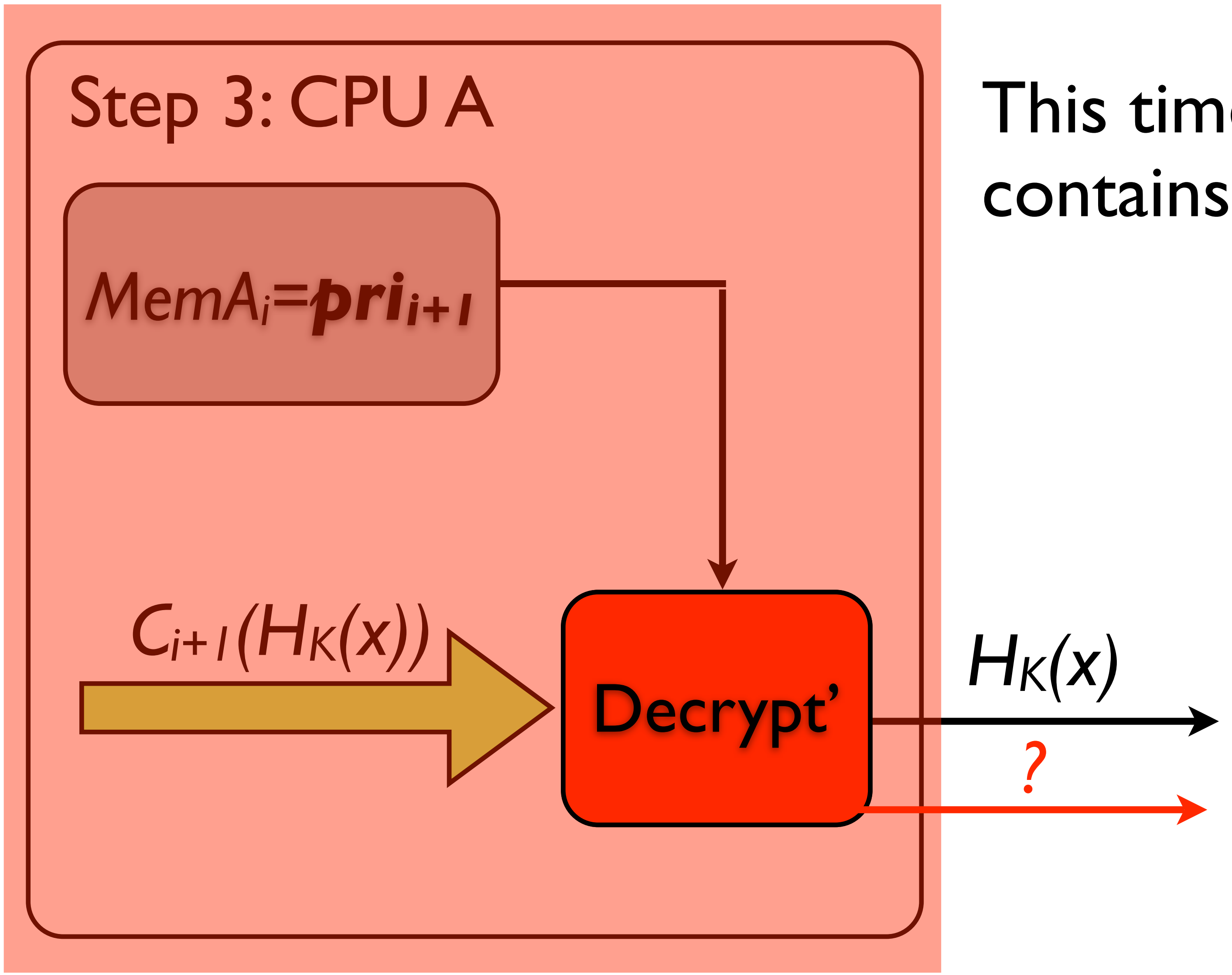


Second Attempt



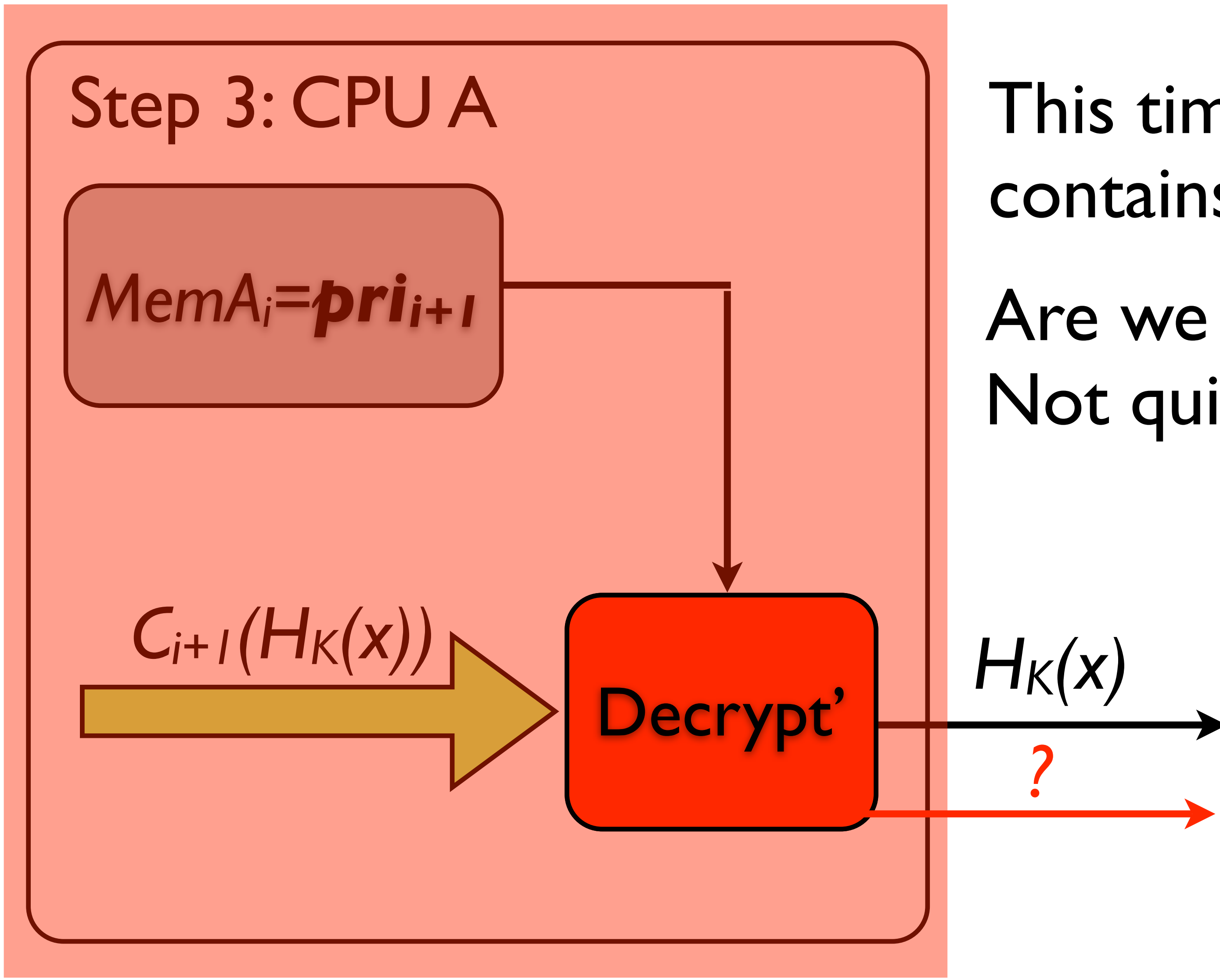
This time $C_{i+1}(H_K(x))$ only contains $H_K(x)$

Second Attempt



This time $C_{i+1}(H_K(x))$ only contains $H_K(x)$

Second Attempt

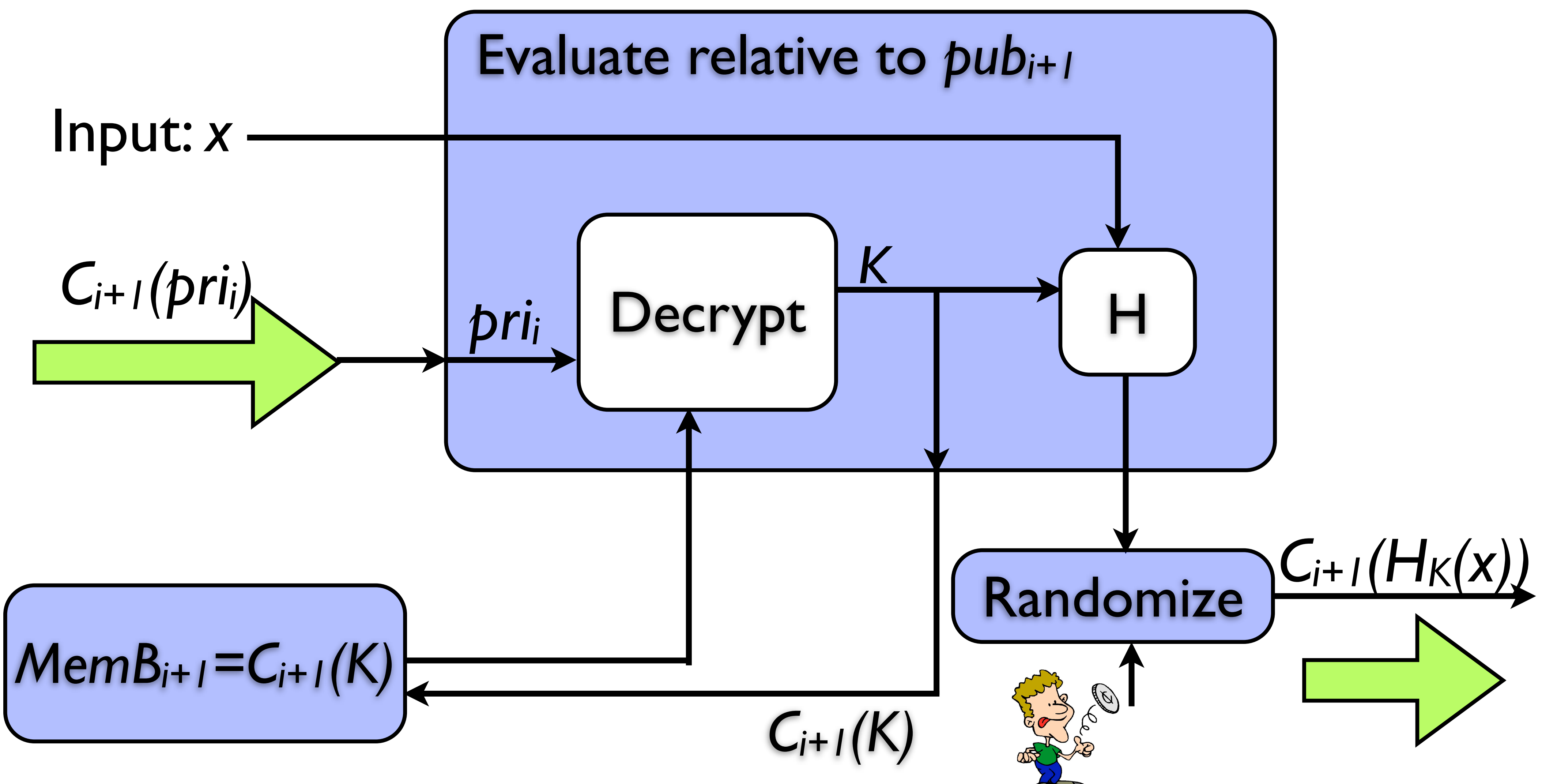


This time $C_{i+1}(H_K(x))$ only contains $H_K(x)$

Are we done?
Not quite...

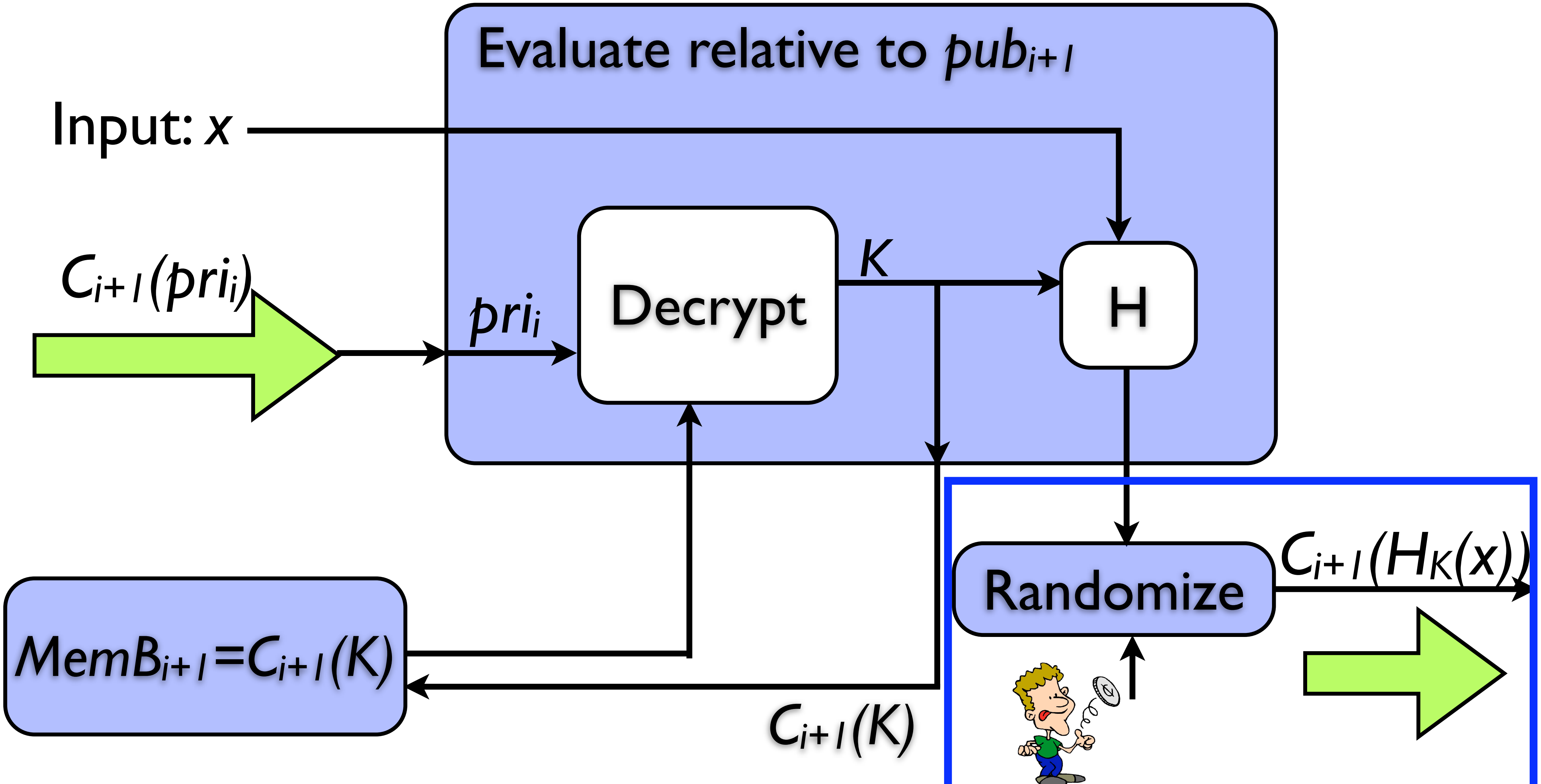
Second Attempt

Step 2': CPU B



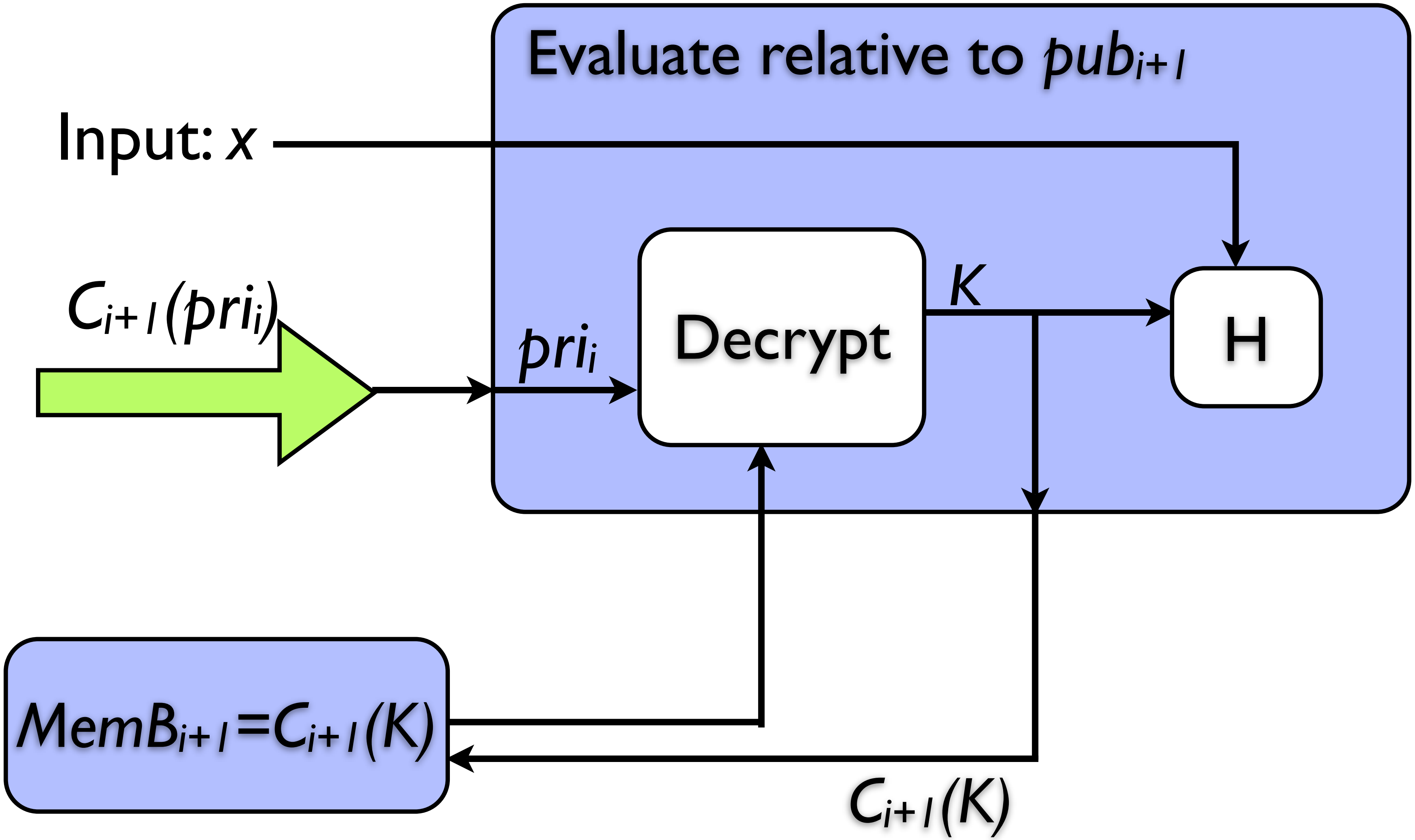
Second Attempt

Step 2': CPU B



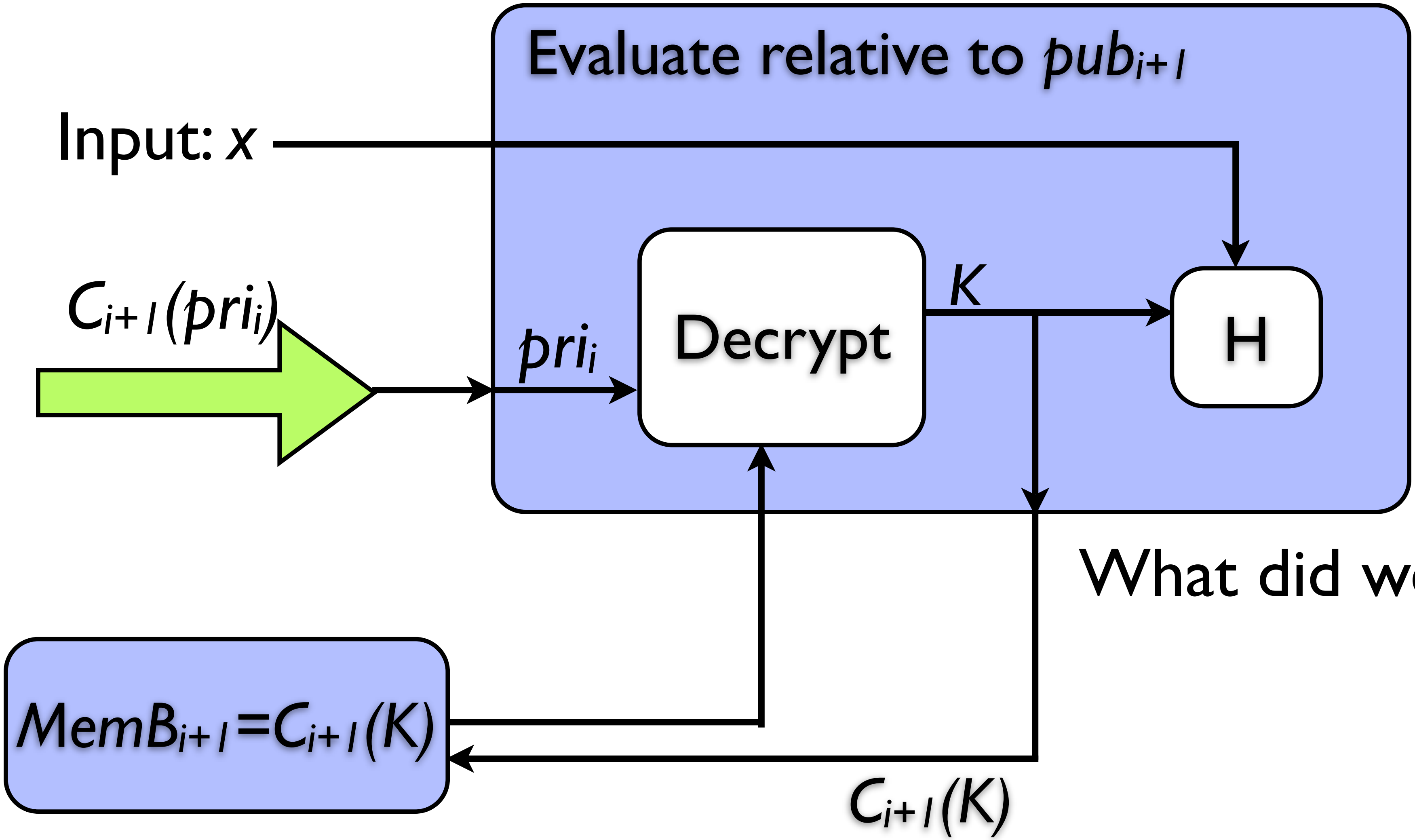
Second Attempt

Step 2': CPU B



Second Attempt

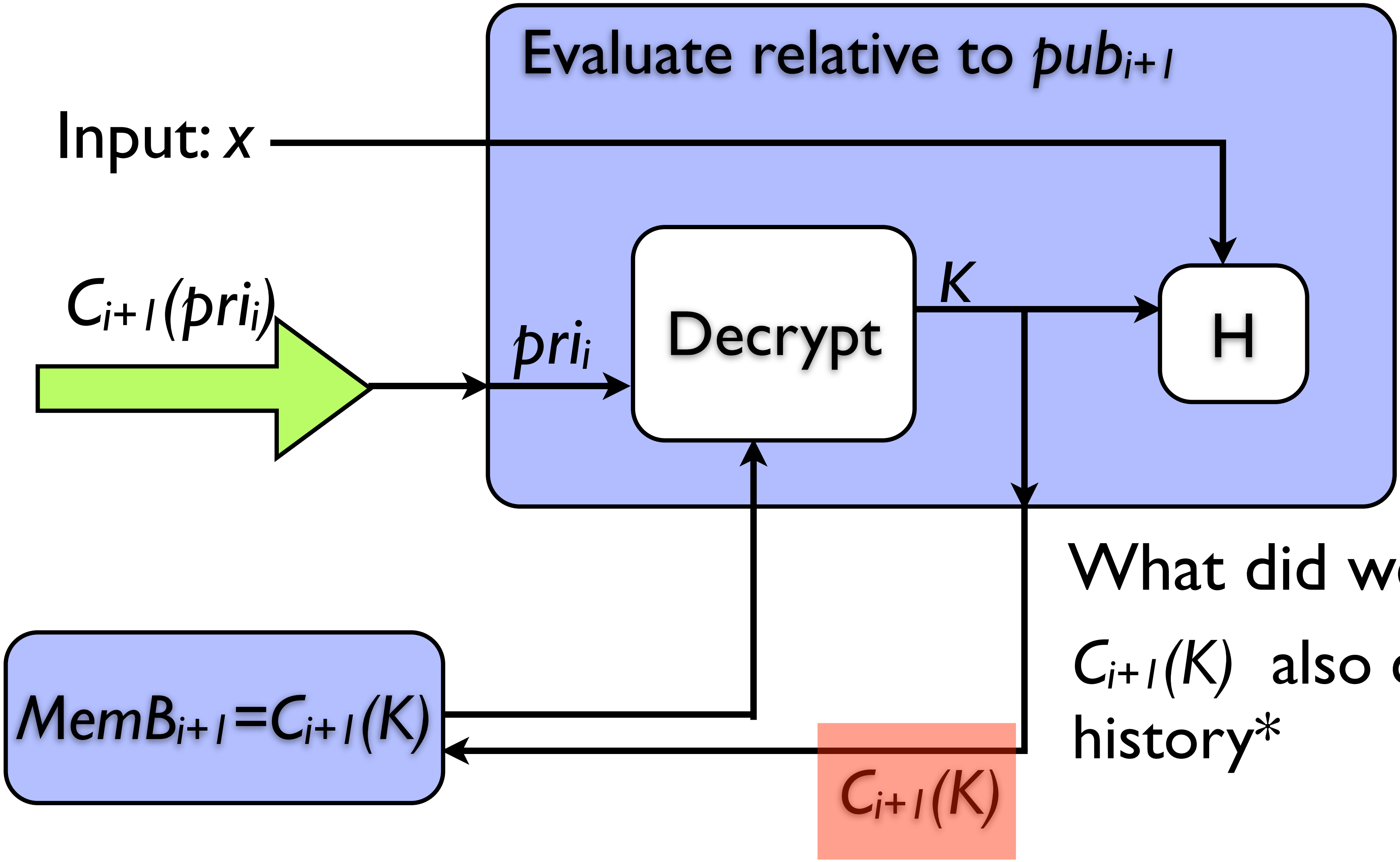
Step 2’: CPU B



What did we forget?

Second Attempt

Step 2': CPU B

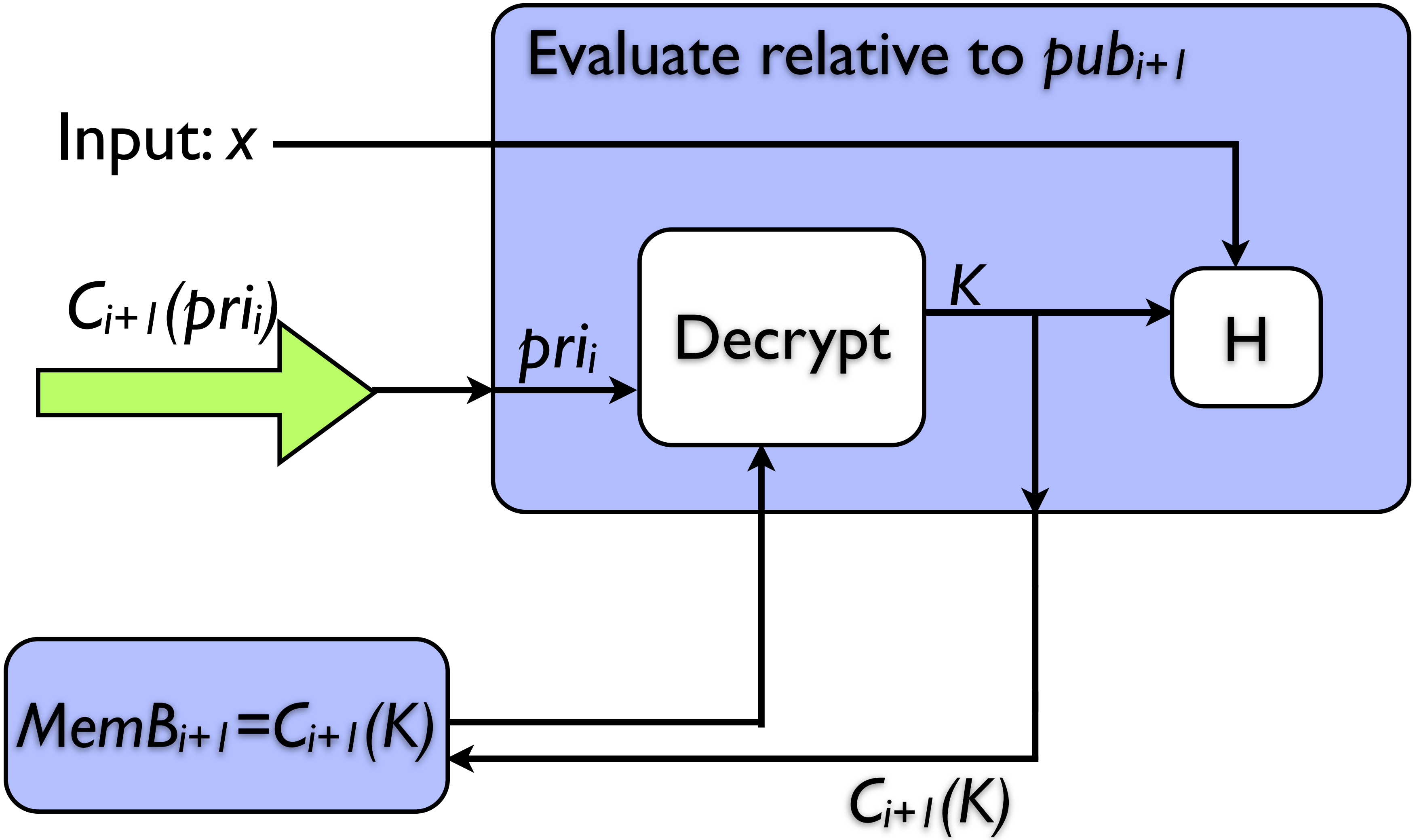


What did we forget?

$C_{i+1}(K)$ also carries history*

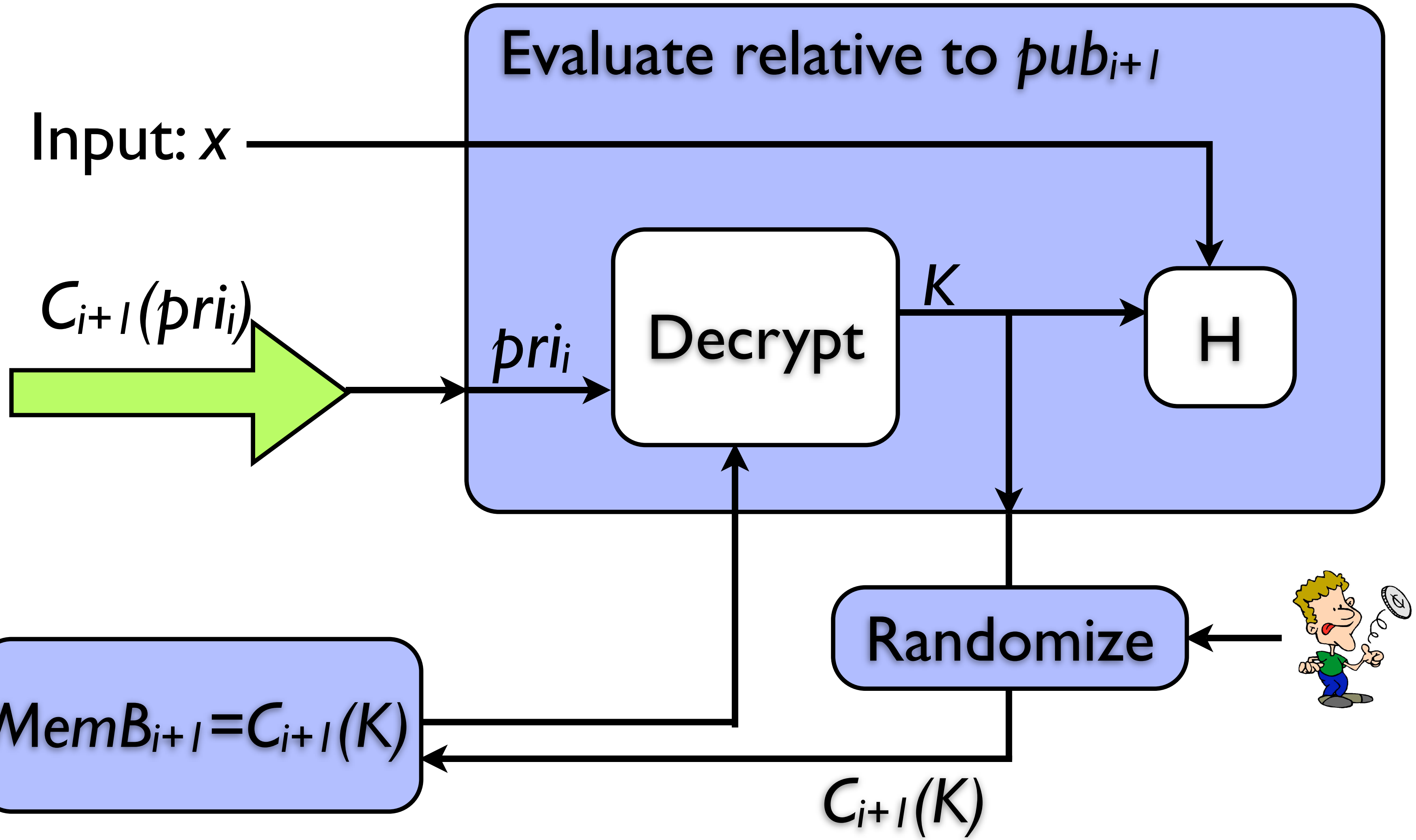
Third Attempt

Step 2'': CPU B



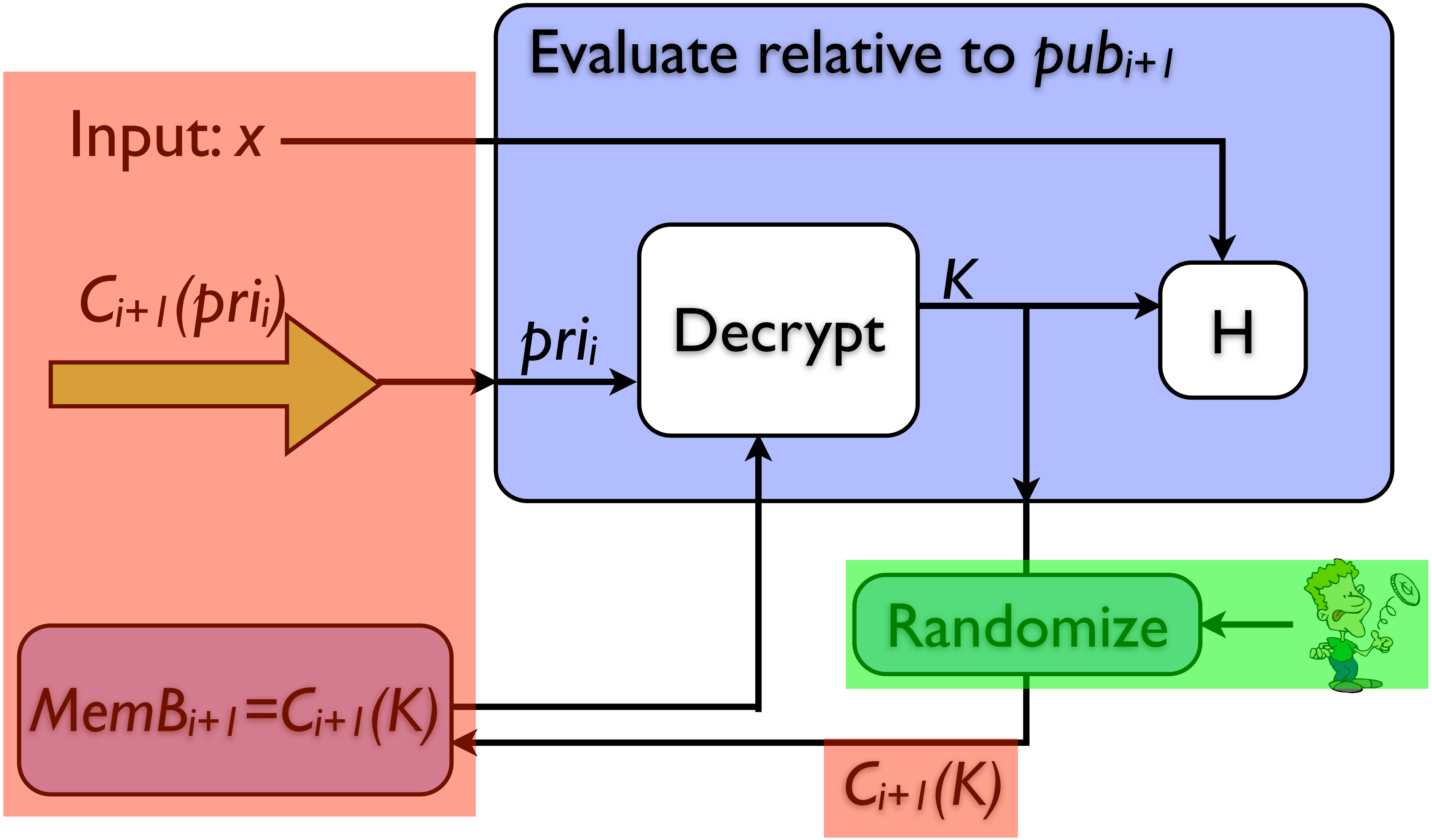
Third Attempt

Step 2’’: CPU B



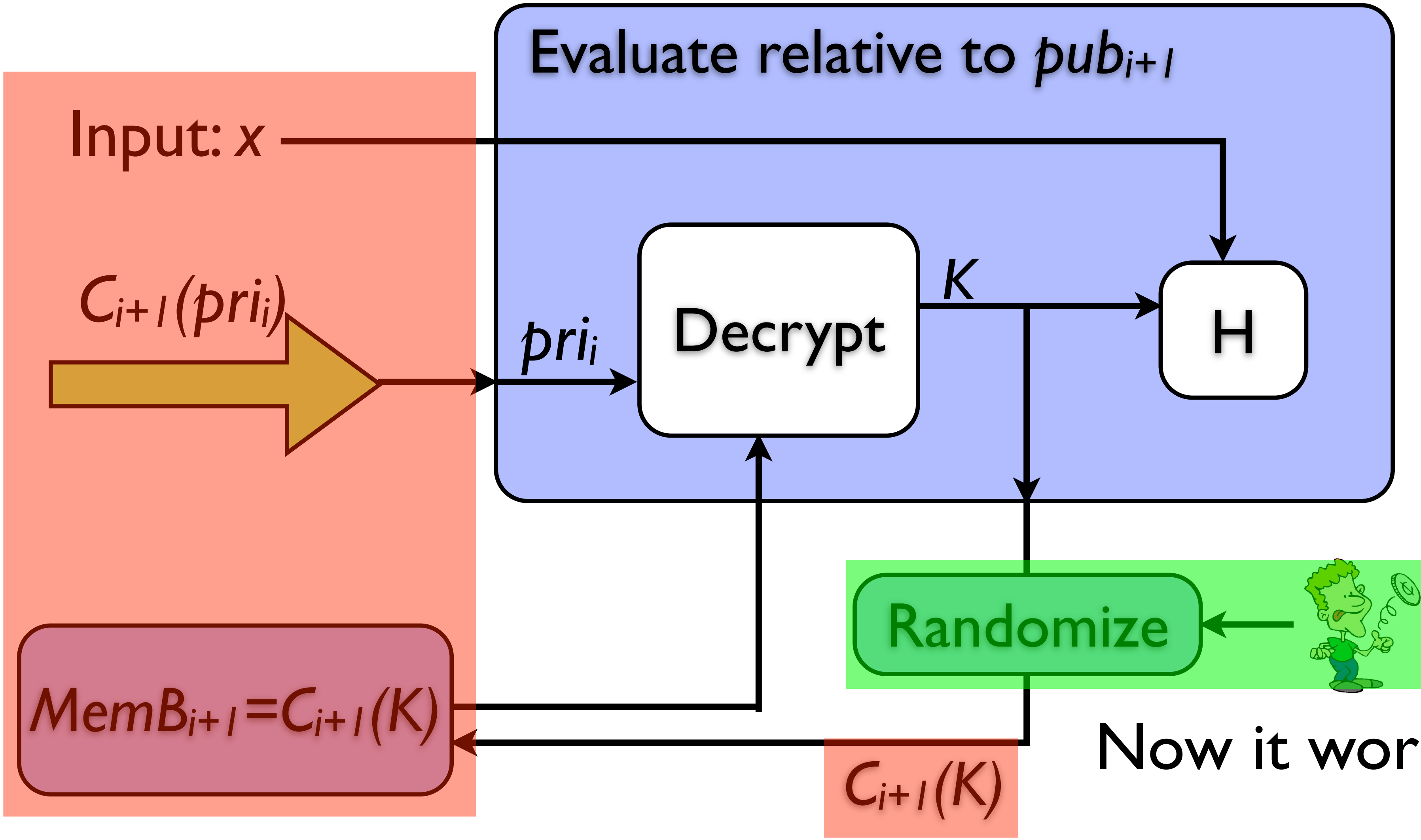
Third Attempt

Step 2'': CPU B



Third Attempt

Step 2'': CPU B



Now it works!

Complete Construction

Memory A: pri_i
Randomness: r_{gen}

Memory B: C_K
Randomness: r, r'

$pub_{i+1}, pri_{i+1} = KeyGen(r_{gen})$

$C_{pri} = Enc(pri_i, pub_{i+1}) \xrightarrow{C_{pri}}$

Set Memory A = pri_{i+1}

$C_{reply} = Evaluate(C_{pri}, C_K, x, H_K(x); r)$

$C'_K = Evaluate(C_{pri}, C_K, x, K; r')$

$\xleftarrow{C'_{reply}}$ $C'_{reply} = Randomize(C_{reply}; r)$

set Memory B = $Randomize(C'_K; r')$

$Y = Dec(C'_{reply}; pri_{i+1})$

Output Y

Complete Construction

Memory A: pri_i
Randomness: r_{gen}

Memory B: C_K
Randomness: r, r'

$pub_{i+1}, pri_{i+1} = KeyGen(r_{gen})$
$C_{pri} = Enc(pri_i, pub_{i+1}) \xrightarrow{C_{pri}}$
Set Memory A $= pri_{i+1}$

$C_{reply} = Evaluate(C_{pri}, C_K, x, H_K(x); r)$
$C'_K = Evaluate(C_{pri}, C_K, x, K; r')$

$\xleftarrow{C'_{reply}}$ $C'_{reply} = Randomize(C_{reply}\,; r)$
set Memory B $= Randomize(C'_K\,; r')$

$Y = Dec(C'_{reply}\,; pri_{i+1})$
Output Y

Proof

Hybrid 1

Memory A: pri_i
Randomness: r_{gen}

Memory B: C_K
Randomness: r, r'

$pub_{i+1}, pri_{i+1} = KeyGen(r_{gen})$

$C_{pri} = Enc(pri_i, pub_{i+1}) \xrightarrow{C_{pri}}$

Set Memory $A = pri_{i+1}$

$C_{reply} = Evaluate(C_{pri}, C_K, x, H_K(x); r)$

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$\xleftarrow{C'_{reply}}$ $C'_{reply} = Randomize(C_{reply}; r)$

set Memory $B = Randomize(C'_K; r')$

$Y = Dec(C'_{reply}; pri_{i+1})$

Output Y

Hybrid 1

Memory A: pri_i
Randomness: r_{gen}

Memory B: C_K
Randomness: r, r'

$pub_{i+1}, pri_{i+1} = KeyGen(r_{gen})$
$C_{pri} = Enc(pri_i, pub_{i+1})$ $\xrightarrow{C_{pri}}$
Set Memory $A = pri_{i+1}$

$C_{reply} = Evaluate(C_{pri}, C_K, x, H_K(x); r)$
$C'_K = Evaluate(C_{pri}, C_K, x, K; r')$

$\xleftarrow{C''_{reply}}$ $C'_{reply} = Randomize(C_{reply}; r)$
set Memory $B = Randomize(C'_K; r')$

$Y = Dec(C'_{reply}; pri_{i+1})$
Output Y

$C''_{reply} = Enc(H_K(x), pub_{i+1})$

Hybrid 1

Memory A: pri_i
Randomness: r_{gen}

Memory B: C_K
Randomness: r, r'

$pub_{i+1}, pri_{i+1} = KeyGen(r_{gen})$
$C_{pri} = Enc(pri_i, pub_{i+1})$ $\xrightarrow{C_{pri}}$
Set Memory $A = pri_{i+1}$

$C_{reply} = Evaluate(C_{pri}, C_K, x, H_K(x); r)$
$C'_K = Evaluate(C_{pri}, C_K, x, K; r')$

$\xleftarrow{C''_{reply}}$ $C'_{reply} = Randomize(C_{reply}\,; r)$
set Memory $B = Randomize(C'_K\,; r')$

$Y = Dec(C'_{reply}\,; pri_{i+1})$
Output Y

$C''_{reply} = Enc(H_K(x), pub_{i+1})$

Doesn't change the distribution

Hybrid 2

Memory A: pri_i
Randomness: r_{gen}

$pub_{i+1}, pri_{i+1} = KeyGen(r_{gen})$
$C_{pri} = Enc(pri_i, pub_{i+1})$ $\xrightarrow{C_{pri}}$
Set Memory A = pri_{i+1}

Memory B: C_K
Randomness: r, r'

$C_{reply} = Evaluate(C_{pri}, C_K, x, H_K(x); r)$
$C'_K = Evaluate(C_{pri}, C_K, x, K; r')$

$\xleftarrow{C''_{reply}}$ $C'_{reply} = Randomize(C_{reply}; r)$
set Memory B = $Randomize(C'_K; r')$

$Y = Dec(C'_{reply}; pri_{i+1})$
Output Y

$C''_{reply} = Enc(H_K(x), pub_{i+1})$

Hybrid 2

Memory A: pri_i
Randomness: r_{gen}

$pub_{i+1}, pri_{i+1} = KeyGen(r_{gen})$
$C_{pri} = Enc(pri_i, pub_{i+1})$ $\xrightarrow{\quad C_{pri} \quad}$
Set Memory $A = pri_{i+1}$

Memory B: C_K
Randomness: r, r'

$C_{reply} = Evaluate(C_{pri}, C_K, x, H_K(x); r)$
$C'_K = Evaluate(C_{pri}, C_K, x, K; r')$

$\xleftarrow{\quad C''_{reply} \quad}$ $C'_{reply} = Randomize(C_{reply}; r)$
set Memory $B = C''_K$

$Y = Dec(C'_{reply}; pri_{i+1})$
Output Y

$C''_{reply} = Enc(H_K(x), pub_{i+1})$

$C''_K = Enc(0...0, pub_{i+1})$

Hybrid 2

Memory A: pri_i
Randomness: r_{gen}

Memory B: C_K
Randomness: r, r'

$pub_{i+1}, pri_{i+1} = KeyGen(r_{gen})$
$C_{pri} = Enc(pri_i, pub_{i+1})$ $\xrightarrow{C_{pri}}$
Set Memory A $= pri_{i+1}$

$C_{reply} = Evaluate(C_{pri}, C_K, x, H_K(x); r)$
$C'_K = Evaluate(C_{pri}, C_K, x, K; r')$

$\xleftarrow{C''_{reply}}$ $C'_{reply} = Randomize(C_{reply}; r)$
set Memory B $= C''_K$

$Y = Dec(C'_{reply}; pri_{i+1})$
Output Y

$C''_{reply} = Enc(H_K(x), pub_{i+1})$
$C''_K = Enc(0...0, pub_{i+1})$

Changes the distribution completely

Why Should This Work?

- Very informally: Ciphertexts are incompressible.
  - This means that leakage on B can help only if Adv knows enough about *pri*
  - But Adv sees only leakage on *pri* which is insufficient to break semantic security

Open Questions

- Can we get rid of the leak-free component?
- Granularity of leakage.

Thank you!