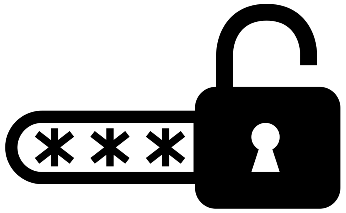
Facets of Information Flow Control

Marco Vassena

CISPA
HELMHOLTZ CENTER FOR INFORMATION SECURITY

Complex Software System

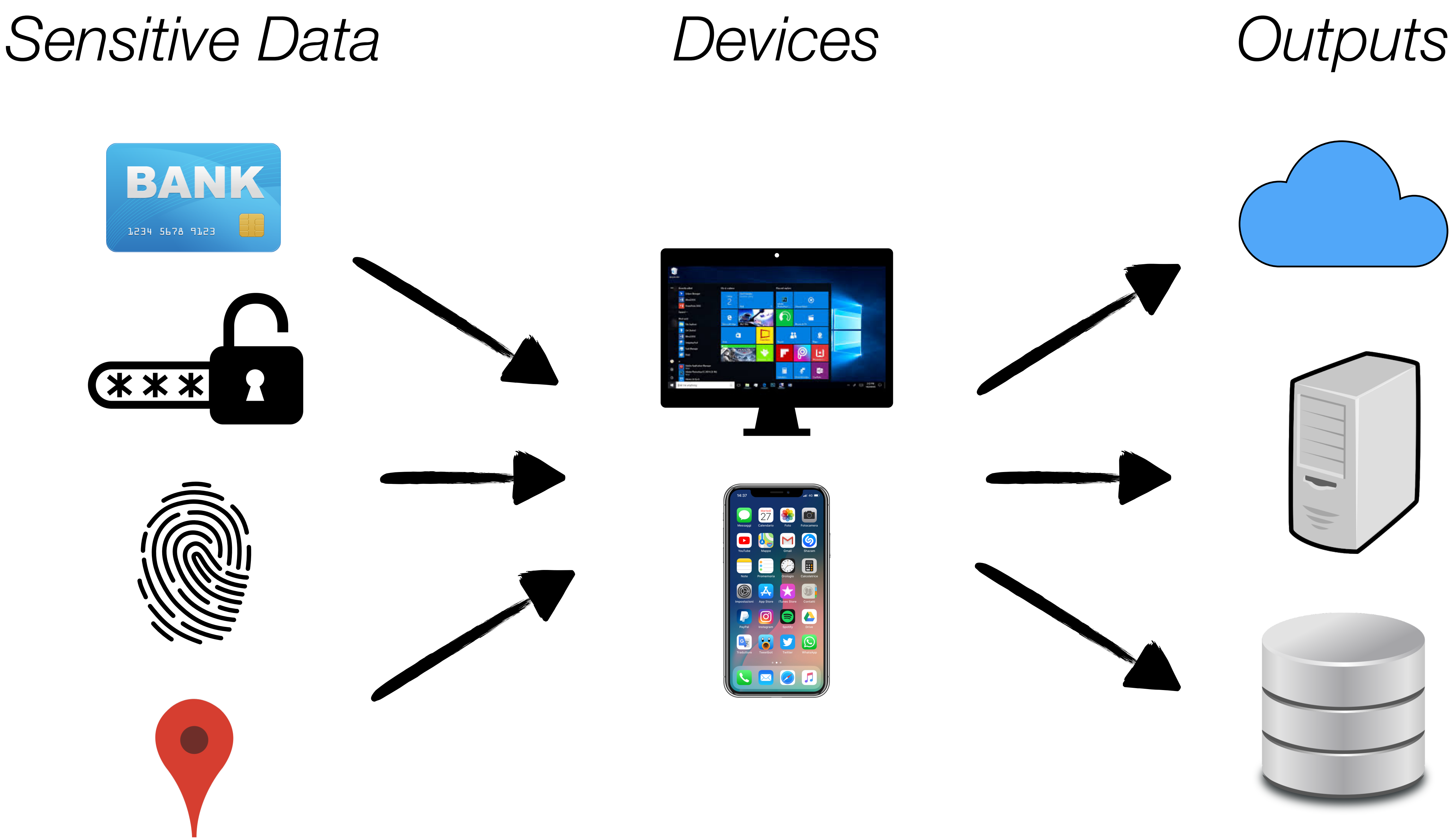
Sensitive Data



Complex Software System

Sensitive Data *Devices*

Complex Software System



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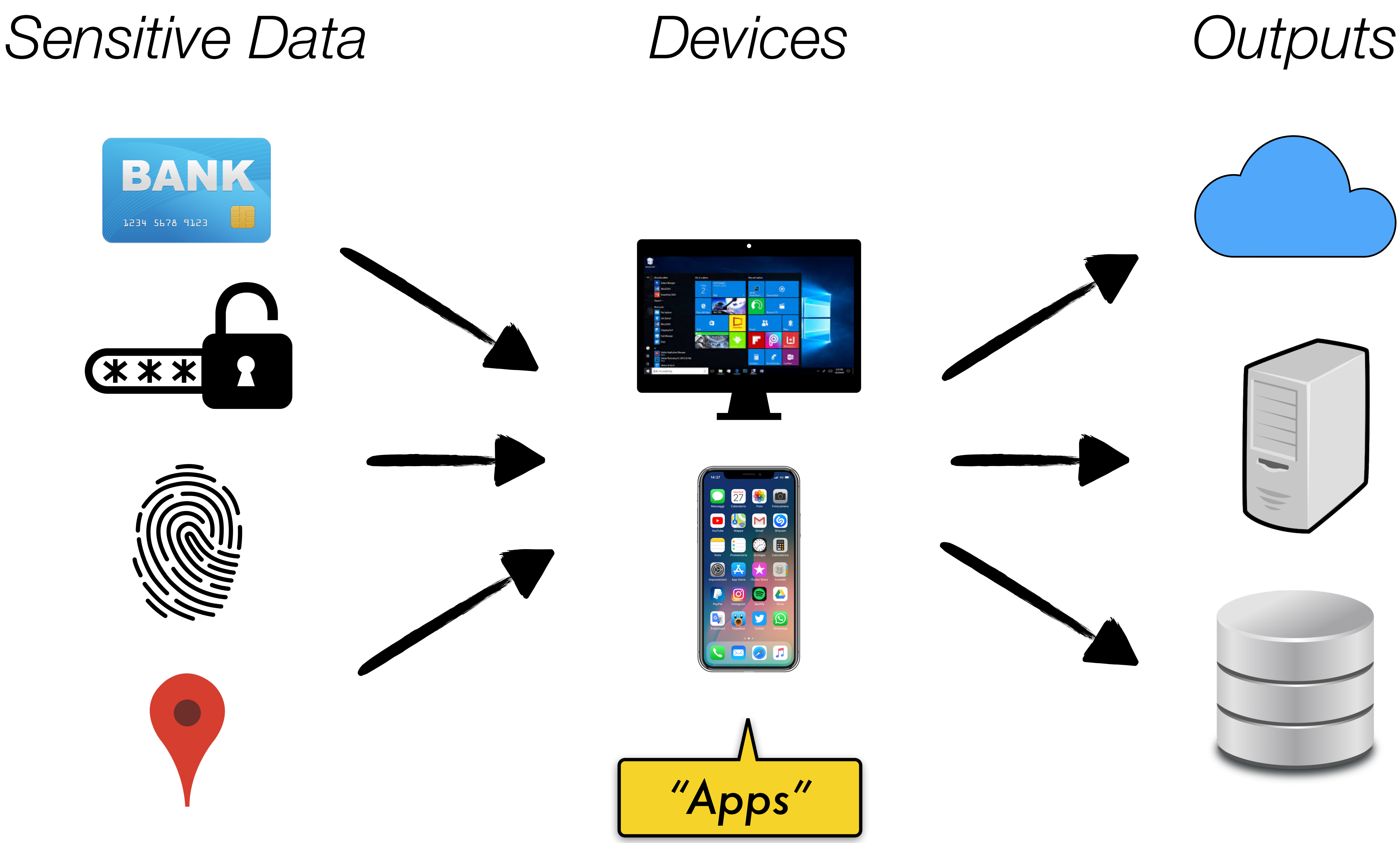
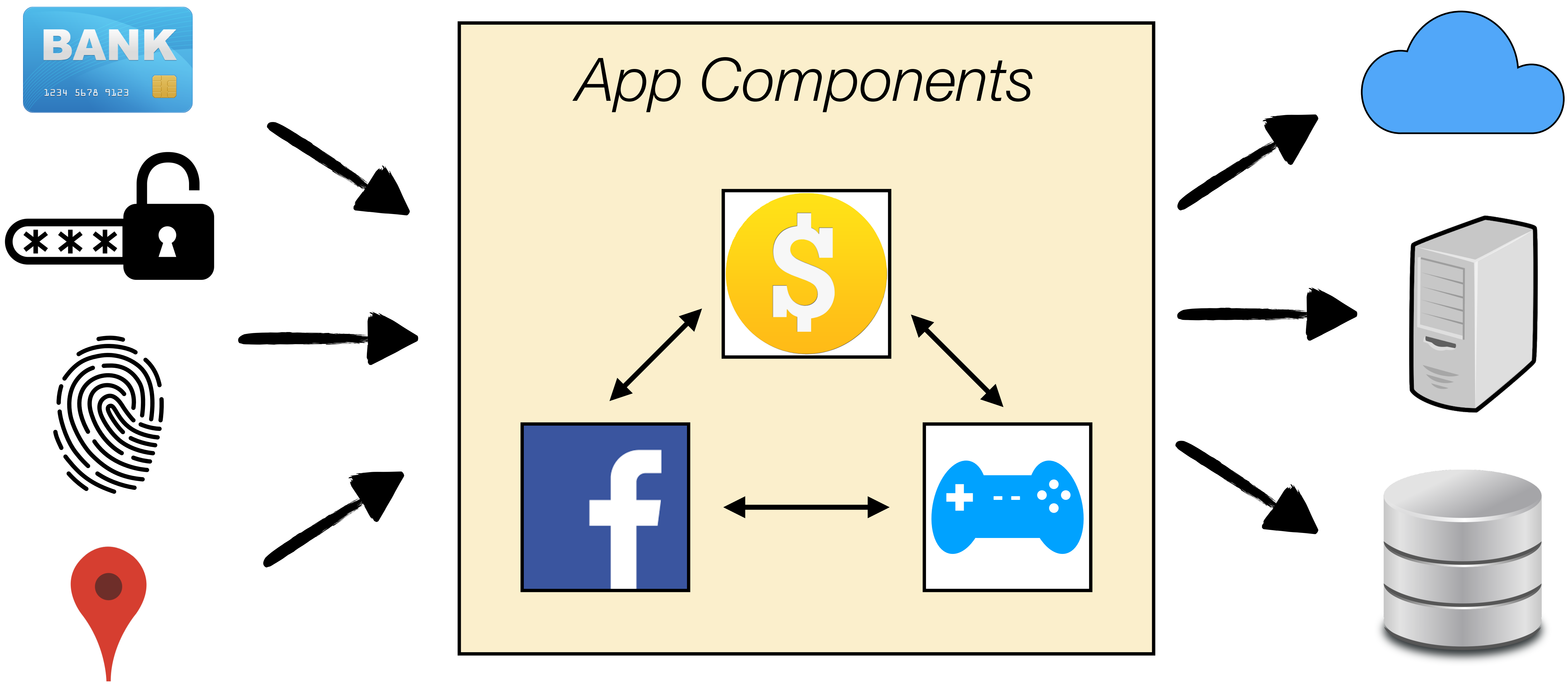


Modern software contains many 3rd party components!



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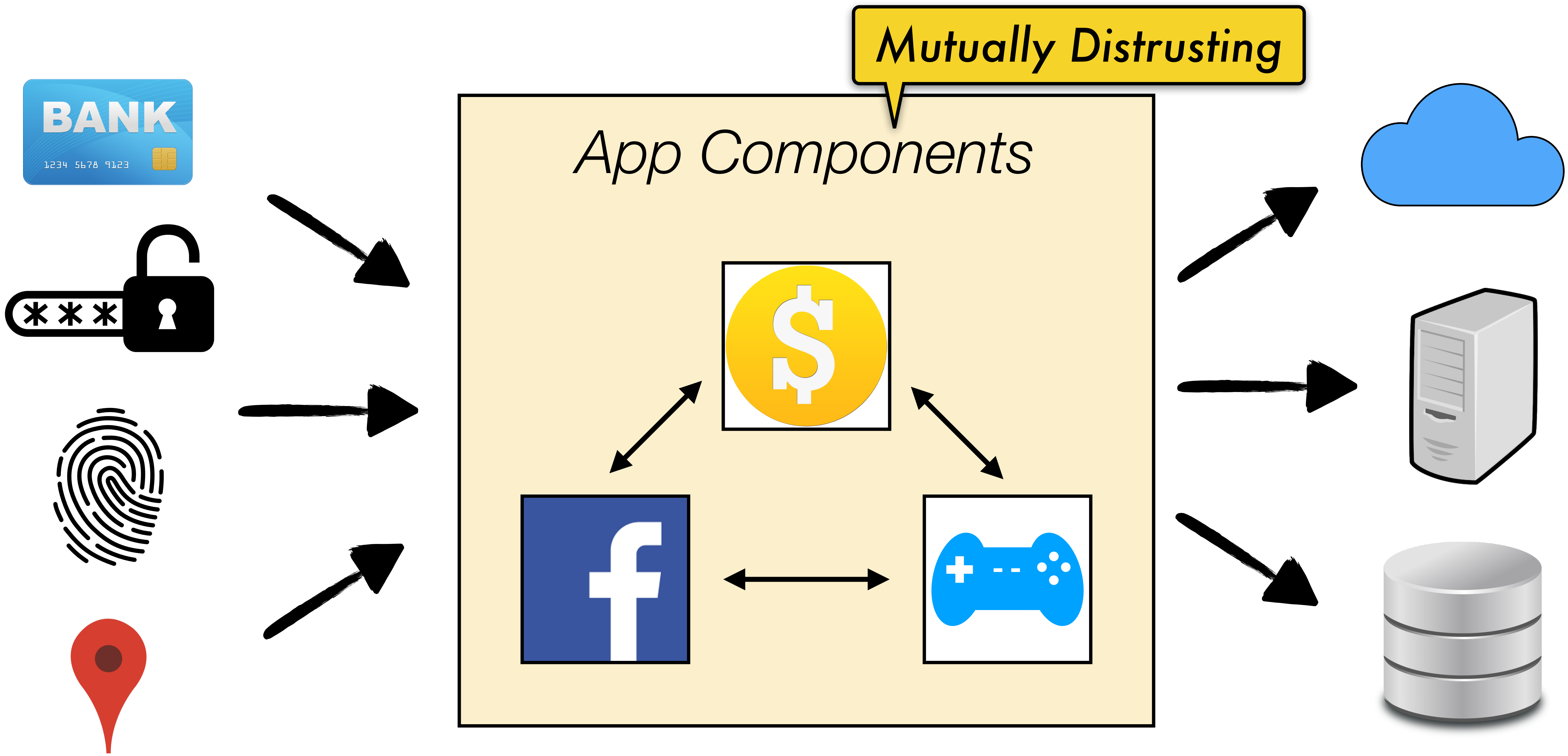

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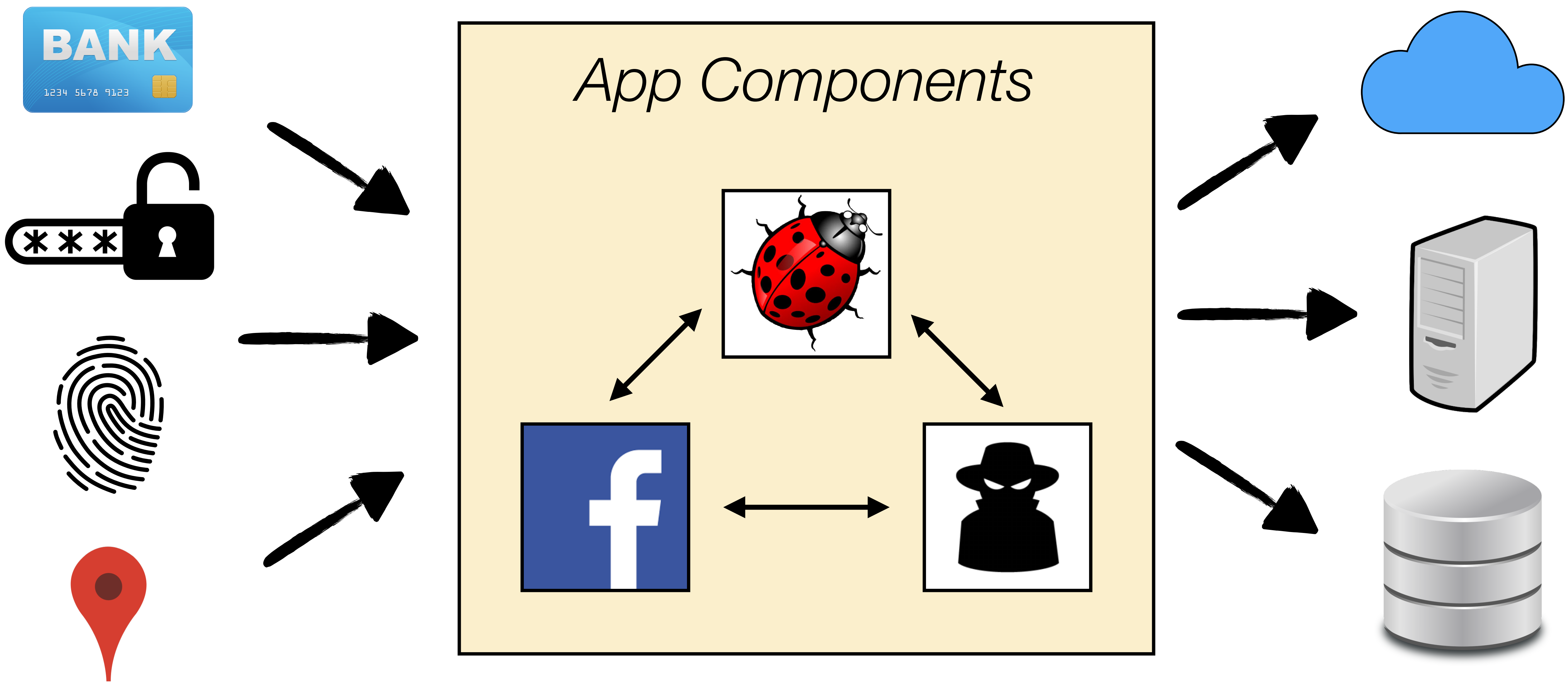

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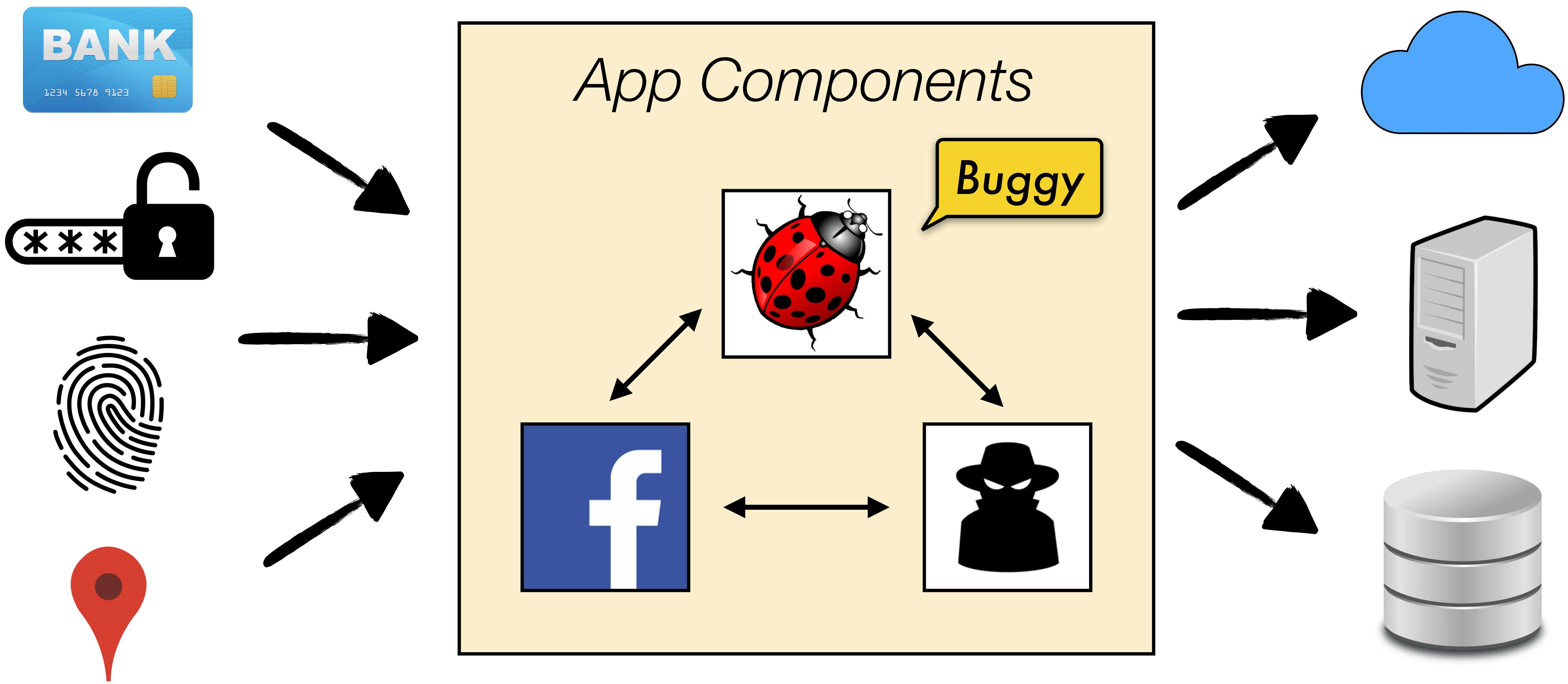

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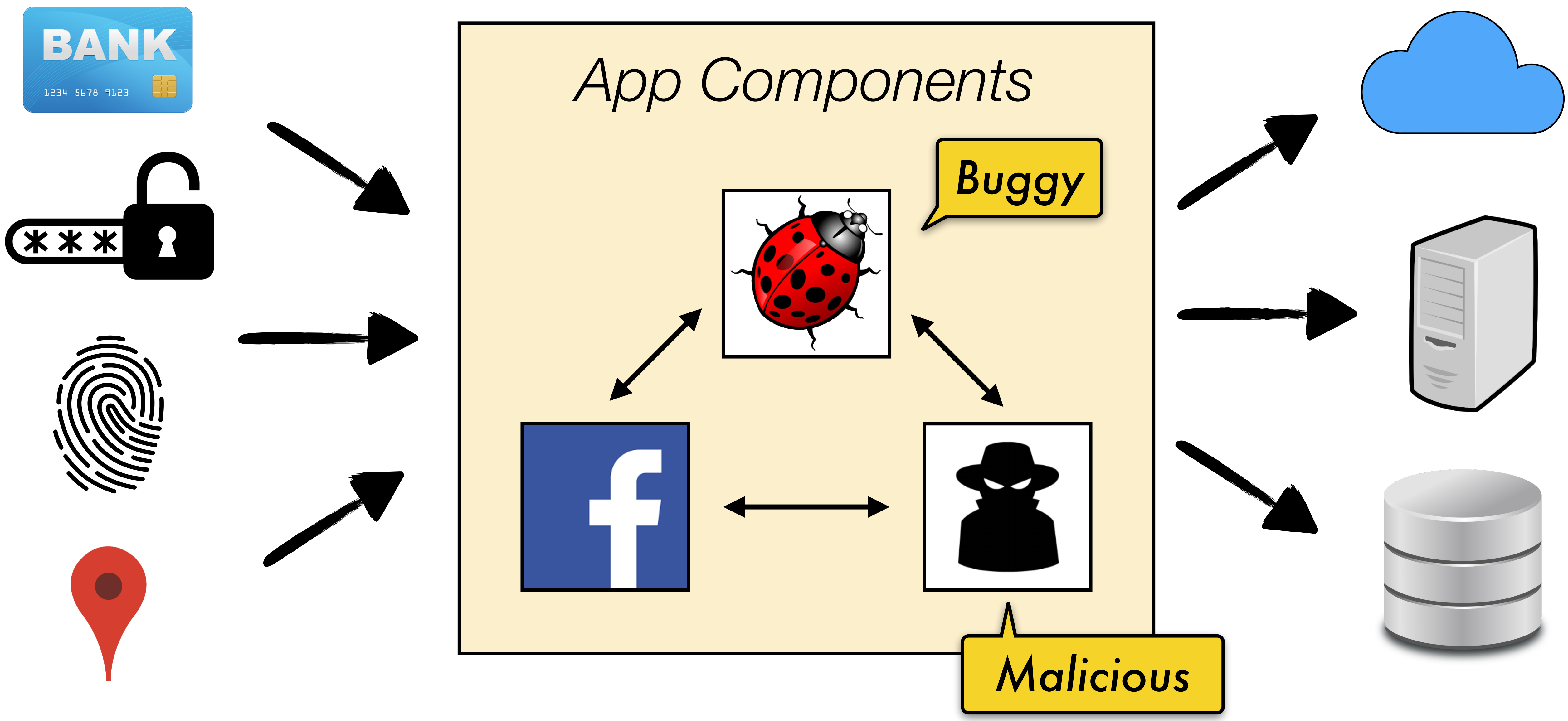

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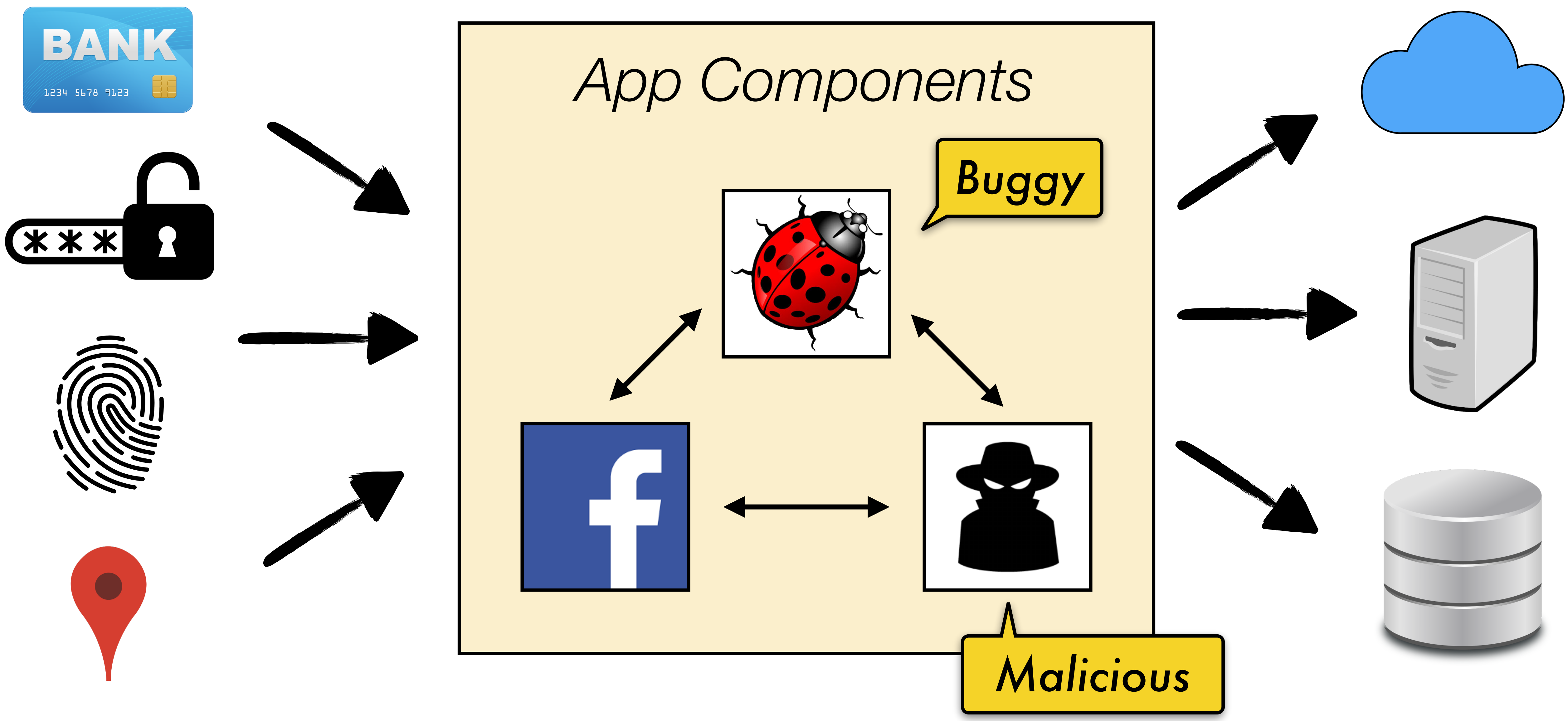
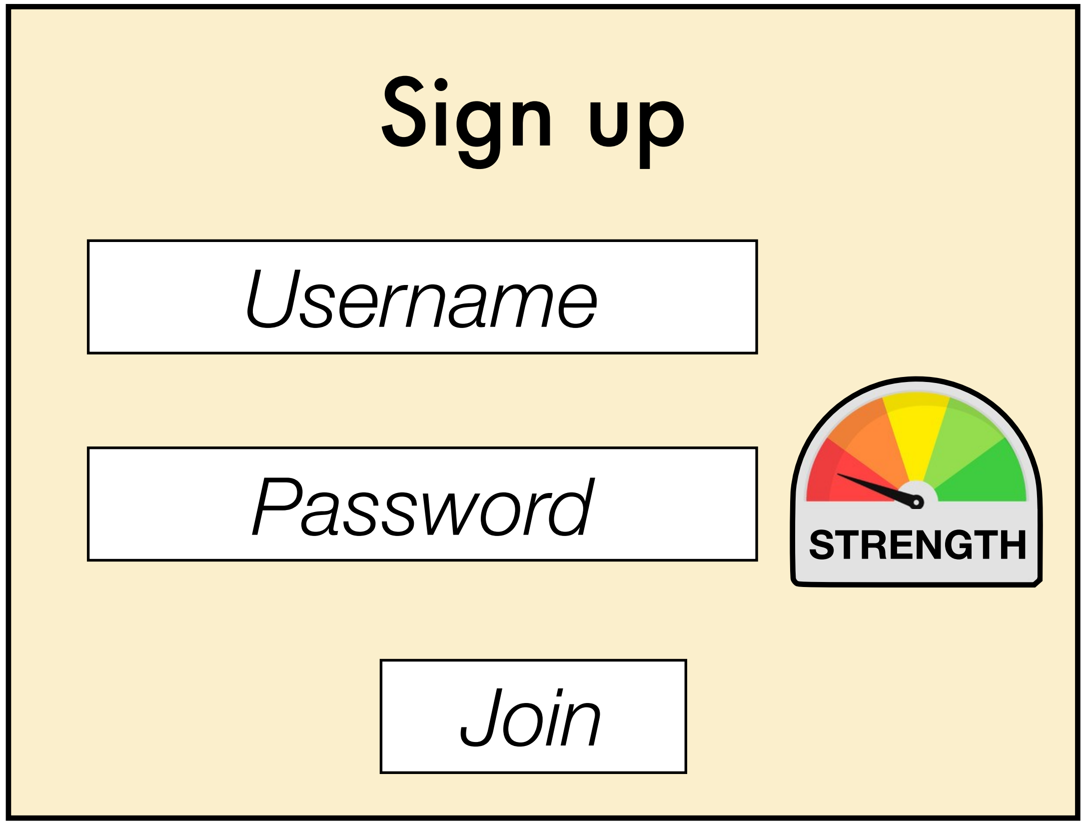


Data ***confidentiality*** *and* ***integrity*** *is at stake*

Example



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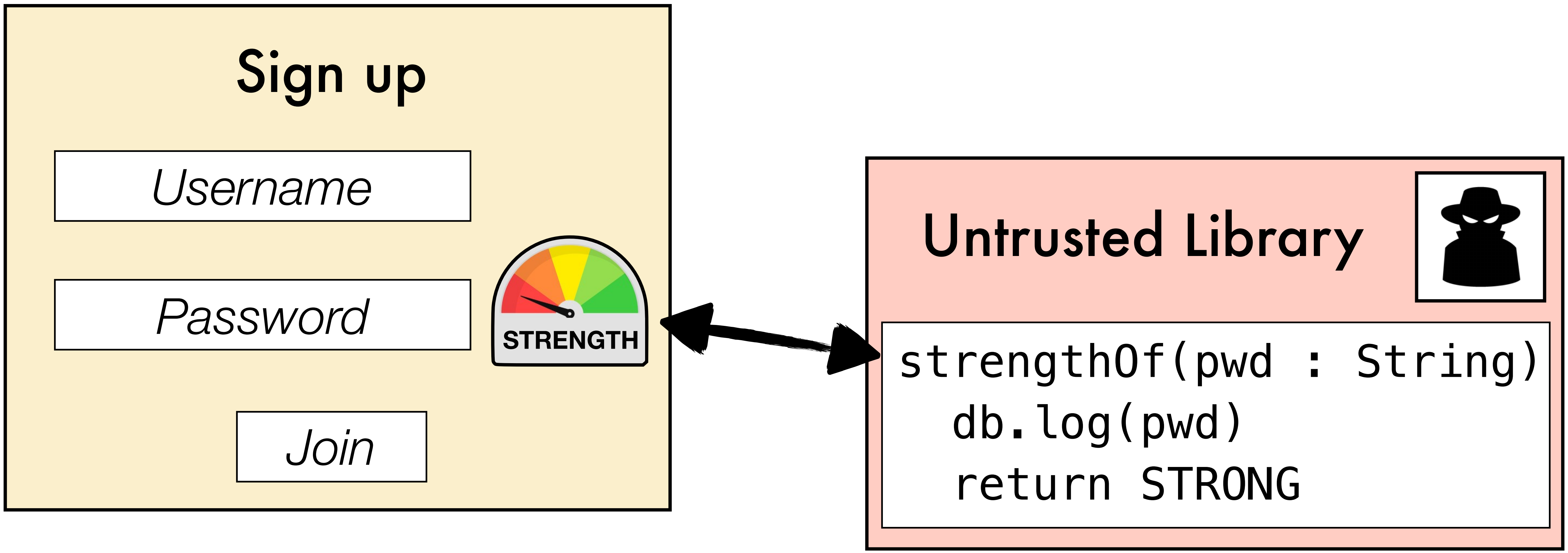
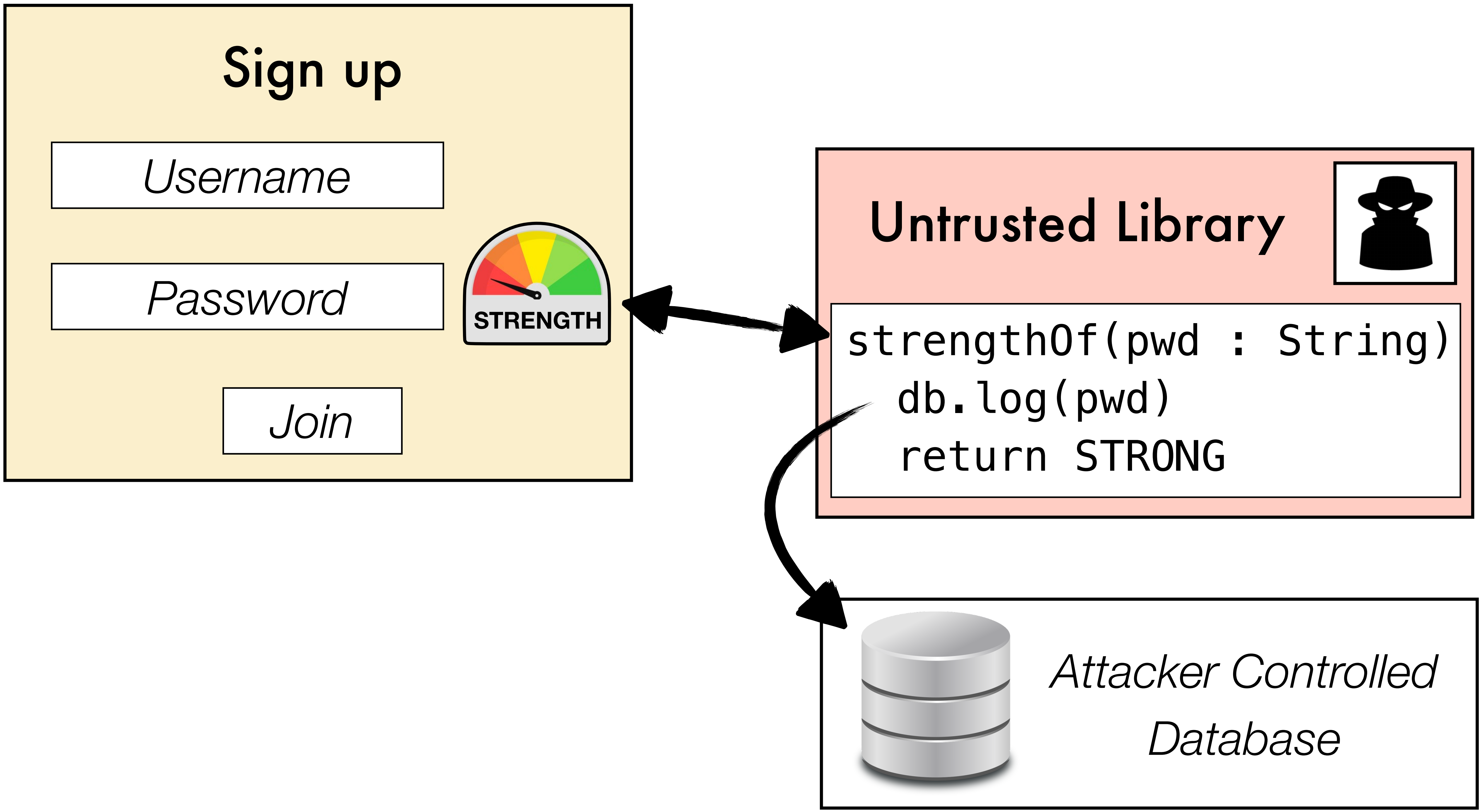

Sign up
Username
Password
STRENGTH
Join
Untrusted Library
strengthOf(pwd : String)
db.log(pwd)
return STRONG

Example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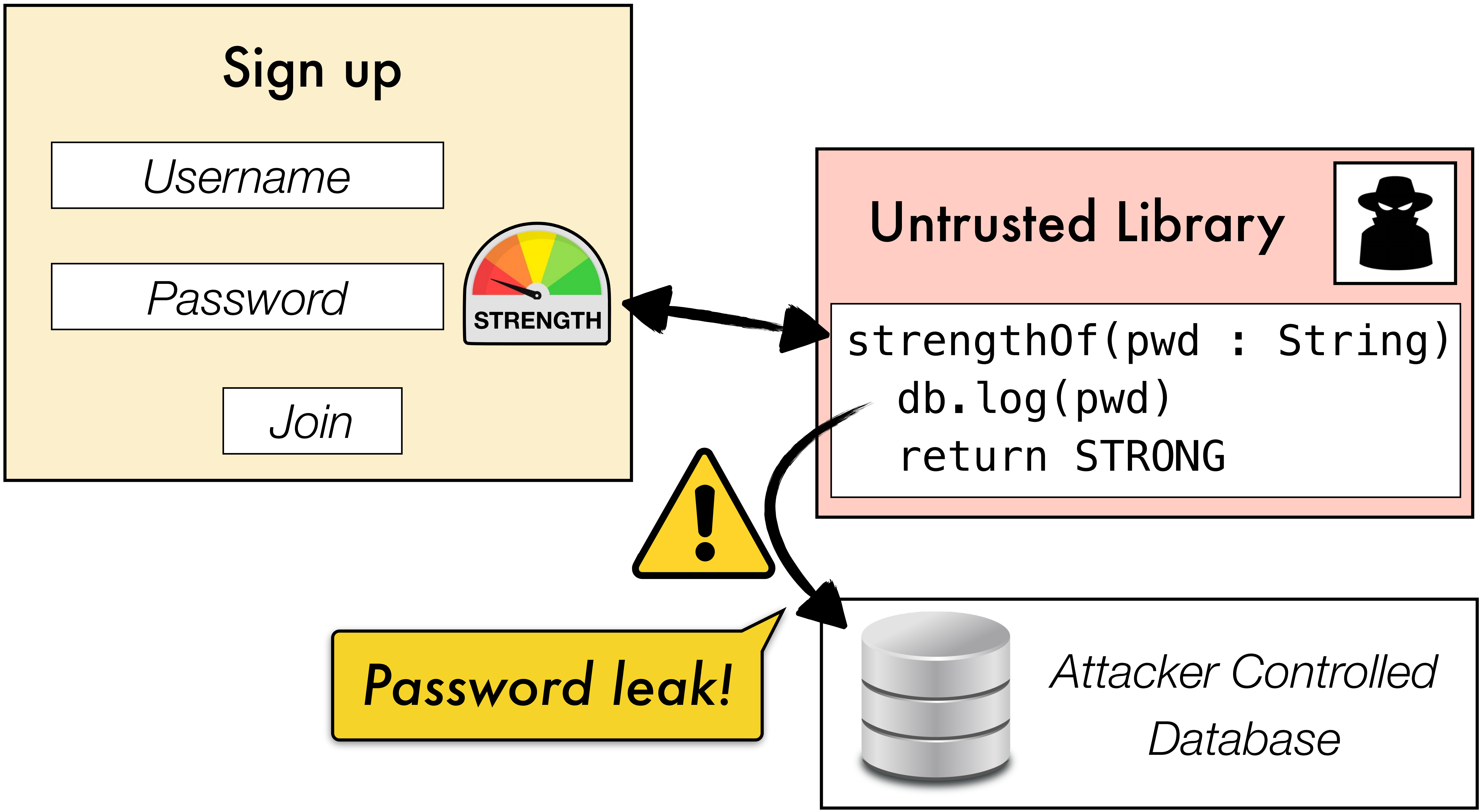
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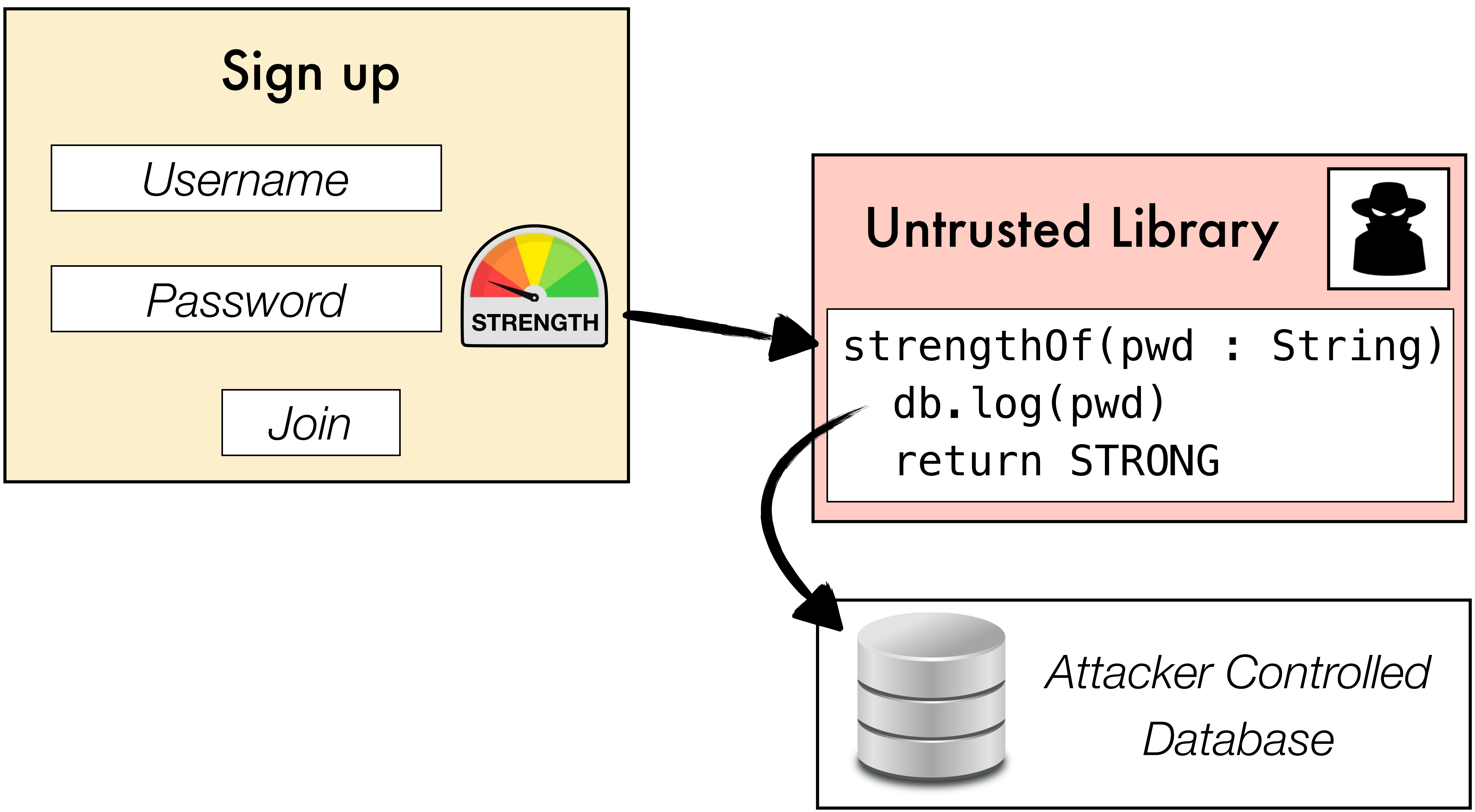
Access Control?

*Restrict **access** to sensitive data in untrusted components*



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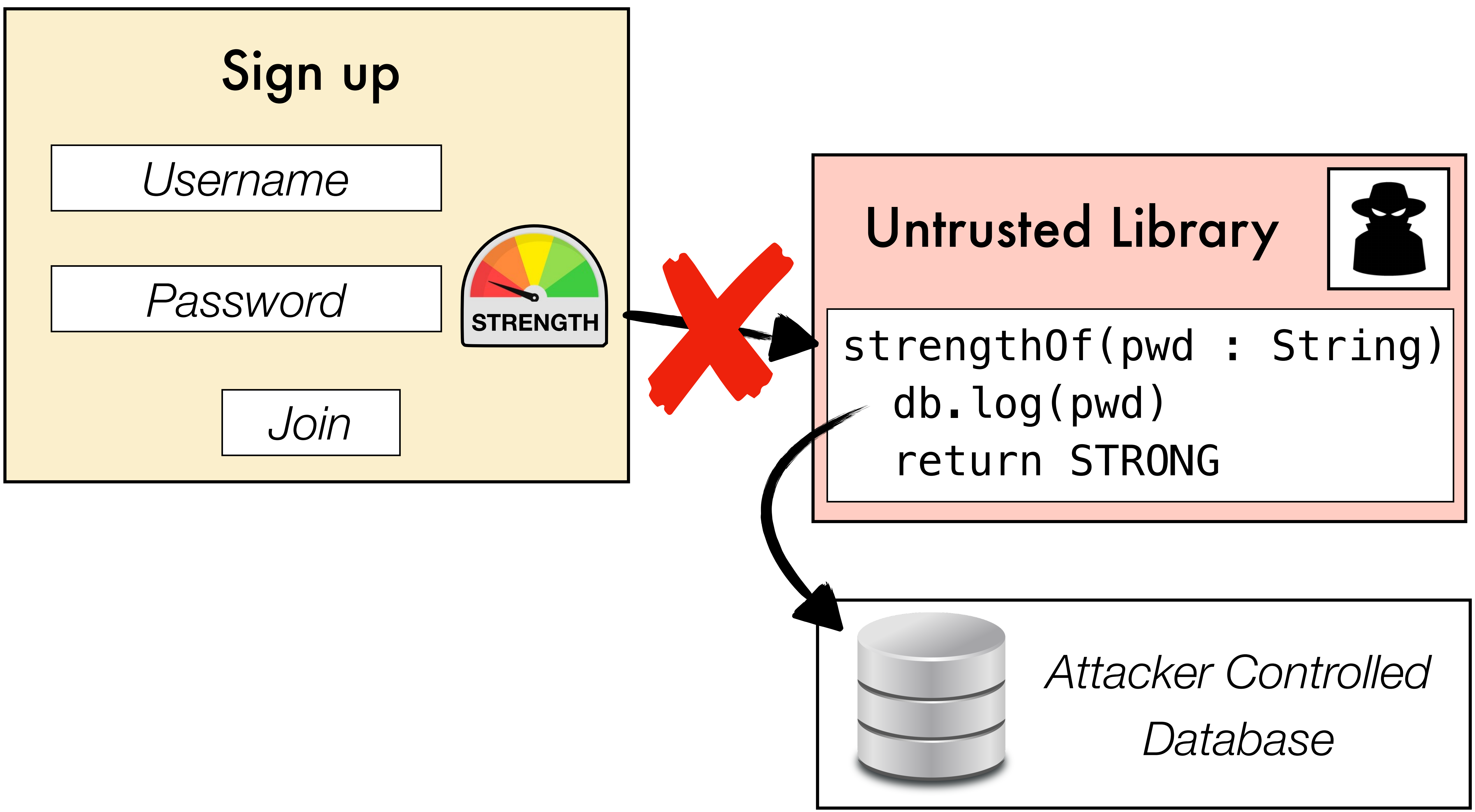

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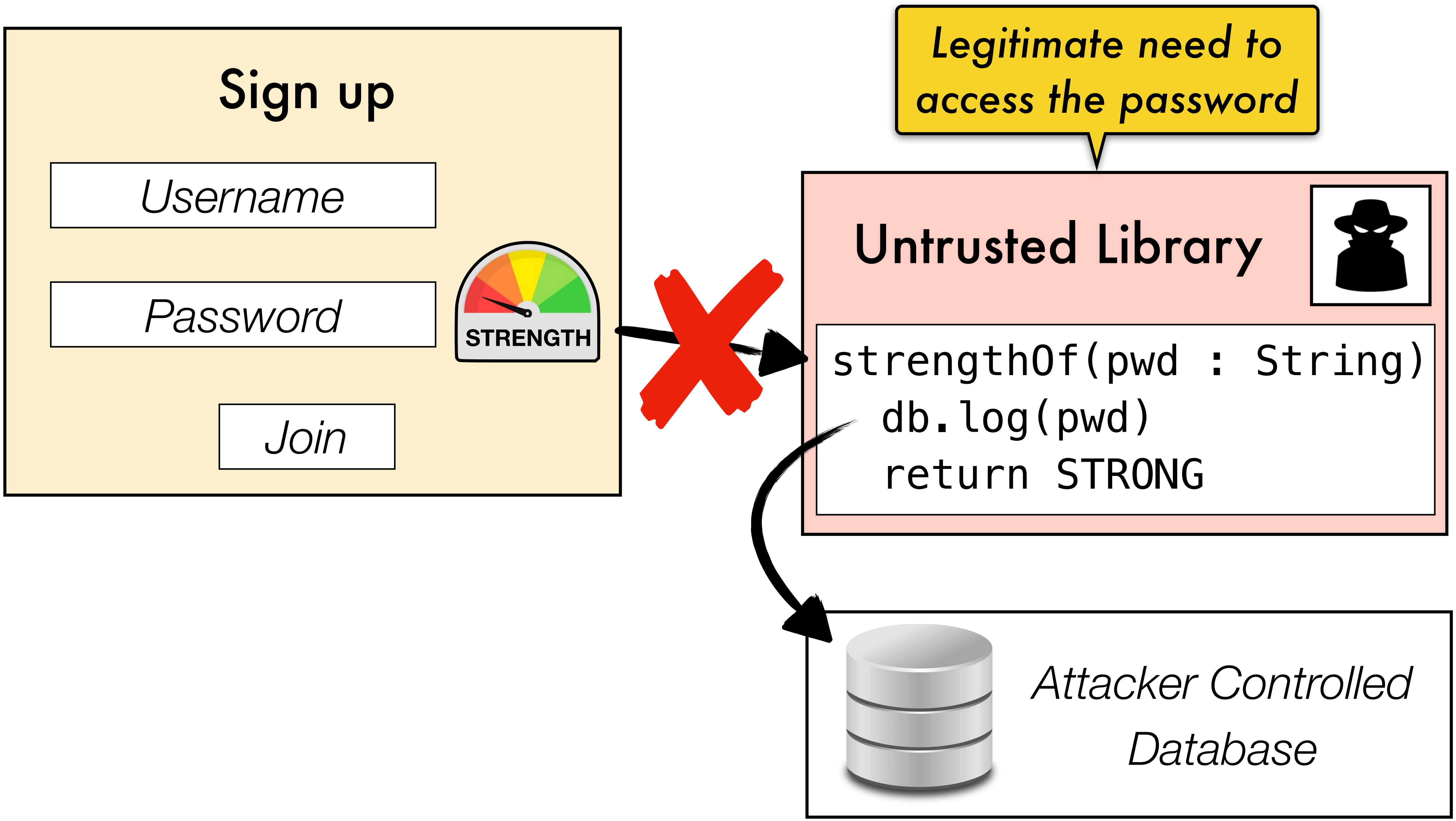

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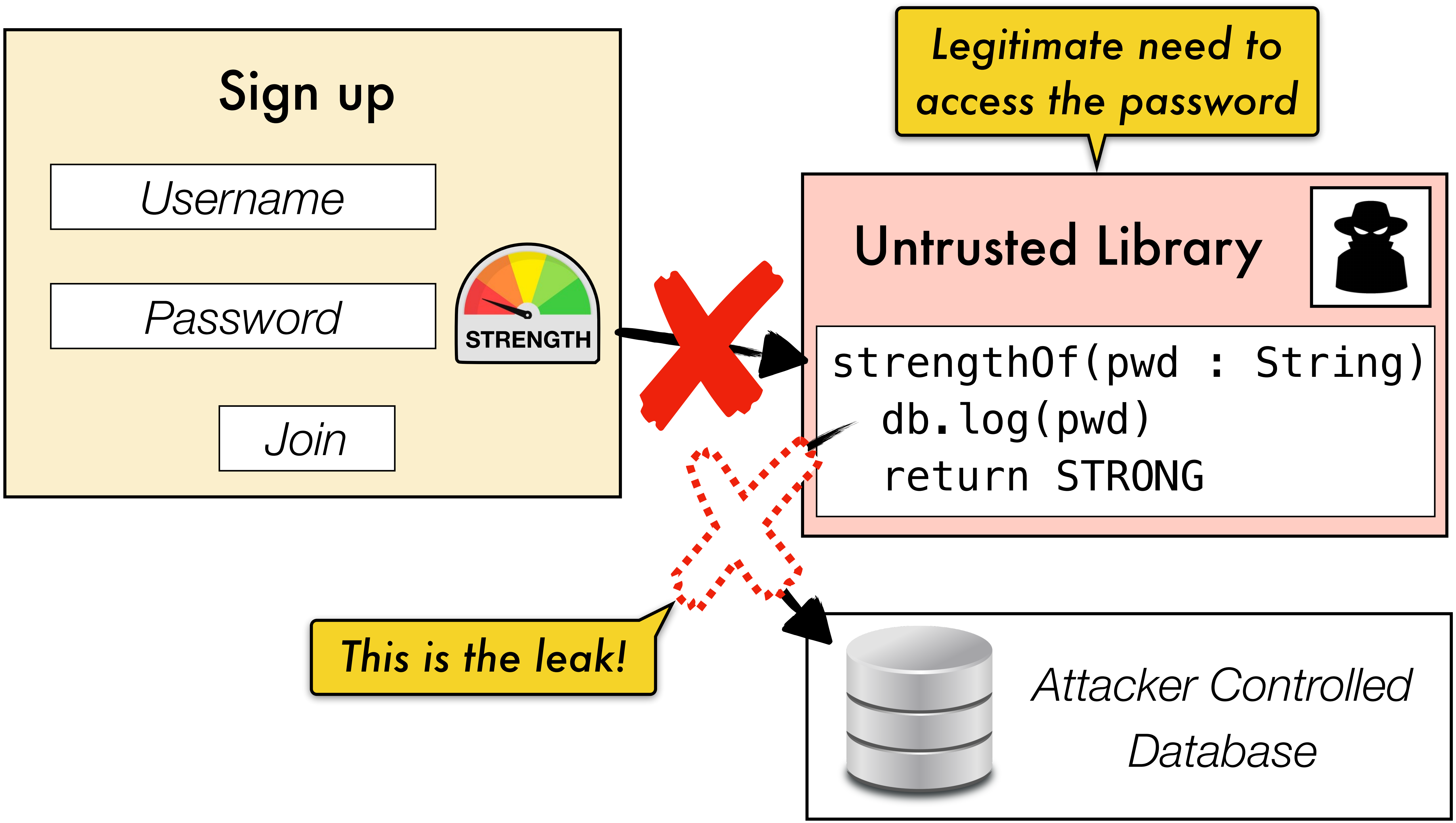

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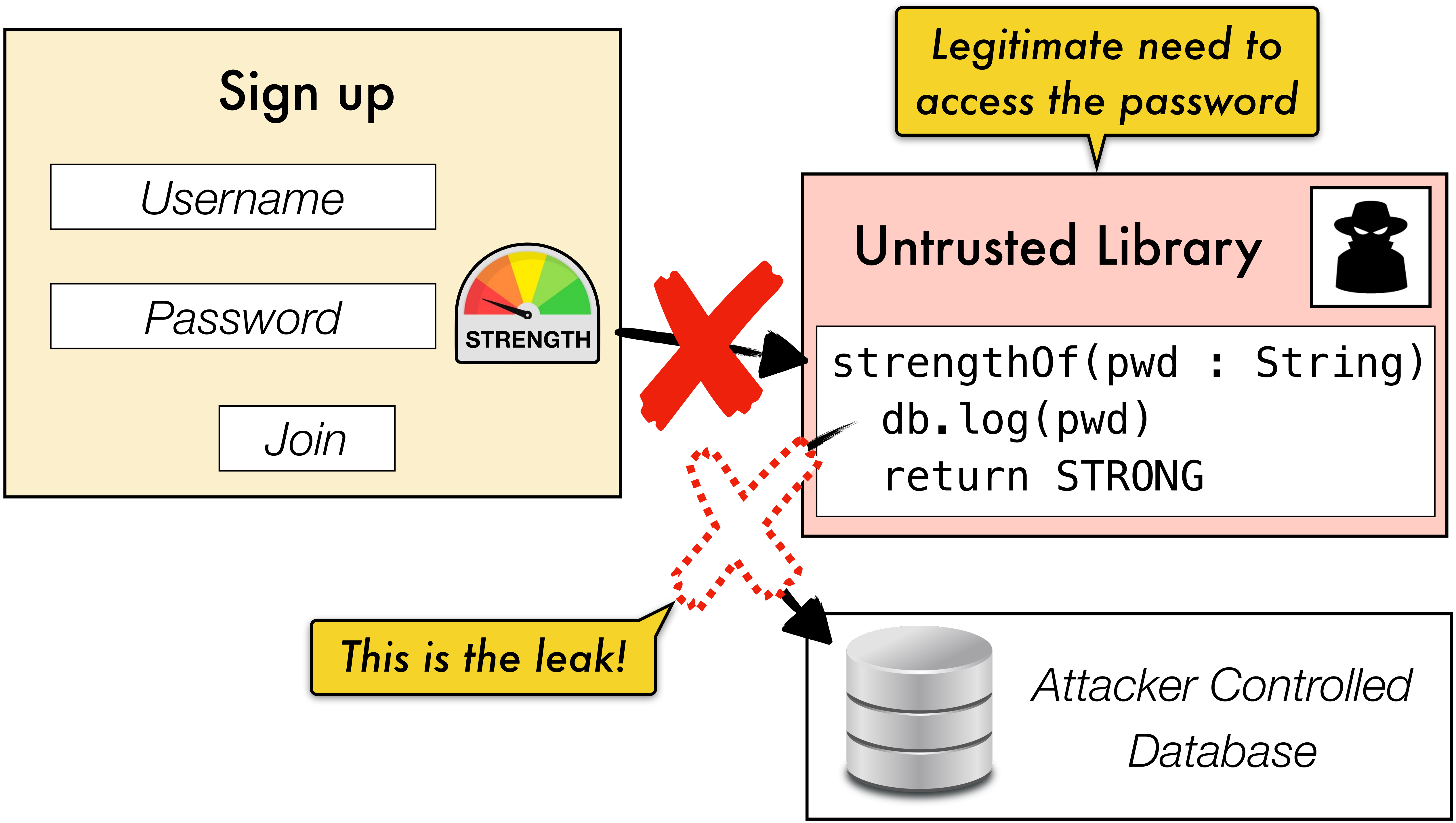
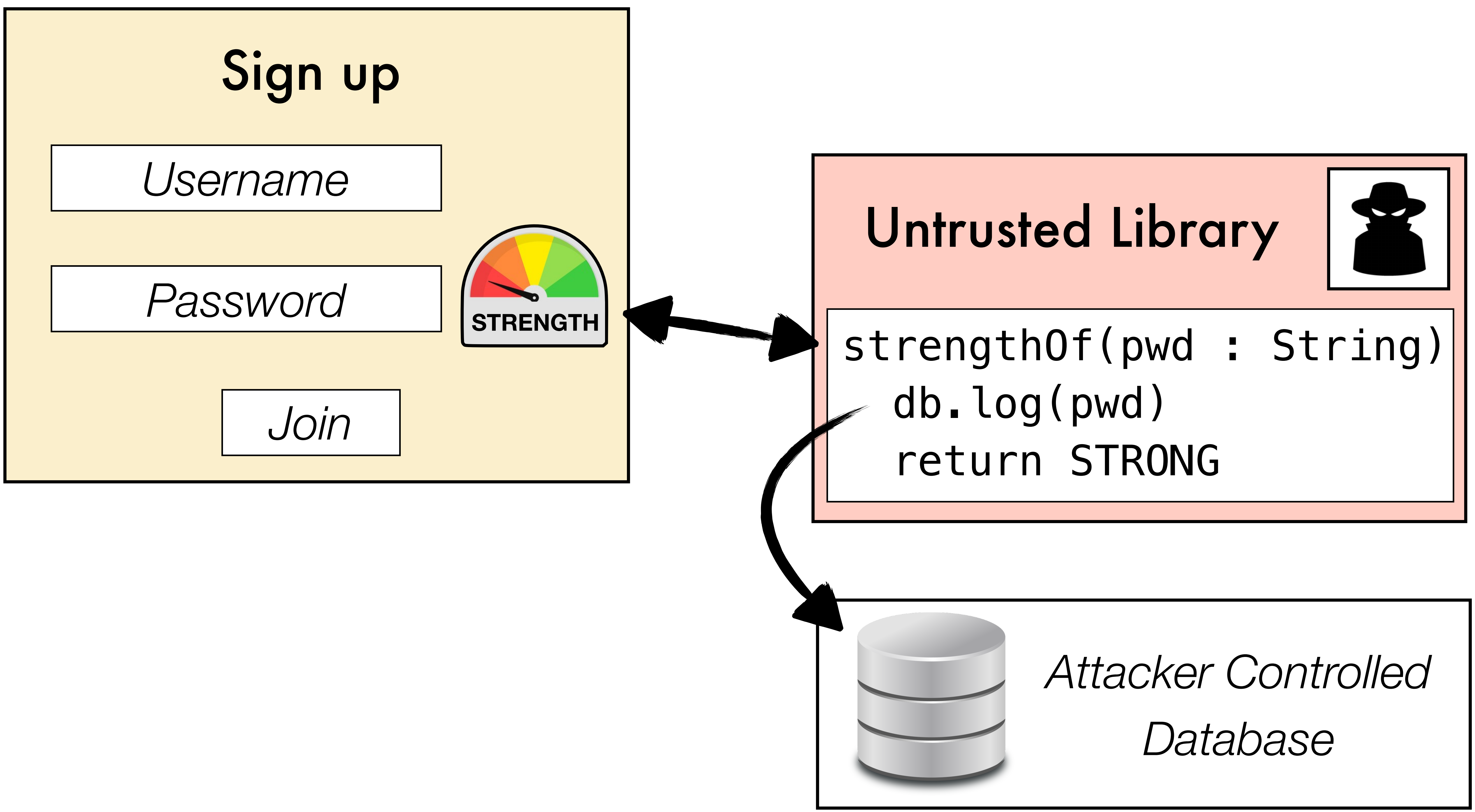


Information Flow Control

*Do not restrict data access, restrict **where** data can flow!*



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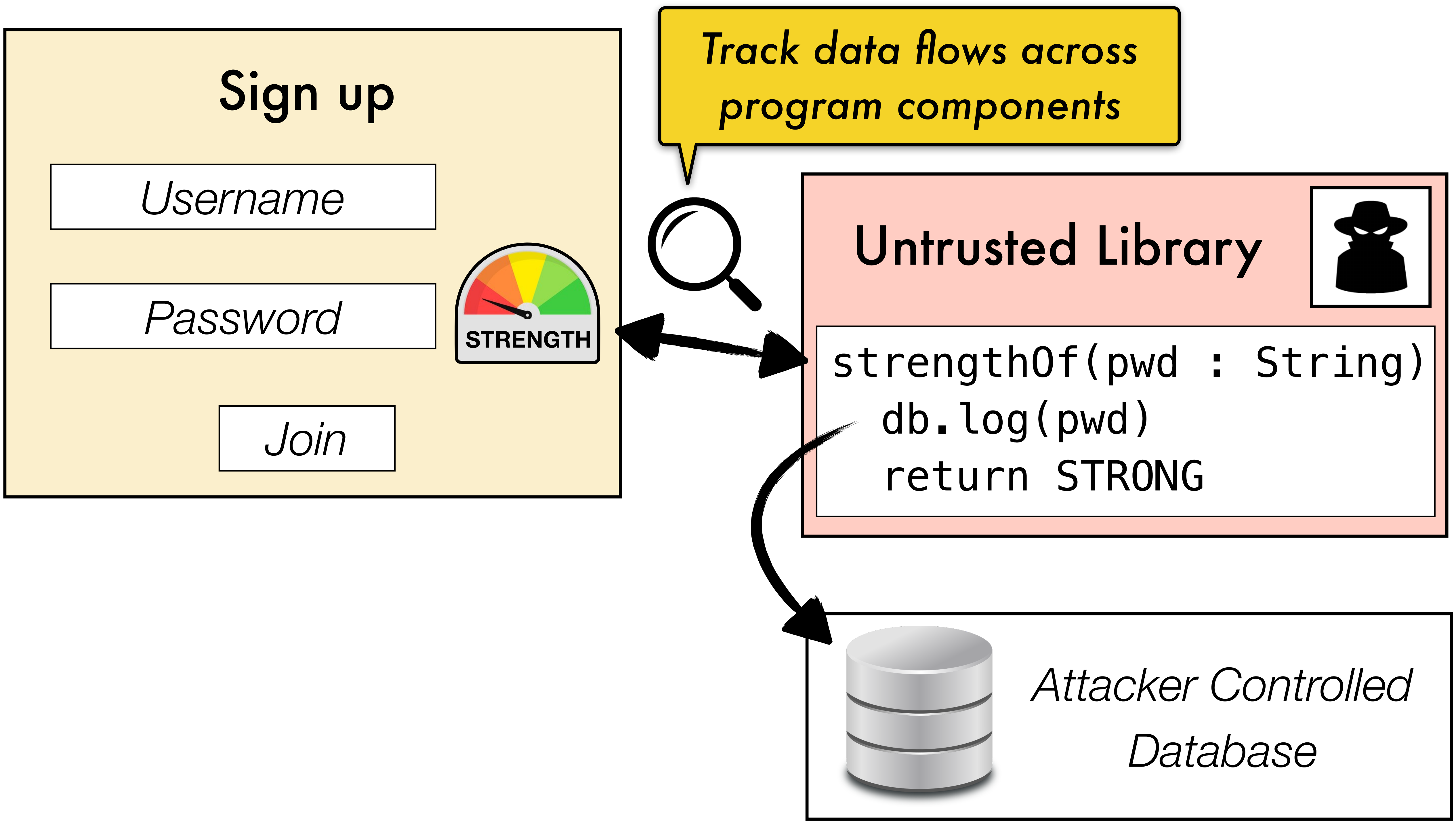

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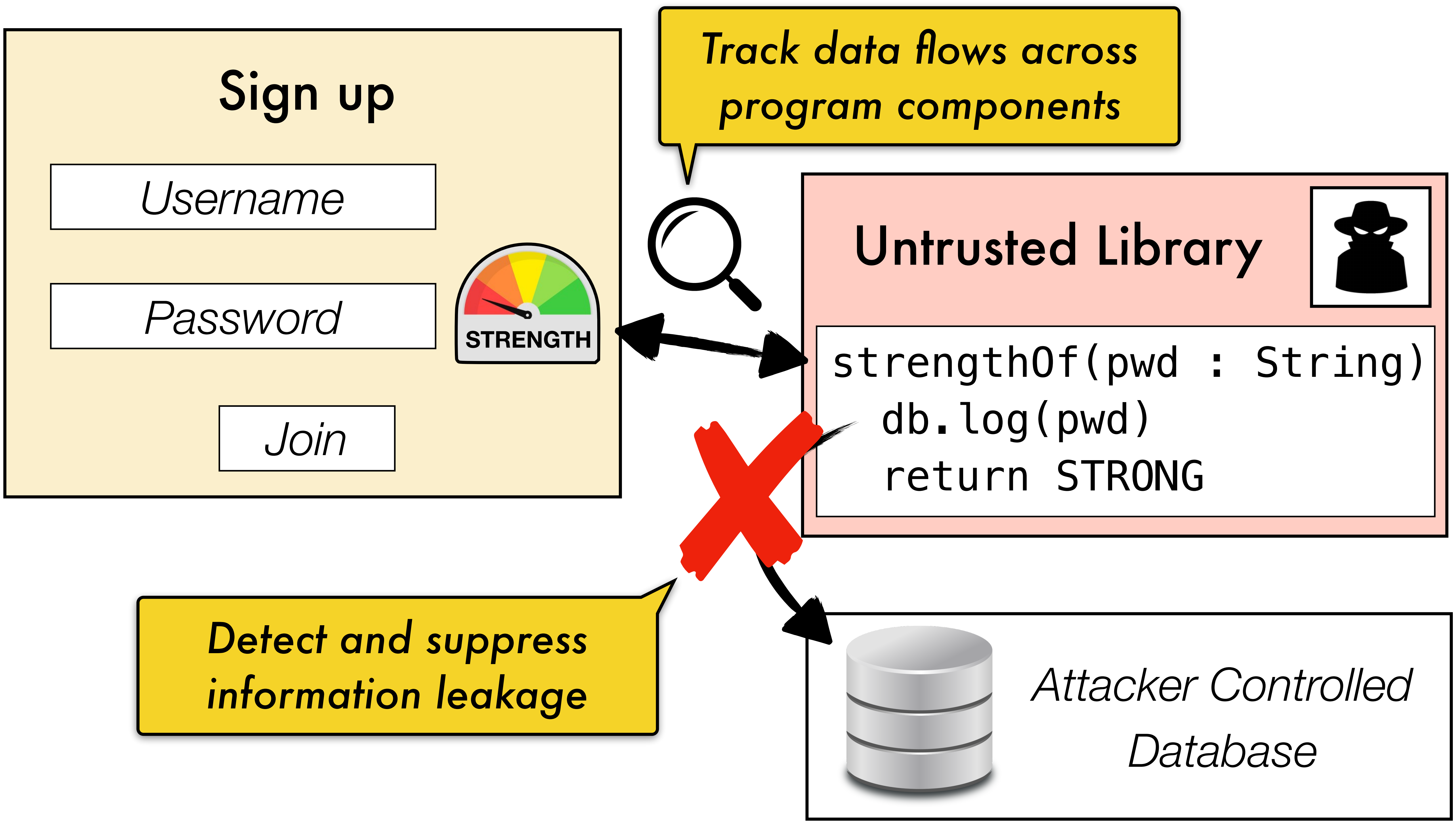

Facets of Language-based IFC

*Associate data with **security levels** to track data flows in programs*

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"Public" and "Secret"

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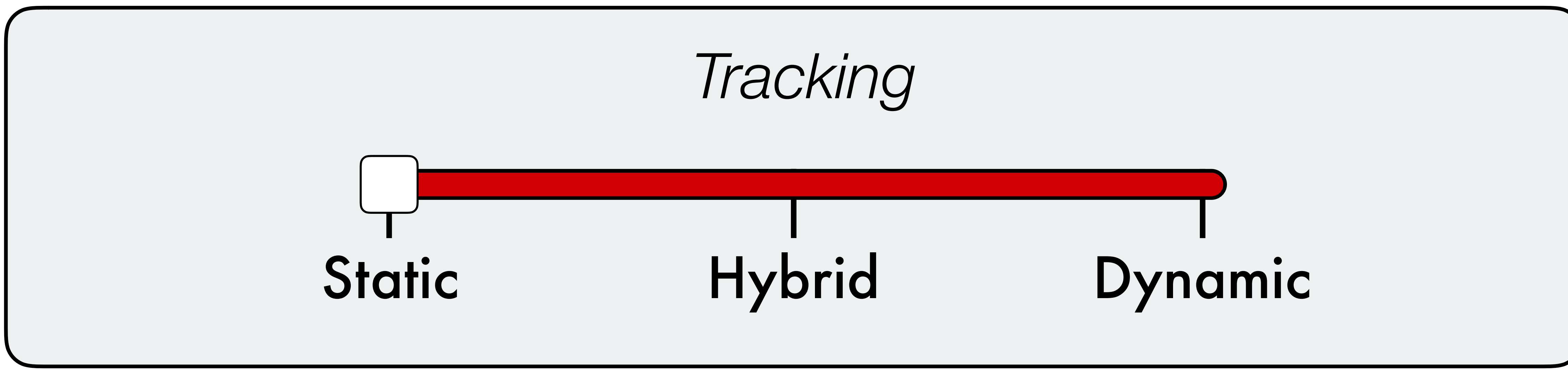

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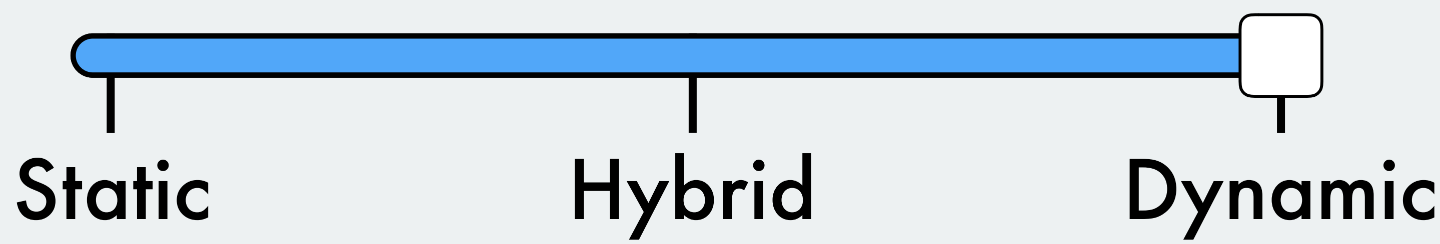
Tracking



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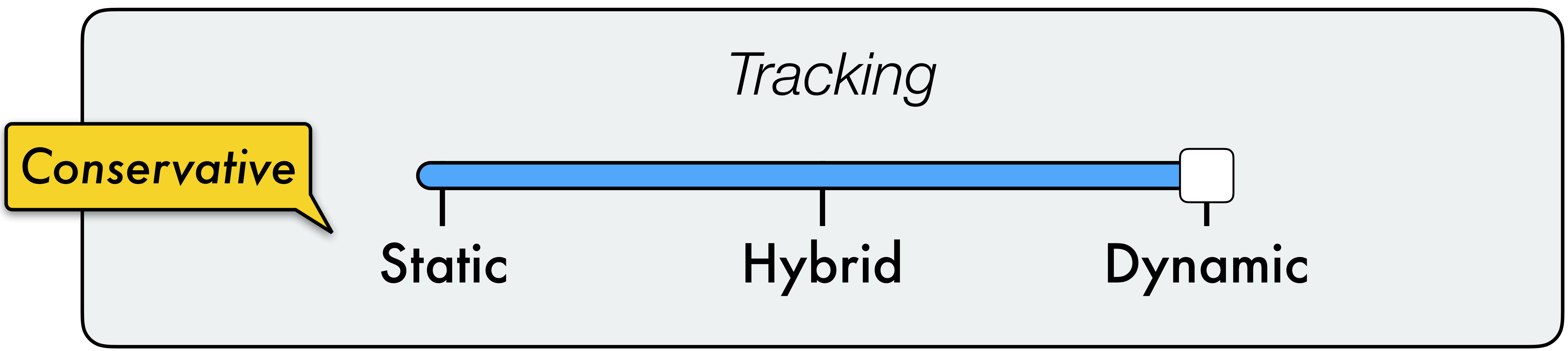

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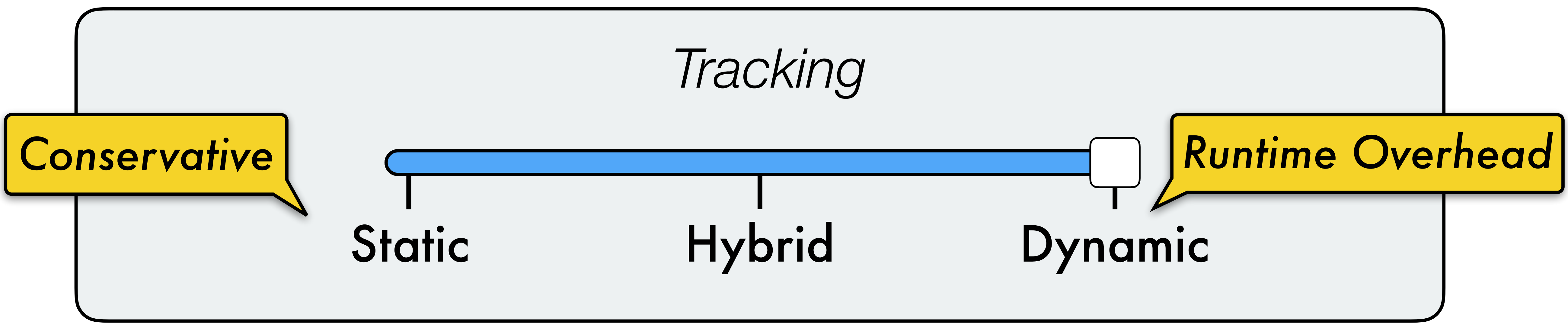

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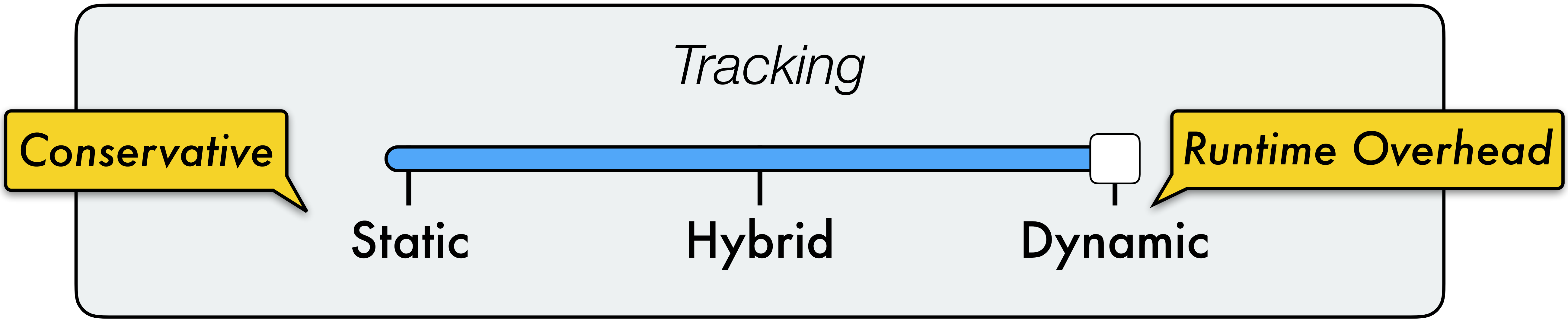

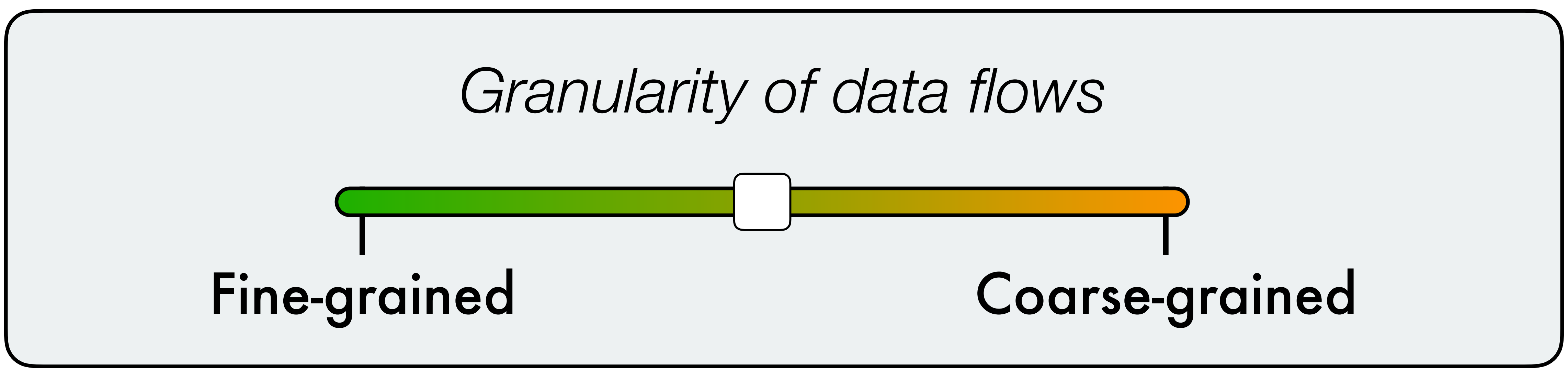

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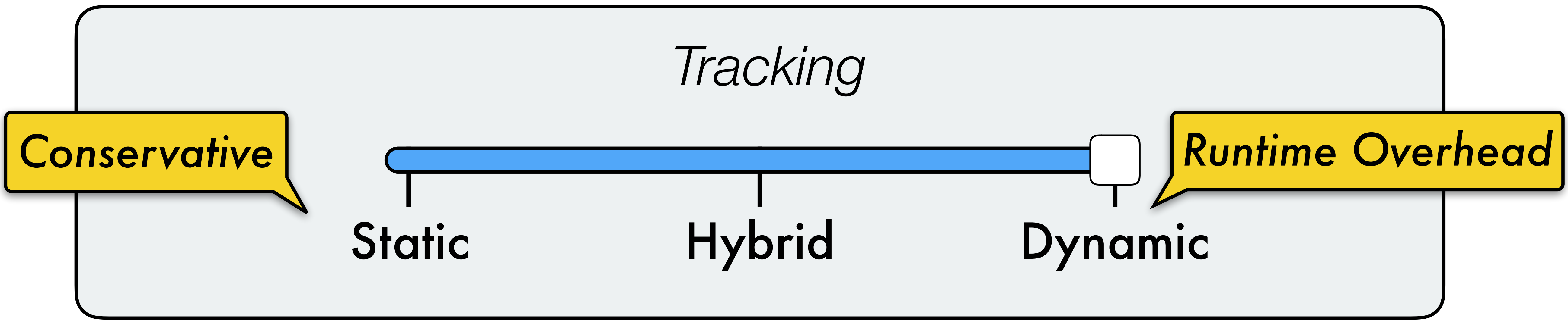

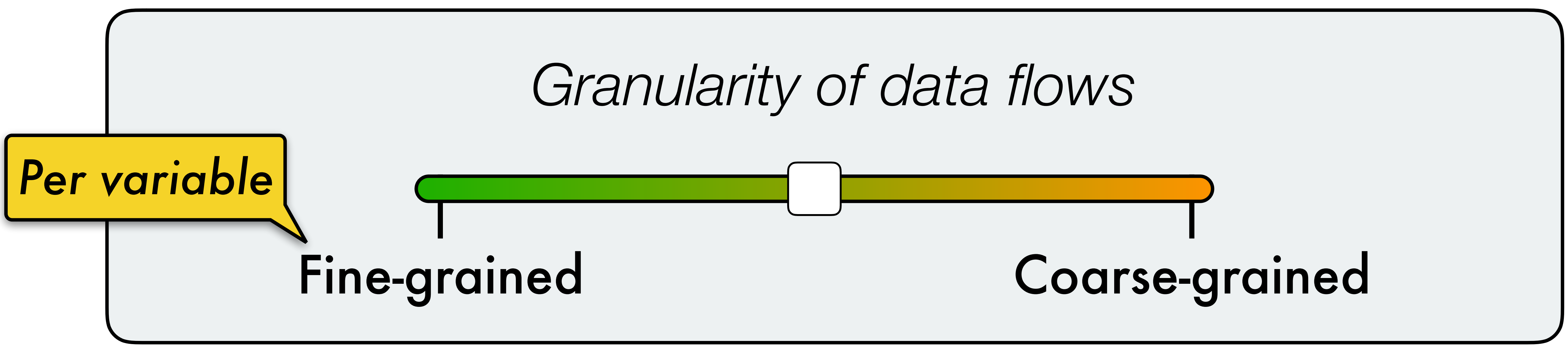

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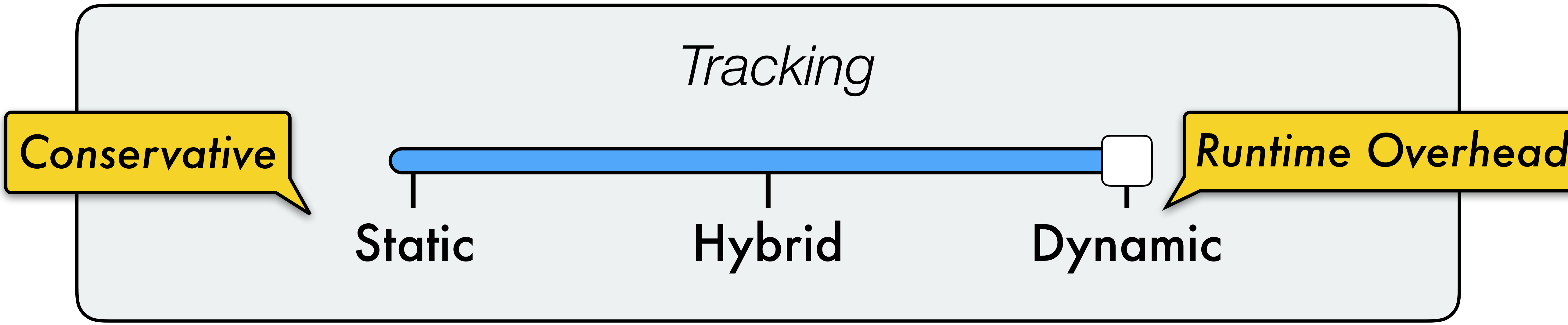

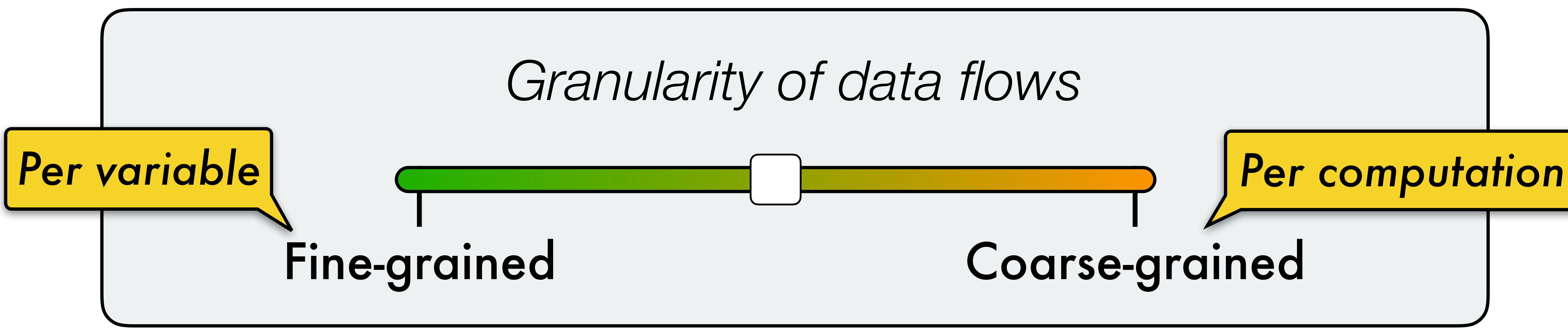

Plan

Overview of different language-based IFC approaches

- Non Interference

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Confidentiality & Integrity

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- 4 IFC Languages

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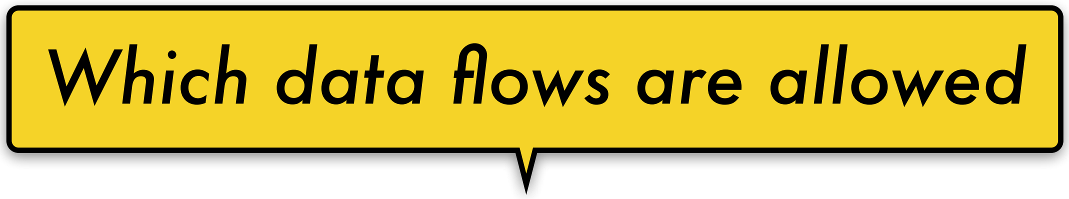
	Static	*Dynamic*
Fine-grained	$\lambda^{\mathbf{SFG}}$	$\lambda^{\mathbf{DFG}}$
Coarse-grained	$\lambda^{\mathbf{SCG}}$	$\lambda^{\mathbf{DCG}}$

Security Policy

Information flow policies are specified by the security lattice

Security Policy



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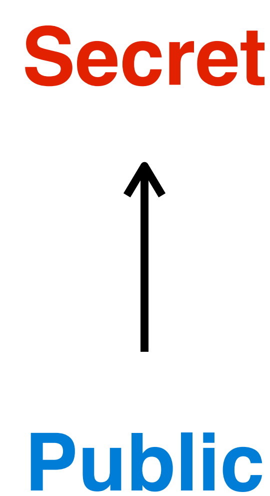
Security Policy

Which data flows are allowed

Information flow policies are specified by the security lattice

Simple lattice for ***confidentiality****:*



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Simple lattice for ***confidentiality****:*

Public and Secret are security labels

Secret

↑

Public

Security Policy

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*"***Secret** *inputs* ***cannot*** *flow to* **Public** *outputs"*

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2-point lattice

*"****Secret*** *inputs* ***cannot*** *flow to* ***Public*** *outputs"*

Simple lattice for ***confidentiality****:*

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↑

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Formally:

$$\mathscr{L}^{\mathbf{C}} = (\{\mathbf{P},\mathbf{S}\} , \sqsubseteq^{\mathbf{C}} , \sqcup^{\mathbf{C}})$$

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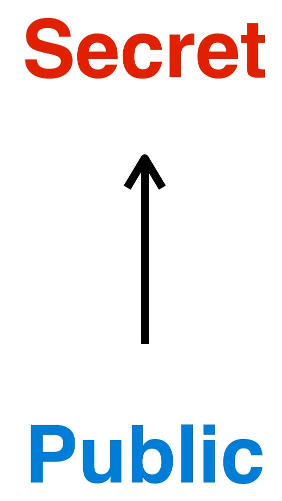

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Partial order between labels

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↑ $\sqsubseteq^{\mathbf{C}}$

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Partial order between labels

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$\uparrow \sqsubseteq^{C}$

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"Dual" lattice for ***integrity****:*

Untrusted

$\uparrow \sqsubseteq_I$

Trusted

*"***Untrusted** *inputs* ***cannot*** *flow to* **Trusted** *outputs"*

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Secret
⊑C
Public
Untrusted
⊑I
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*Simple lattice for **confidentiality** and **integrity**:*

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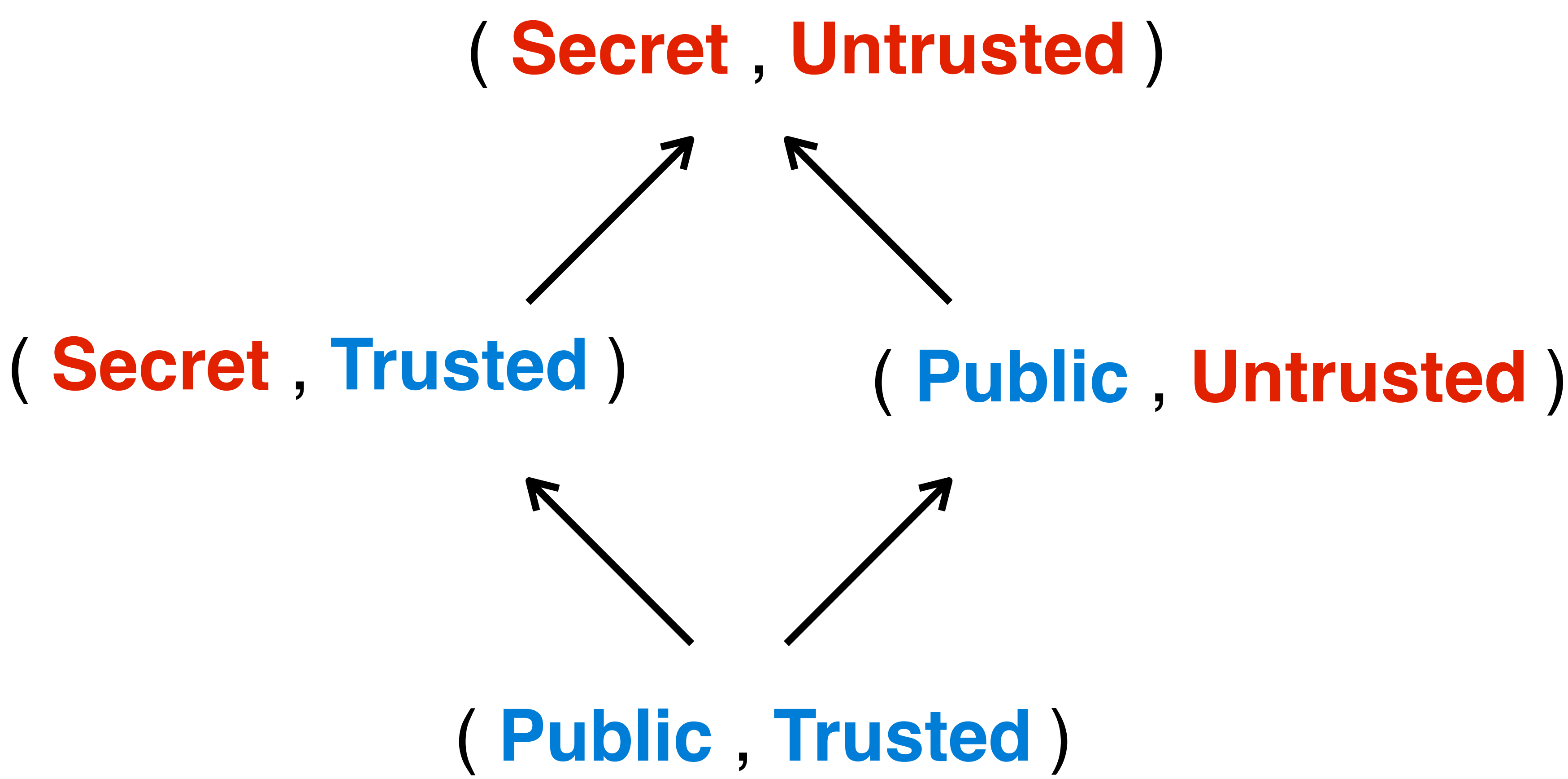

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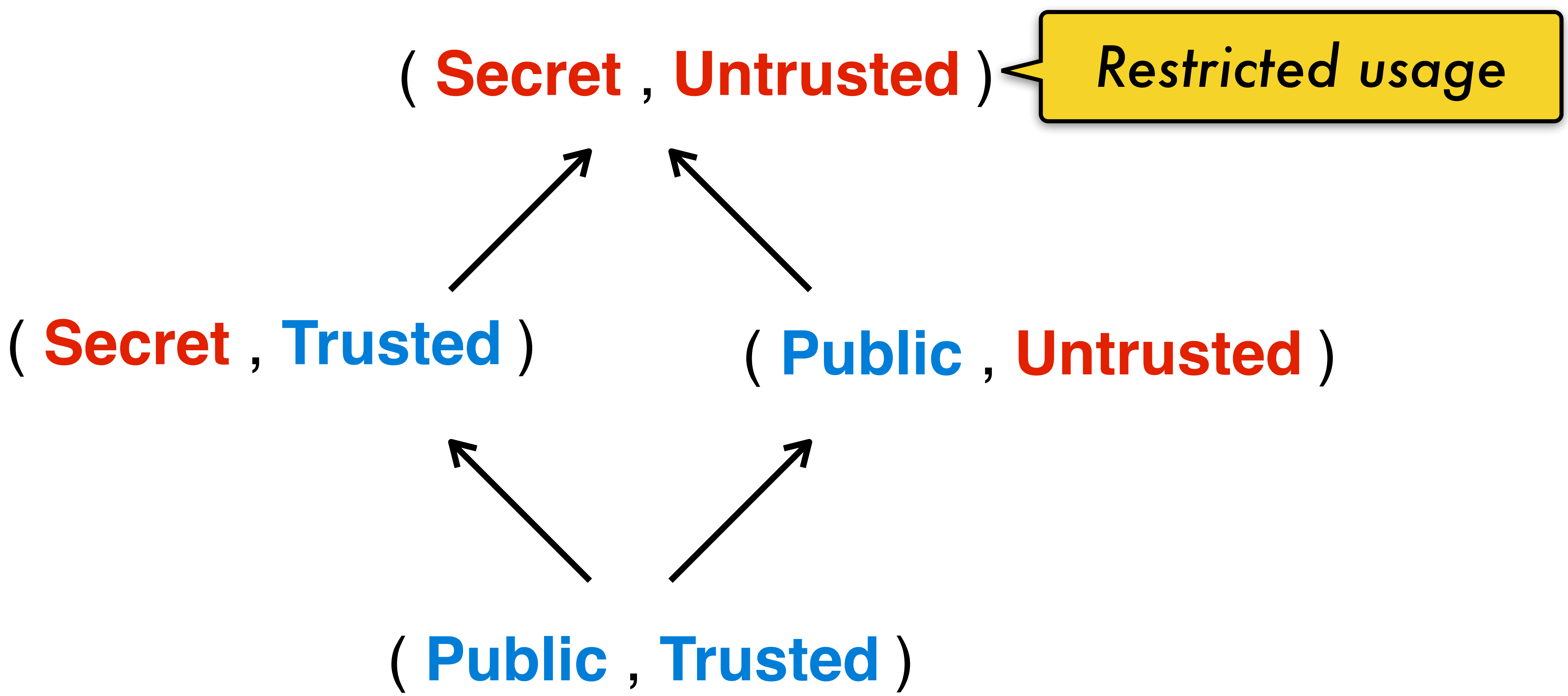

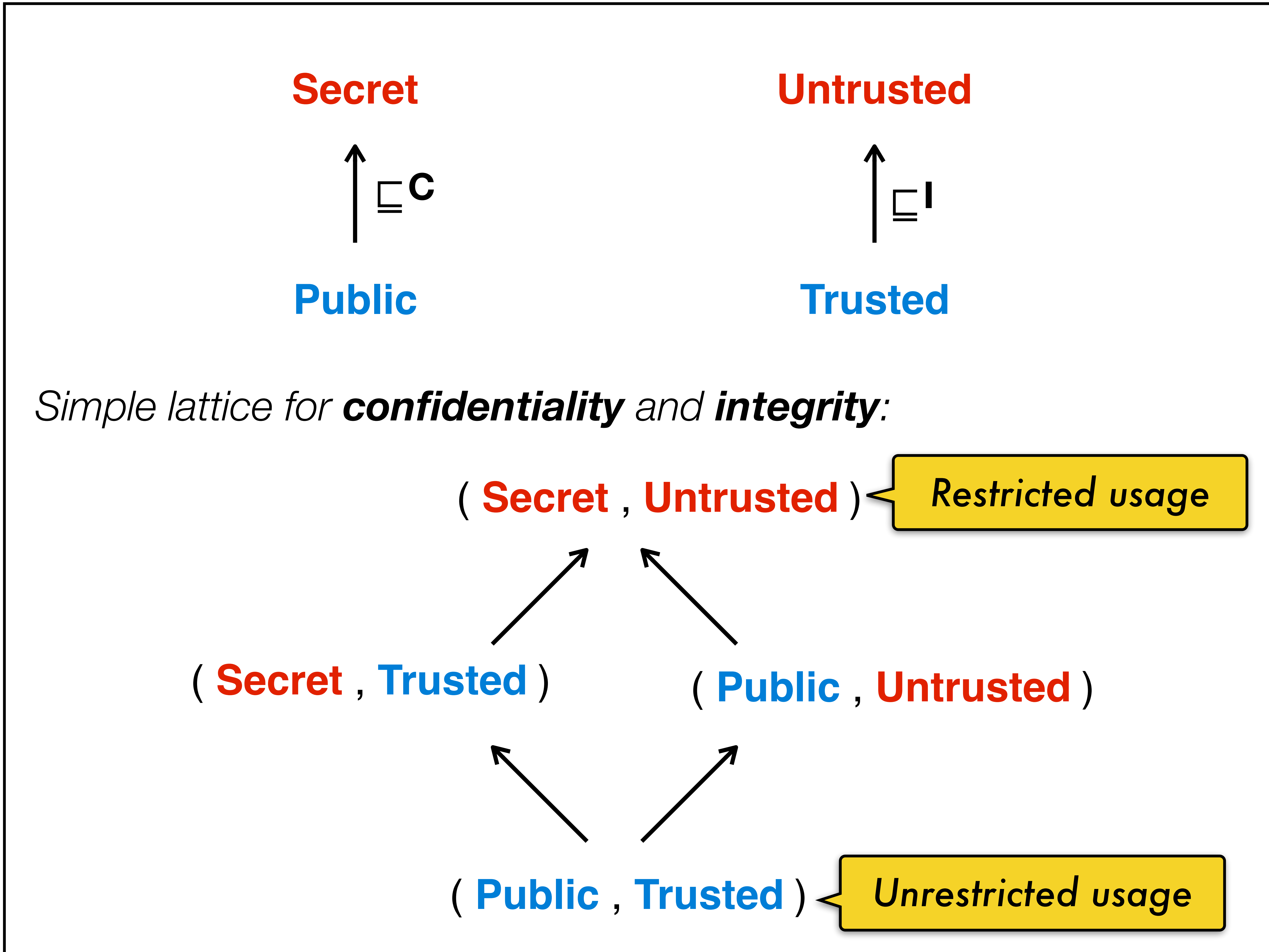
Secret
⊑C
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Simple lattice for confidentiality and integrity:
(Secret , Untrusted)
Restricted usage
(Secret , Trusted)
(Public , Untrusted)
(Public , Trusted)
Unrestricted usage

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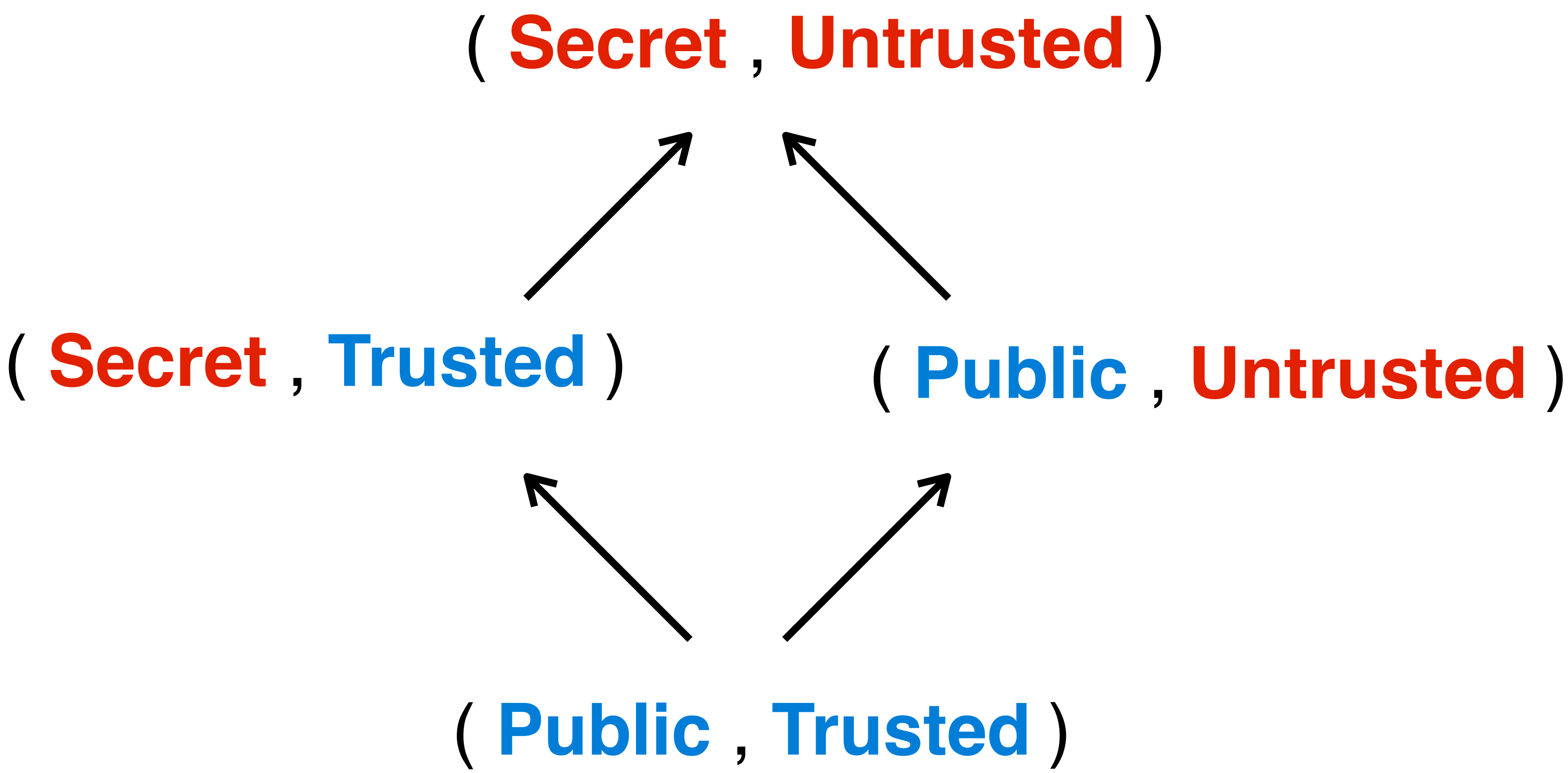

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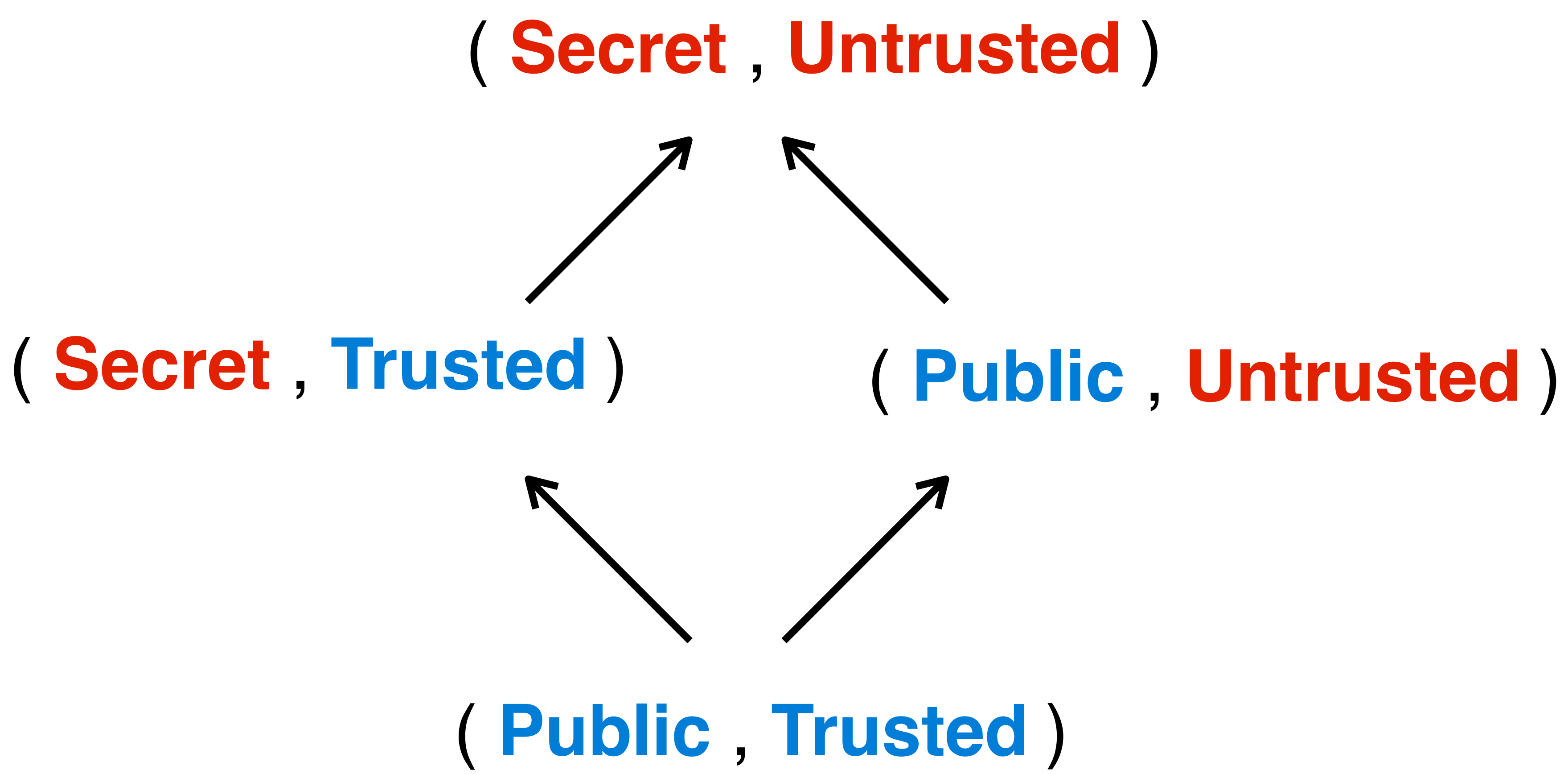

Formally:

$$\mathscr{L}^{CI} = (\{P,S\} \times \{T,U\} , \sqsubseteq^{C} \times \sqsubseteq^{I} , \sqcup^{C} \times \sqcup^{I})$$

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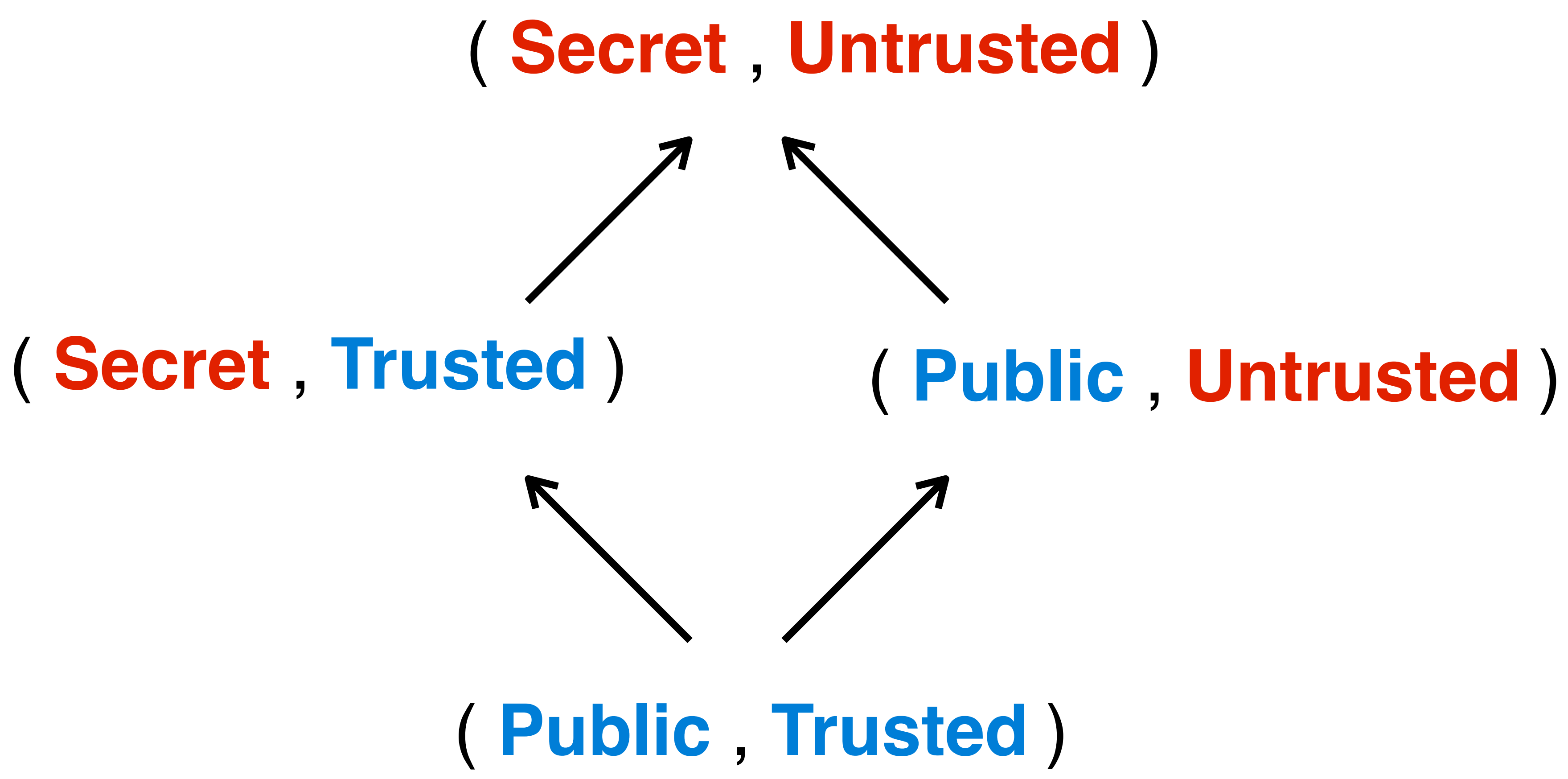

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Notice

$$(S , T) \not\sqsubseteq^{CI} (P , U) \qquad (P , U) \not\sqsubseteq^{CI} (S , T)$$

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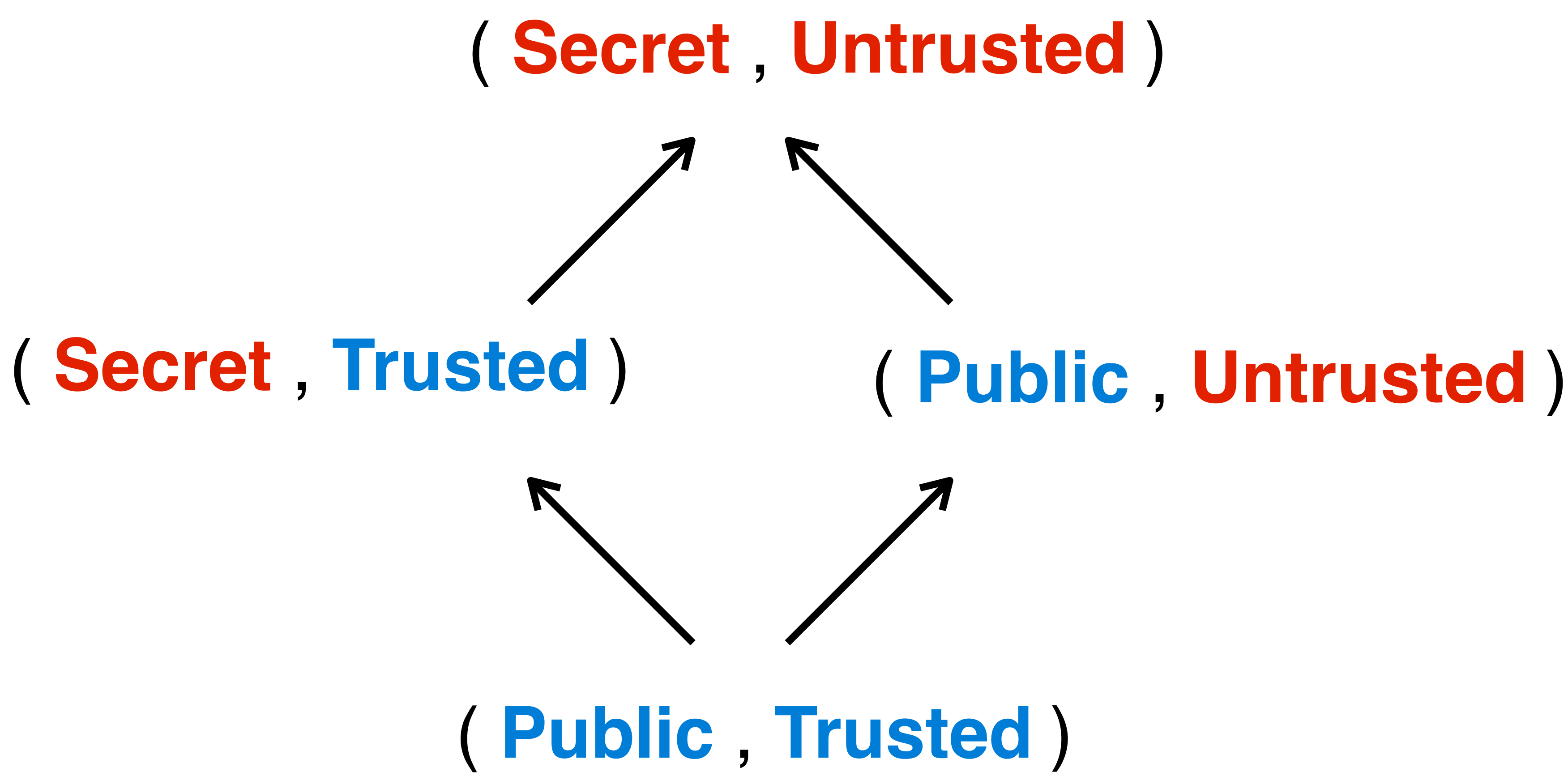

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Mutually Incomparable

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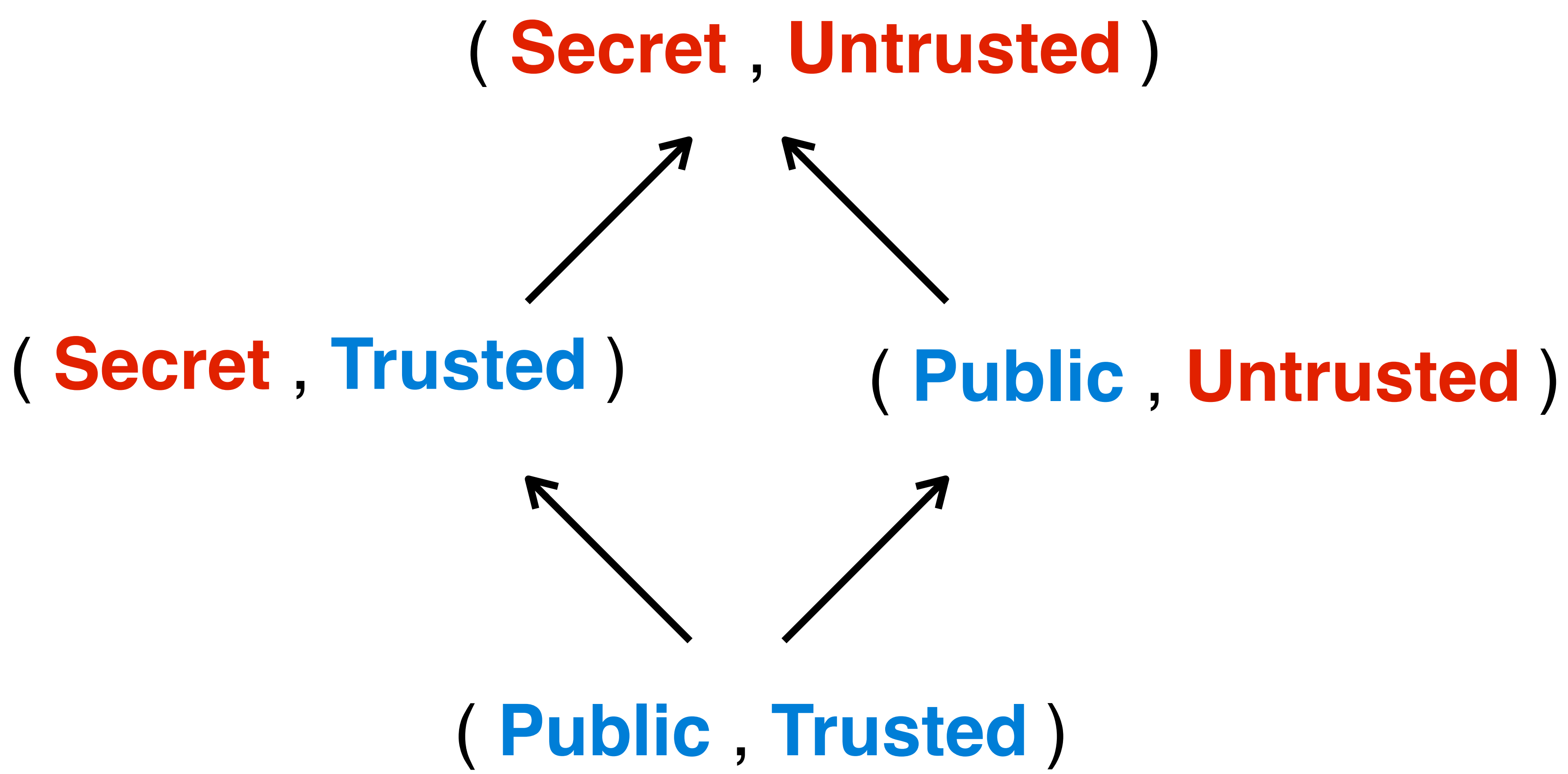

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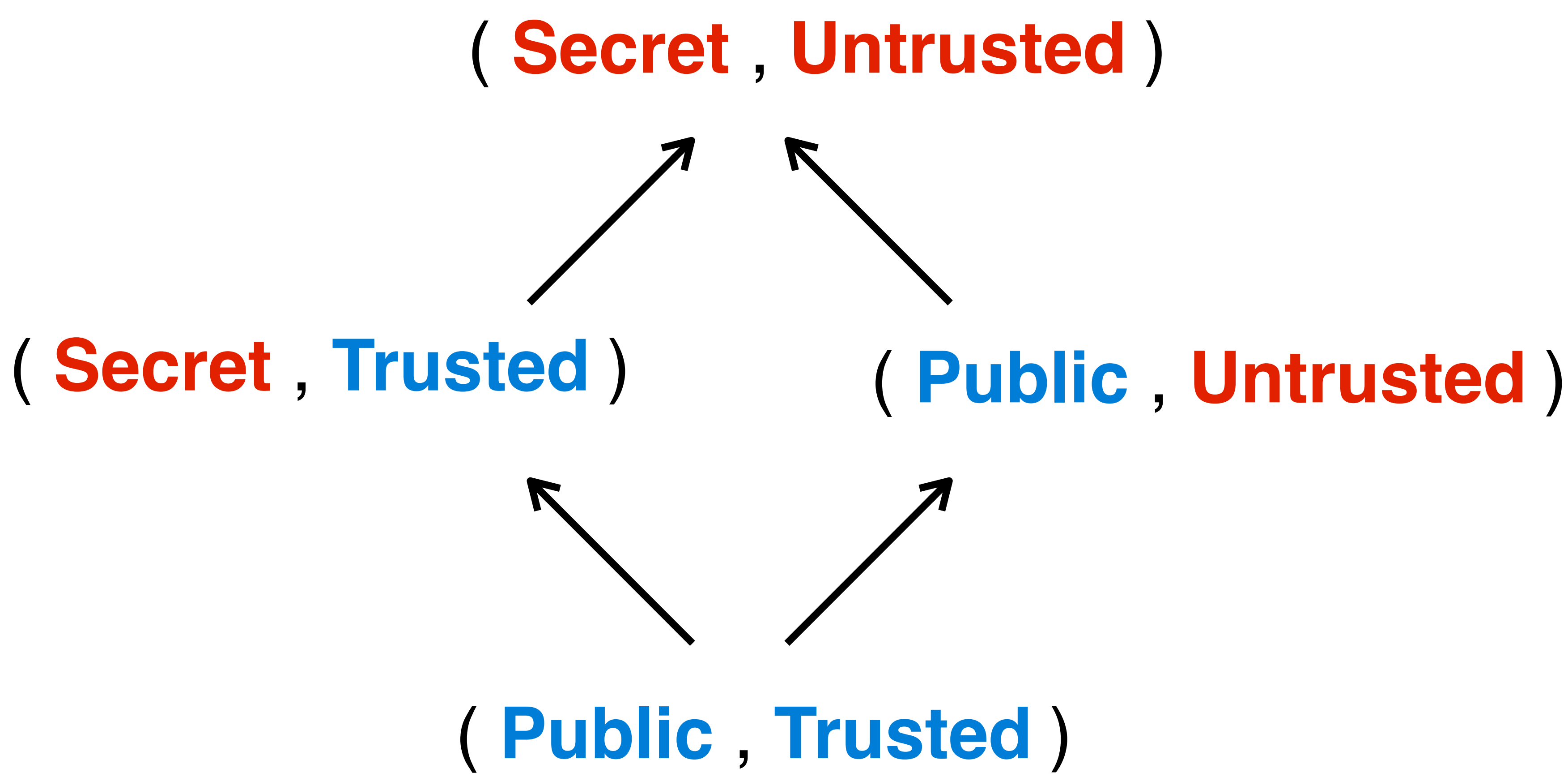

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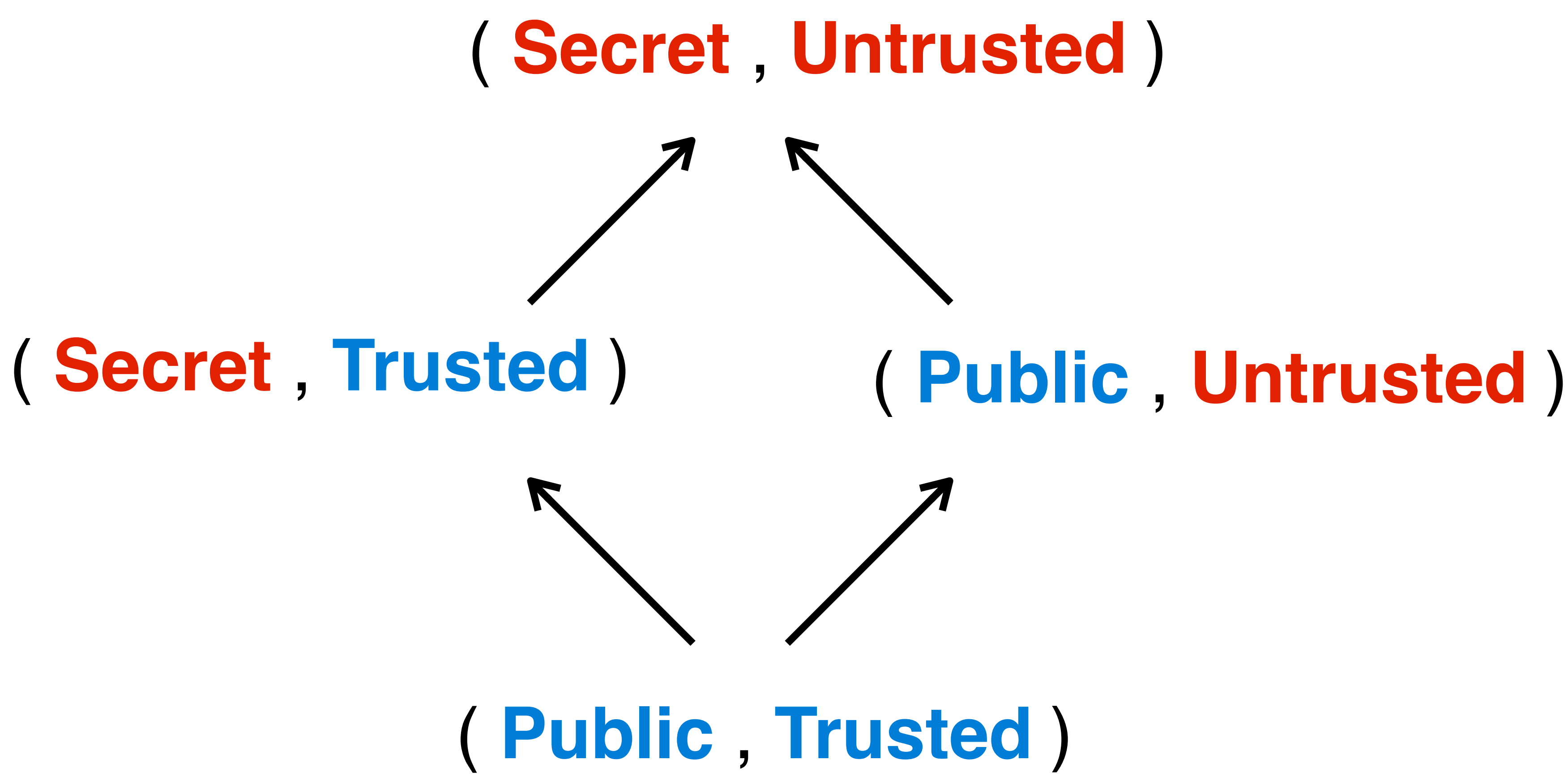

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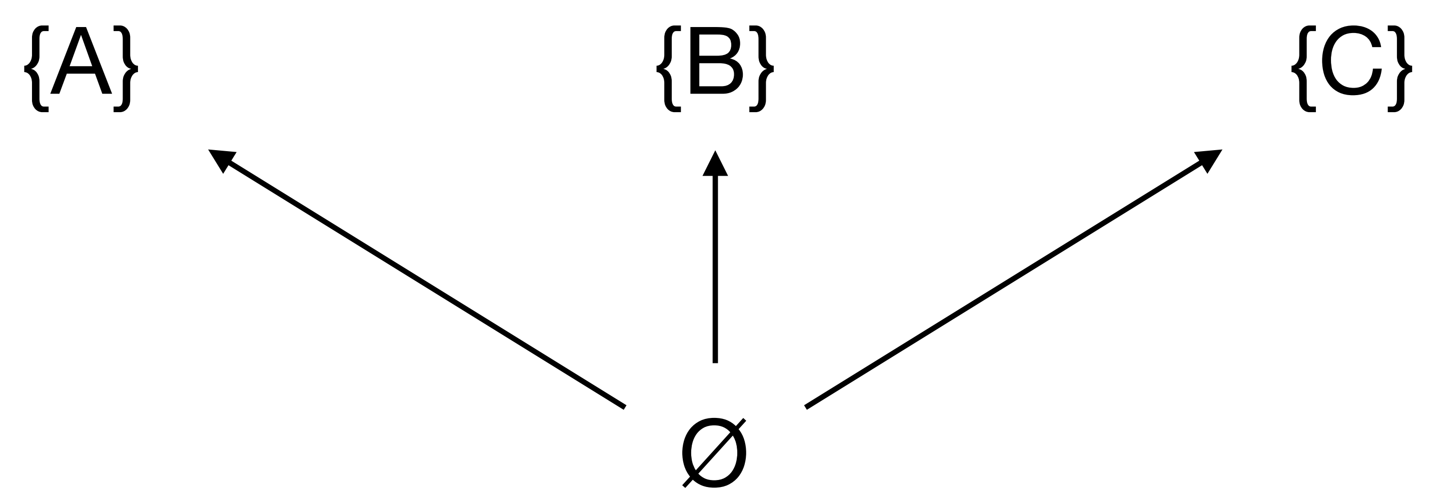

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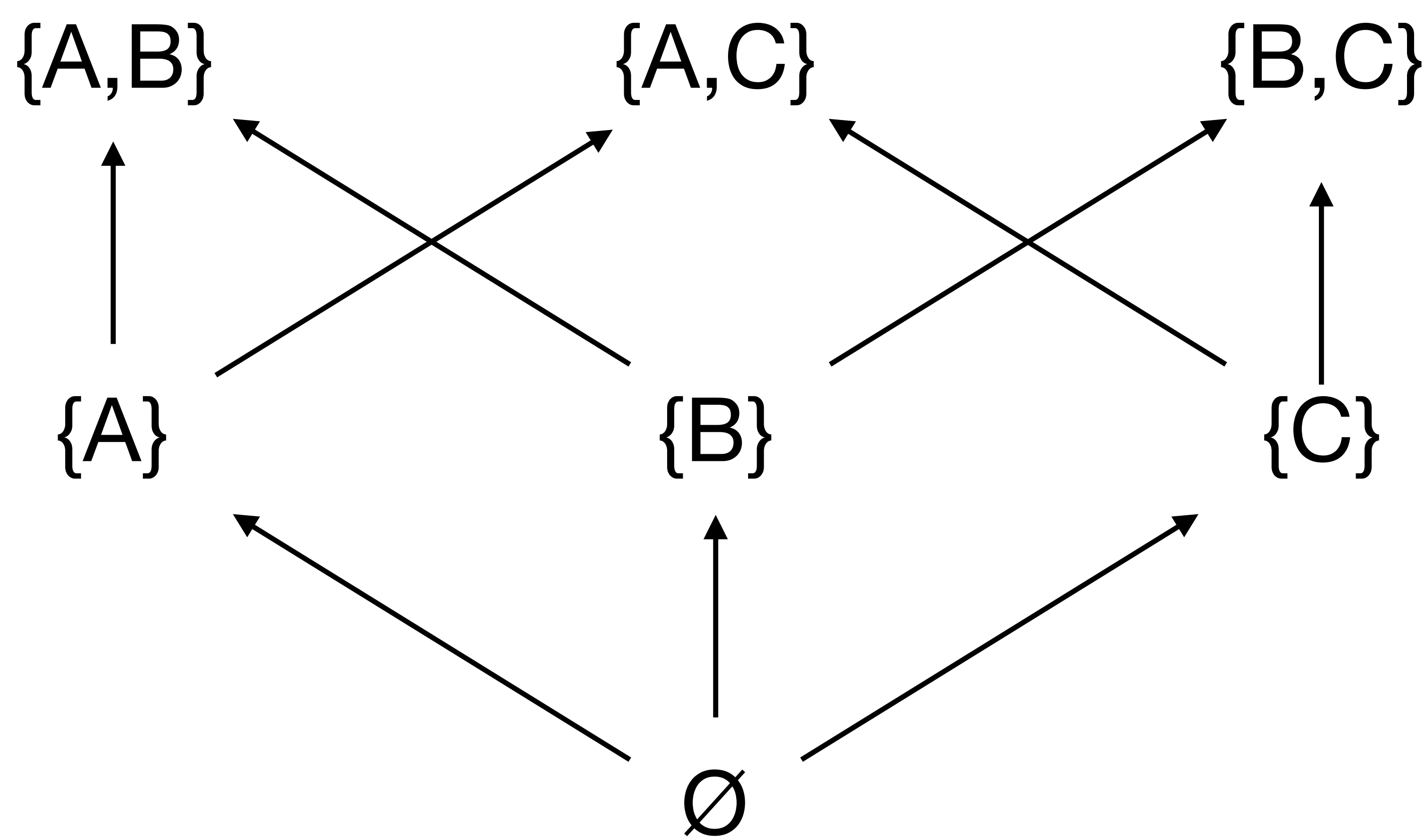

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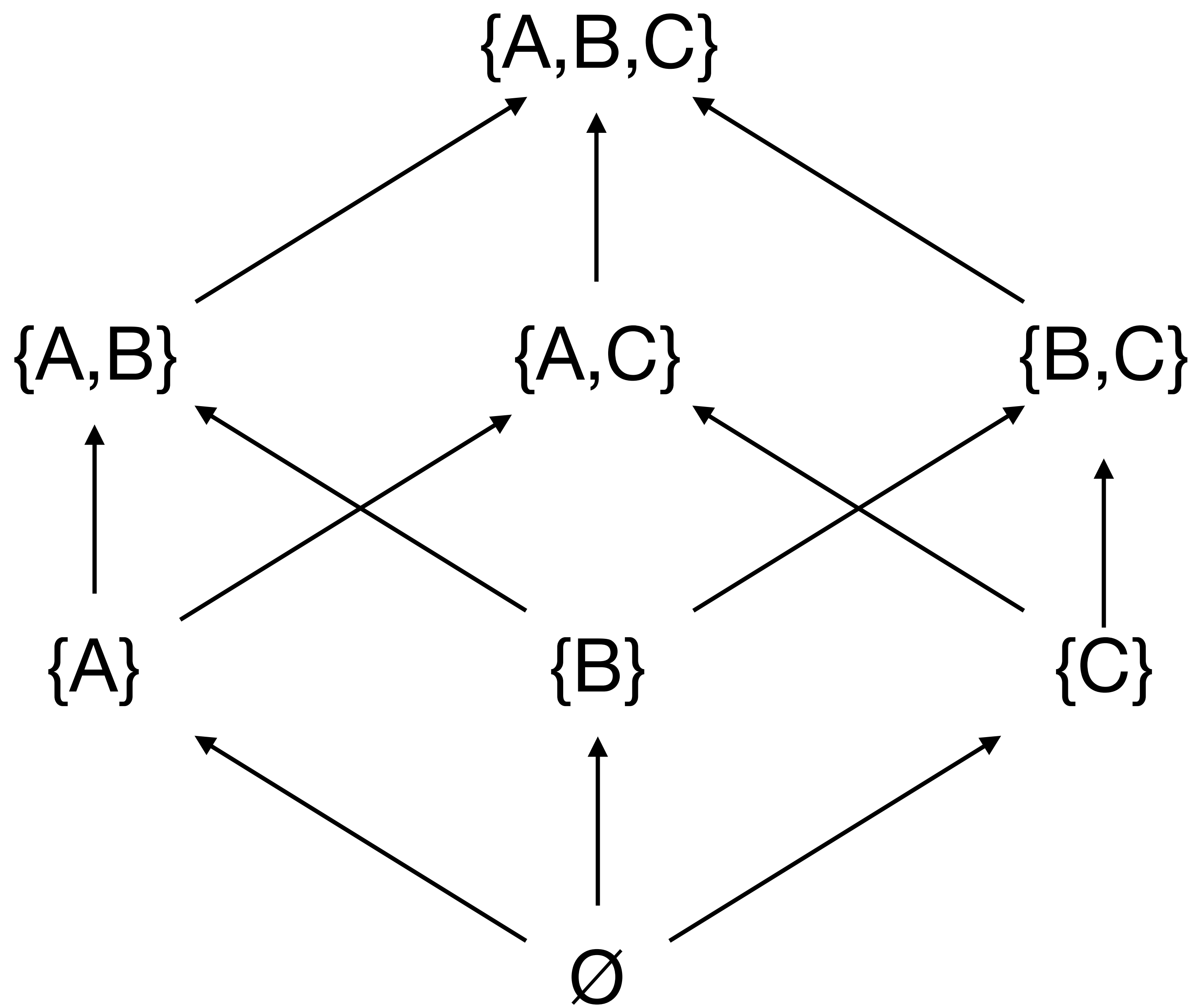

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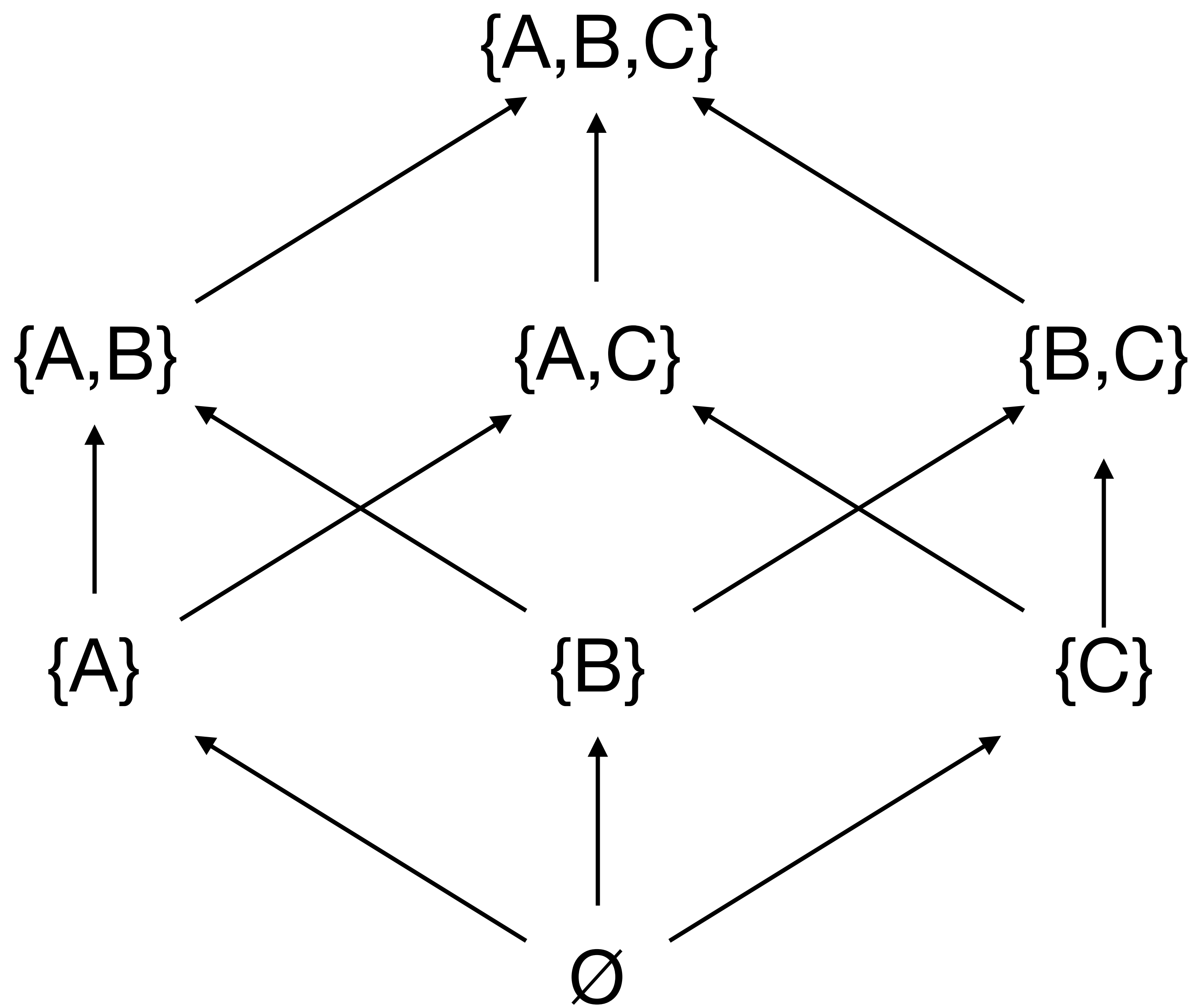

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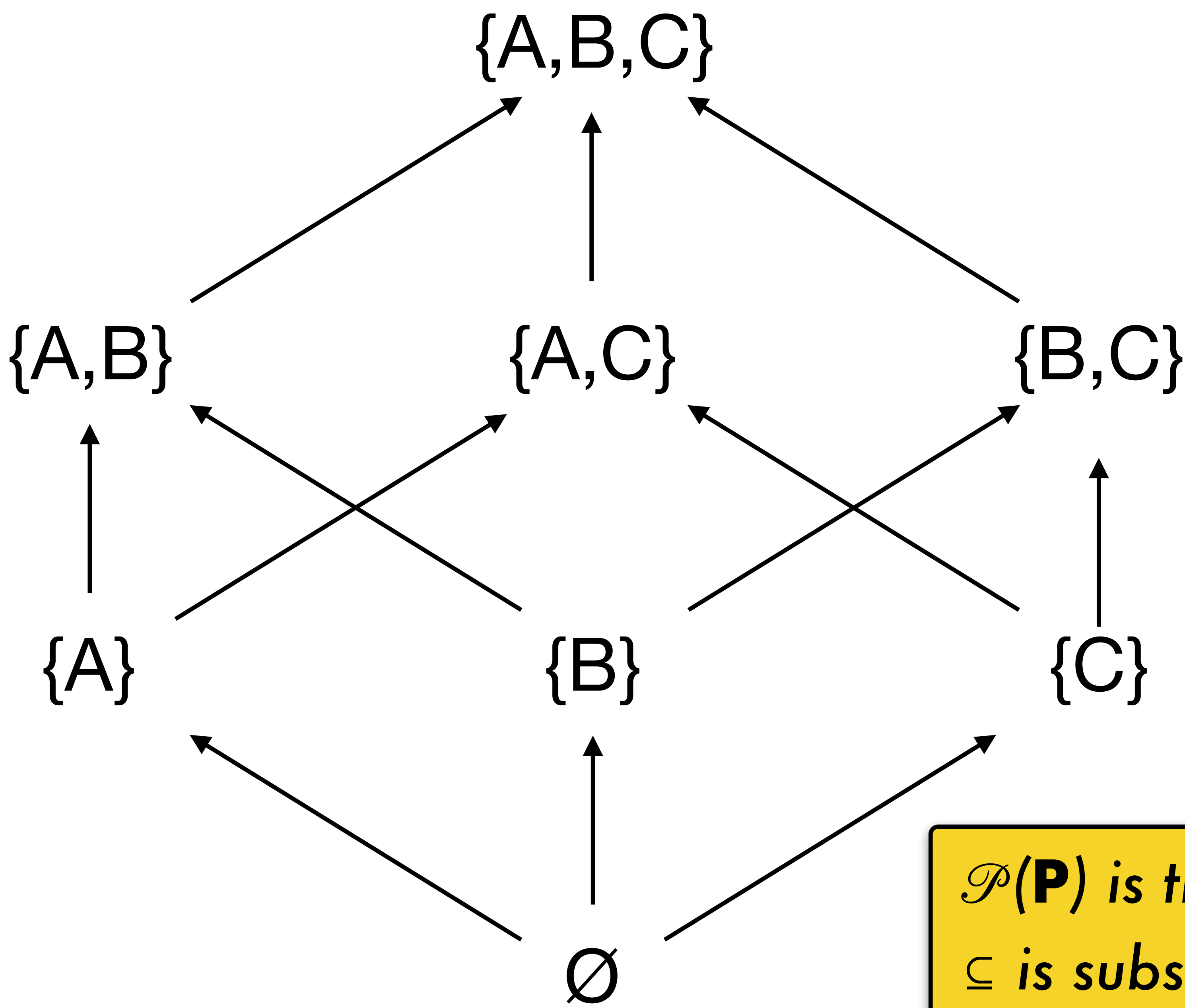

$\mathscr{P}(\mathbf{P})$ *is the power set of* **P**

$\subseteq$ *is subset inclusion*

$\cup$ *is set union*

Formally: $\mathscr{L}^{\mathbf{P}} = (\ \mathscr{P}(\mathbf{P})\ ,\ \subseteq\ ,\ \cup\ )$

*In general we work with an **abstract lattice** with standard properties*

$$\mathscr{L} = (\boldsymbol{L} , \sqsubseteq , \sqcup)$$

$\sqsubseteq$ *is reflexive, transitive, and antisymmetric.*

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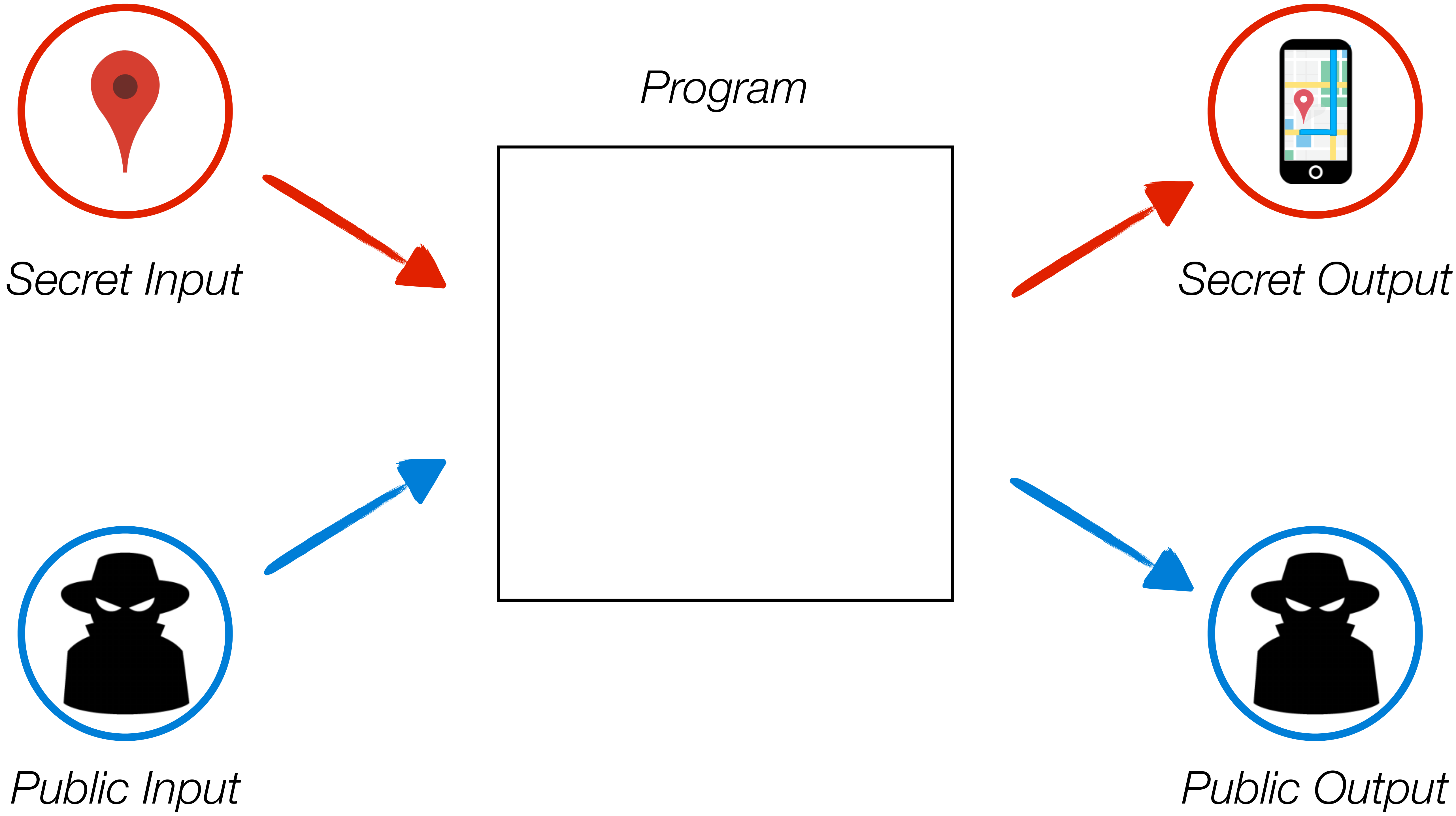
Join and partial order "agree"

$$\forall \ \ell_1 \ \ell_2 \ \ell_3 \ . \ \ell_1 \sqsubseteq \ell_1 \sqcup \ell_2 \ \wedge \ \ell_2 \sqsubseteq \ell_1 \sqcup \ell_2$$

Non-Interference

Public *outputs must not depend on* ***secret*** *inputs.*



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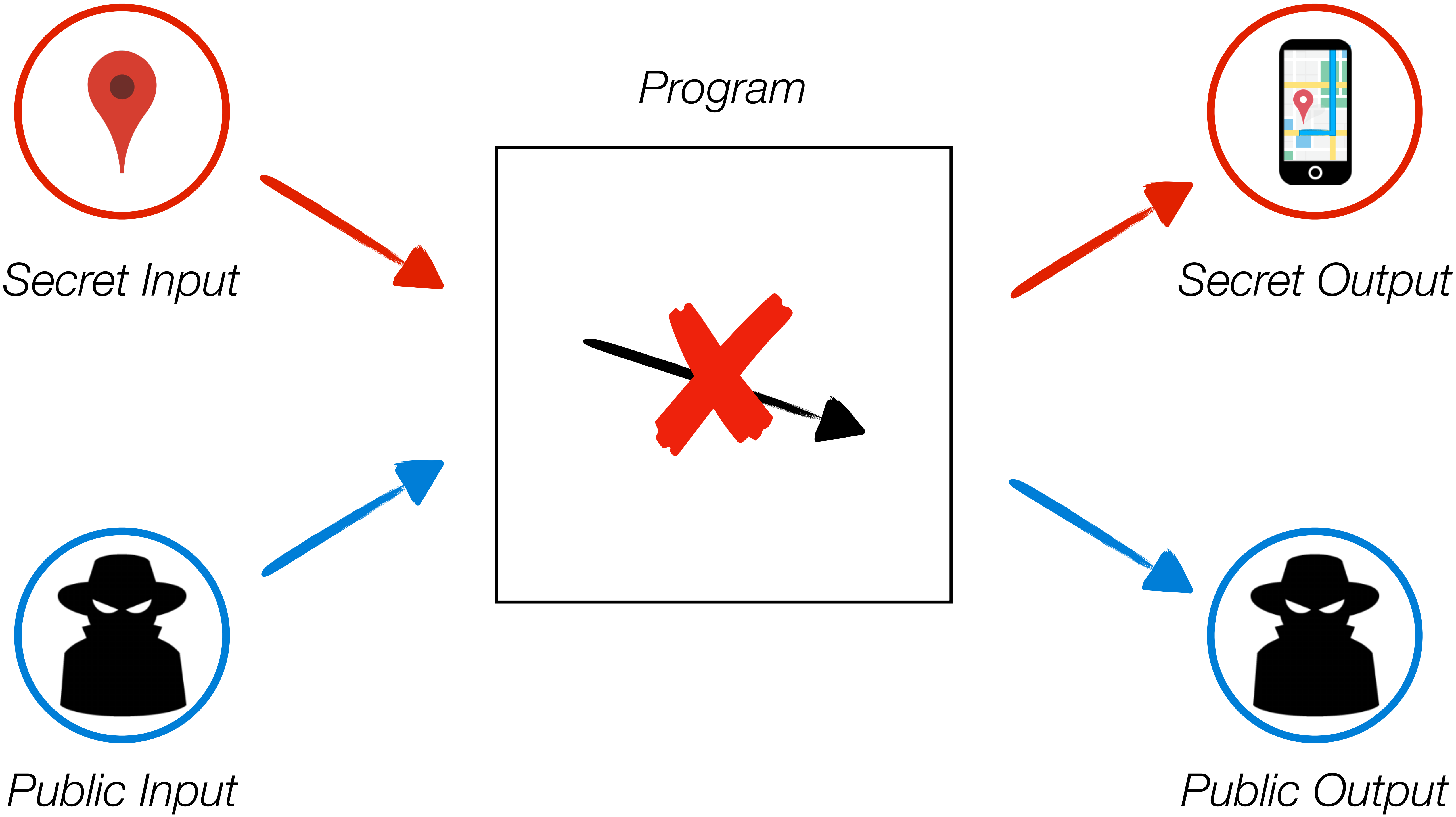

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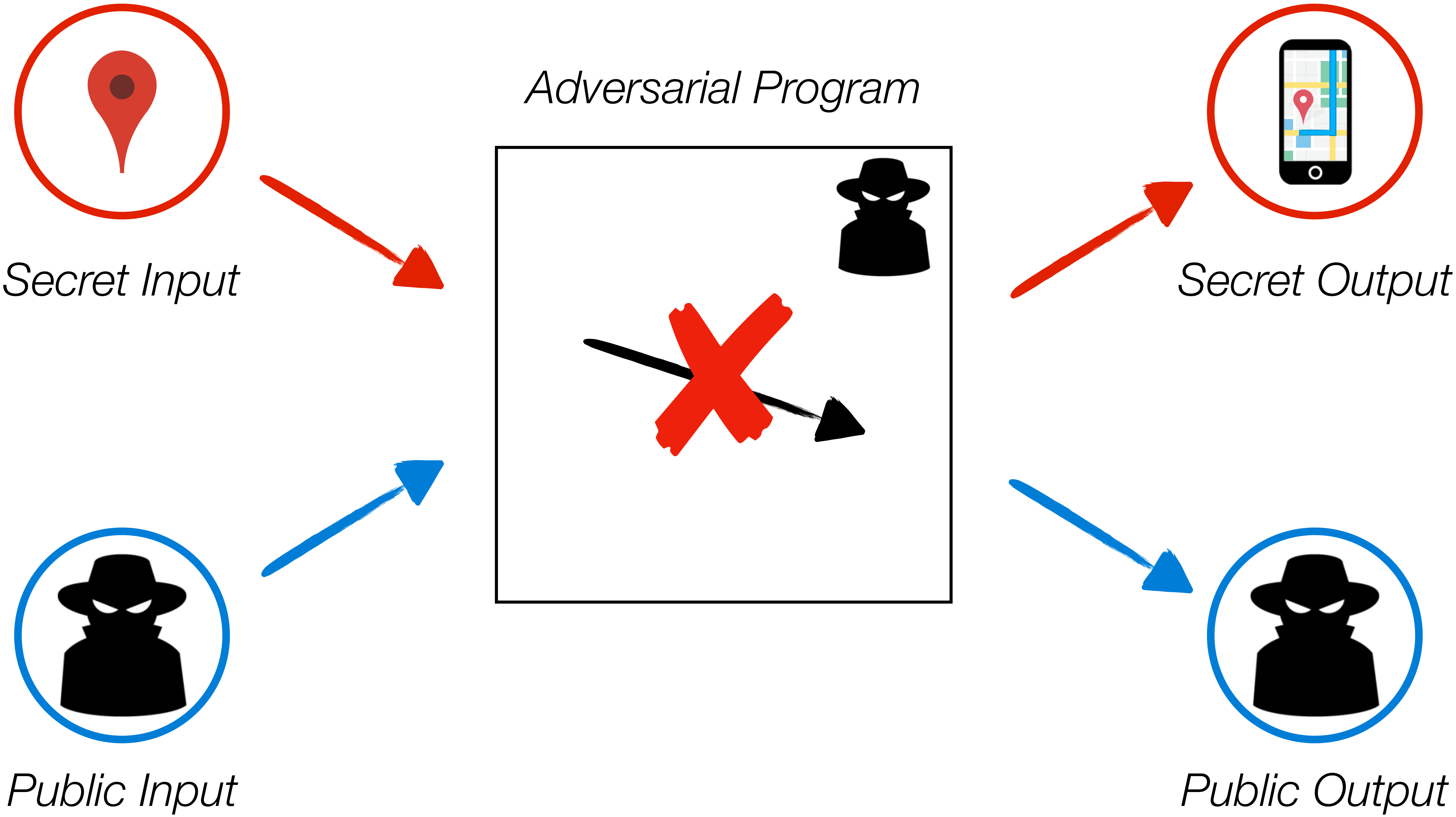

Quiz

Do the following programs satisfy non-interference?

```
h := input^H()
l := input^L()
output^H(l + h)
```

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Public and secret data can flow to secret outputs

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Secret data must not flow to public outputs

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This is an example of an ***explicit flow***

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Most IFC languages reject this program

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False positive

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Outline

Overview of different language-based IFC approaches

- Non Interference
- 4 IFC Languages

	Static	*Dynamic*
Fine-grained	$\lambda^{\mathbf{SFG}}$	$\lambda^{\mathbf{DFG}}$
Coarse-grained	$\lambda^{\mathbf{SCG}}$	$\lambda^{\mathbf{DCG}}$

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Static Fine-grained IFC

$\lambda^{\textbf{SFG}}$

Syntax

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Labeled Types $\tau ::= s^{\ell}$

Simple Types $s ::= \textbf{unit} \mid \tau \rightarrow \tau \mid \tau + \tau \mid \tau \times \tau$

Static Fine-grained IFC

λ^{SFG}

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Expressions	e ::=	() | x | λx.e | e e
		| ⟨e , e⟩ | **fst**(e) | **snd**(e)
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Environments	θ ∈ Var ⇀ Value

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$\lambda^{\textsf{SFG}}$

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Values $v ::= () \mid (x.e\ ,\ \theta) \mid \langle v\ ,\ v \rangle \mid \textbf{inl}(v) \mid \textbf{inr}(v)$

Function Closure

Environments $\theta \in \mathrm{Var} \rightharpoonup \mathrm{Value}$

Dynamic Semantics $e \Downarrow^{\theta} v$

$\lambda^{\textbf{SFG}}$

Dynamic Semantics

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Standard: no security checks!

λ^{SFG}

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$\Gamma \vdash e : \tau$ *where* $\Gamma \in Var \rightarrow LTypes$

$\lambda^{\mathbf{SFG}}$

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λSFG

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$$\Gamma \nvdash \textbf{if } h \textbf{ then } l_1 \textbf{ else } l_2 : Bool^{L}$$

with typing environment

$$\Gamma = [\ h \mapsto Bool^{H}\ ,\ l_1 \mapsto Bool^{L}\ ,\ l_2 \mapsto Bool^{L}\ ]$$

λ^{SFG}

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λSFG

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Syntactic Sugar

λ^{SFG}

Static Semantics

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λ^SFG

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Observations & Remarks

Elimination rules include security checks

$\lambda^{\mathbf{SFG}}$

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Elimination rules include security checks

Avoid implicit leaks through the result

λ^{SFG}

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Introduction rules only generate label ⊥

λSFG

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λSFG

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To state and prove non-interference we also need:

λ^{SFG}

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λSFG

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Similar to the intro rules for expressions

λSFG

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Similar to the intro rules for expressions

$\vdash \theta : \Gamma$

Environment and typing contexts "agree"

Subtyping Relation

τ <: τ

$$\frac{\ell_1 \sqsubseteq \ell_2 \qquad s_1 <: s_2}{{s_1}^{\ell_1} <: {s_2}^{\ell_2}} \quad \text{[Sub-LType]}$$

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$s <: s$

unit <: unit [Sub-Unit]

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Structural for sums and pairs

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Covariant in the result

Subtyping Relation

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Contravariant in the argument

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Covariant in the result

$\boxed{\tau <: \tau}$

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Exercise. *Prove that* $\texttt{Bool}^{\texttt{H}} \to \texttt{Bool}^{\texttt{L}} <: \texttt{Bool}^{\texttt{L}} \to \texttt{Bool}^{\texttt{H}}$

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Non-Interference for $\lambda^{\mathbf{SFG}}$

For all $\lambda^{\mathbf{SFG}}$ types, expressions, and values such that:

$$\mathtt{x} : \tau \vdash \mathtt{e} : \mathtt{Bool}^{\mathbf{L}}$$

Non-Interference for λ^{SFG}

For all λ^{SFG} *types, expressions, and values such that:*

Secret *input*

$$x : \tau \vdash e : \text{Bool}^{L}$$

Non-Interference for λ^{SFG}

For all λ^{SFG} types, expressions, and values such that:

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L *is the attacker security level*

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$\tau = s^{\ell}$ *such that* $\ell \not\sqsubseteq \mathbf{L}$

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Any 2 ***secret*** *input values*

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Non-Interference for λ^{SFG}

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Any 2 ***secret*** *input values*

$$v_1 : \tau$$

$$v_2 : \tau$$

If

$$\left. \begin{array}{l} e \Downarrow_{[x \mapsto v_1]} v \\ e \Downarrow_{[x \mapsto v_2]} v' \end{array} \right\}$$

Non-Interference for λ^{SFG}

For all λ^{SFG} types, expressions, and values such that:

$$x : \tau \vdash e : Bool^{L}$$

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*Same **public** output*

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$$e \Downarrow^{[x \mapsto v_2]} v'$$

then $v = v'$

Same ***public*** *output*

*"**Public** outputs do not depend on **secret** inputs"*

Proof Technique

1 *Define a* ***logical relation*** *for programs giving* ***equal public outputs***

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$$e_1 \Downarrow^{\theta_1} v_1 \;\wedge\; e_2 \Downarrow^{\theta_2} v_2 \implies (v_1, v_2) \in \mathbf{V}[\![\, \tau \,]\!]^{L} \}$$

Proof Technique

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Equivalent values at level L

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If $\Gamma \vdash e : \tau$ *then*

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Equivalent input envs at L

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Equivalent input envs at L

3 *Derive non-interference as a **corollary***

λ^{SFG} with References

λ^{SFG}

Syntax with references

Simple Types $\quad s ::= \cdots \mid \textbf{Ref}\ \tau \mid \tau \xrightarrow{\ell} \tau$

$\lambda^{\textsf{SFG}}$ with References

$\lambda^{\textsf{SFG}}$

Syntax with references

Keep tracks of side-effects

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λ^{SFG} with References

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Address in store

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Store	Σ

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Dynamic Semantics

$$\langle \Sigma, e \rangle \Downarrow^{\theta} \langle \Sigma', v \rangle$$

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Standard

Static Semantics

$$\Gamma \vdash_{\mathbf{pc}} e : \tau$$

Static Semantics

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"Program Counter" label

λSFG

Static Semantics

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*The **pc** label is a **lower bound** on the **write effects** of the program* e

$\lambda^{\mathbf{SFG}}$

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Program e ***cannot*** *create and write references labeled below the* **pc**

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λSFG

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Eliminate implicit leaks through the store

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Exercise. *Prove that the following program is* ***ill-typed****:*

$\Gamma \nvdash_{\mathsf{L}}$ **if** h **then** l := true **else** () : **unit**$^{\mathsf{H}}$

Static Semantics

λ^{SFG}

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Exercise. *Prove that the following program is* ***ill-typed****:*

$$\Gamma \nvdash_{L} \textbf{if}\ h\ \textbf{then}\ l := \mathtt{true}\ \textbf{else}\ ()\ :\ \textbf{unit}^{H}$$

with typing environment

$$\Gamma = [\ h \mapsto \mathtt{Bool}^{H}\ ,\ l \mapsto (\textbf{Ref}\ \mathtt{Bool}^{L})^{L}\ ]$$

Subtyping Relation

s <: s

$$\frac{\tau_1' <: \tau_1 \qquad \tau_2 <: \tau_2' \qquad \ell' \sqsubseteq \ell}{\tau_1 \xrightarrow{\ell} \tau_2 <: \tau_1' \xrightarrow{\ell'} \tau_2'} \quad \text{[Sub-Fun]}$$

Subtyping Relation

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$$\frac{\tau <: \tau'}{\textbf{Ref } \tau <: \textbf{Ref } \tau'}$$

Invariant

$$\frac{}{\textbf{Ref } \tau <: \textbf{Ref } \tau}$$

Contravariant

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References ?

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✗	✓	✗

Exercise

Find a well-typed program that leaks if we consider references ***covariant****:*

Covariant ✗

$$\frac{\tau <: \tau'}{\textbf{Ref}\ \tau <: \textbf{Ref}\ \tau'}$$

Find a well-typed program that leaks if we consider references ***contravariant****:*

Contravariant ✗

$$\frac{\tau' <: \tau}{\textbf{Ref}\ \tau <: \textbf{Ref}\ \tau'}$$

Soundness issues!

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`Ref Bool`^{L} *can be* ***written*** *as* `Ref Bool`^{H}

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let h_ref = l_ref in
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  !l_ref
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```

Well-typed but leak!

Covariant ✗

`Ref Bool`^{L} *can be* ***written*** *as* `Ref Bool`^{H}

Contravariant ✗

`Ref Bool`^{H} *can be* ***read*** *as* `Ref Bool`^{L}

*References are input (**read**) and output (**write**) channels!*

Invariant ✓

$$\frac{}{\texttt{Ref}\ \tau <: \texttt{Ref}\ \tau}\quad \text{[Sub-Ref]}$$

Soundness Proof

Non-Interference for λ$^{\textbf{SFG}}$ with ***higher-order state***

Soundness Proof

The store can contain references

Non-Interference for λ^{SFG} with ***higher-order state***

Soundness Proof

The store can contain references

Non-Interference for λ^{SFG} with ***higher-order state***

↑

Step-indexed Kripke *logical relation*

Soundness Proof

The store can contain references

Non-Interference for λ^{SFG} with ***higher-order state***

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Avoid circular reasoning

Step-indexed Kripke *logical relation*

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Non-Interference for λ^{SFG} with ***higher-order state***

↑

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Step-indexed Kripke *logical relation*

See "On the Expressiveness and Semantics of Information Flow Types" by Rajani and Garg

Outline

Overview of different language-based IFC approaches

- Non Interference
- **4 IFC Languages**

	Static	*Dynamic*
Fine-grained	$\lambda^{\textbf{SFG}}$	$\lambda^{\textbf{DFG}}$
Coarse-grained	$\lambda^{\textbf{SCG}}$	$\lambda^{\textbf{DCG}}$

Outline

Overview of different language-based IFC approaches

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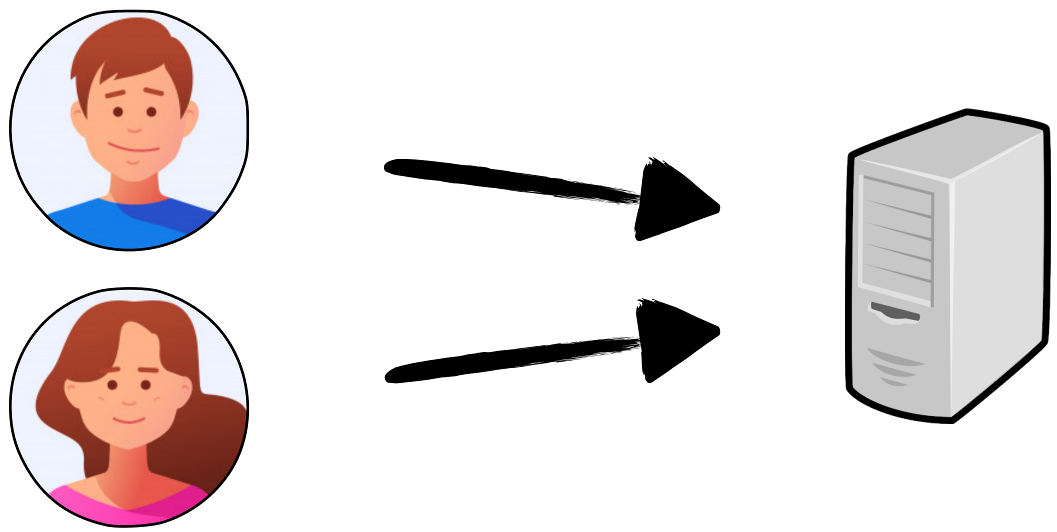
Dynamic Fine-Grained IFC

Enforce dynamic security policies



Dynamic Fine-Grained IFC

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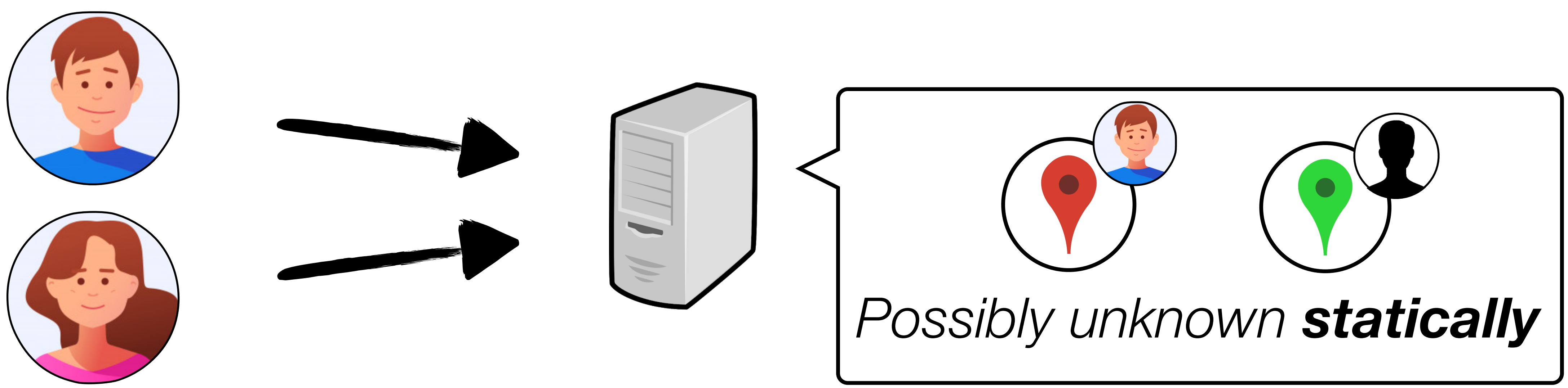

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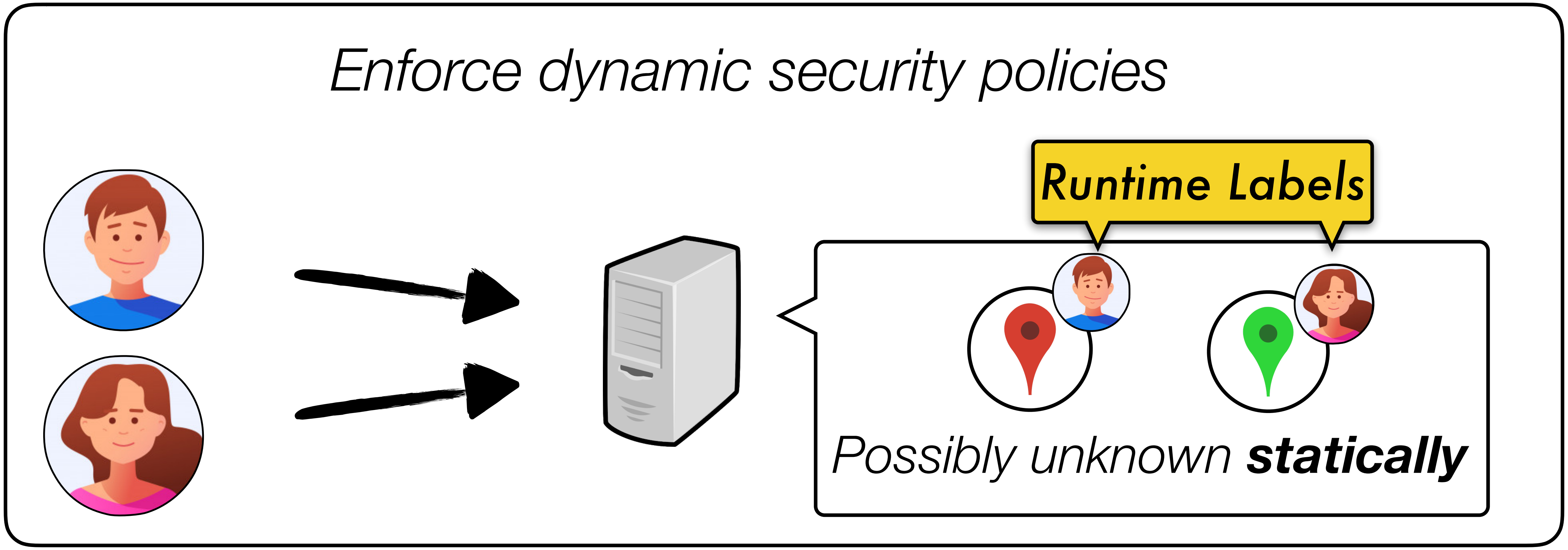

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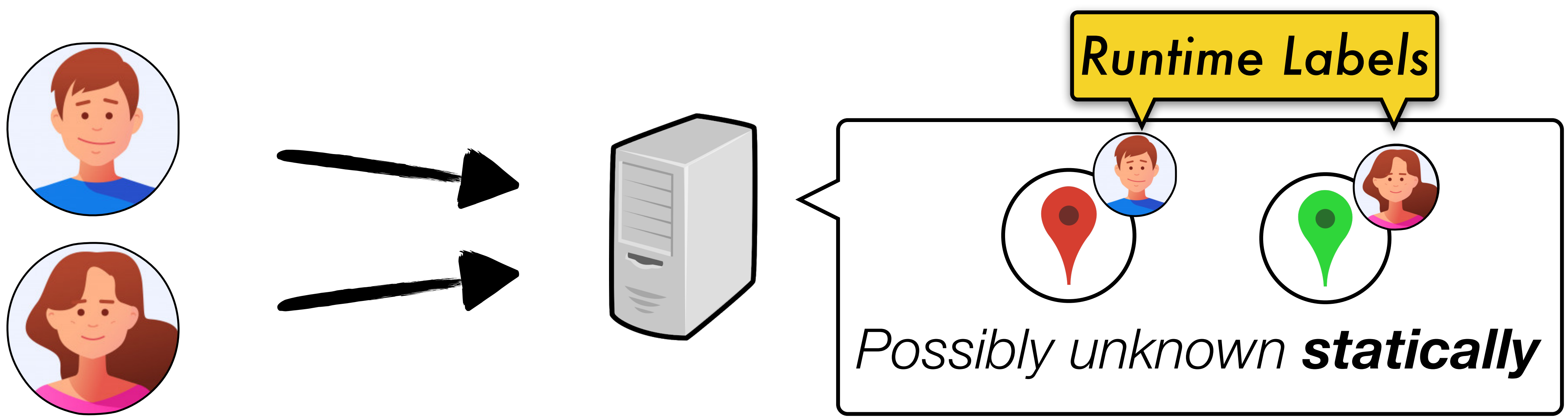
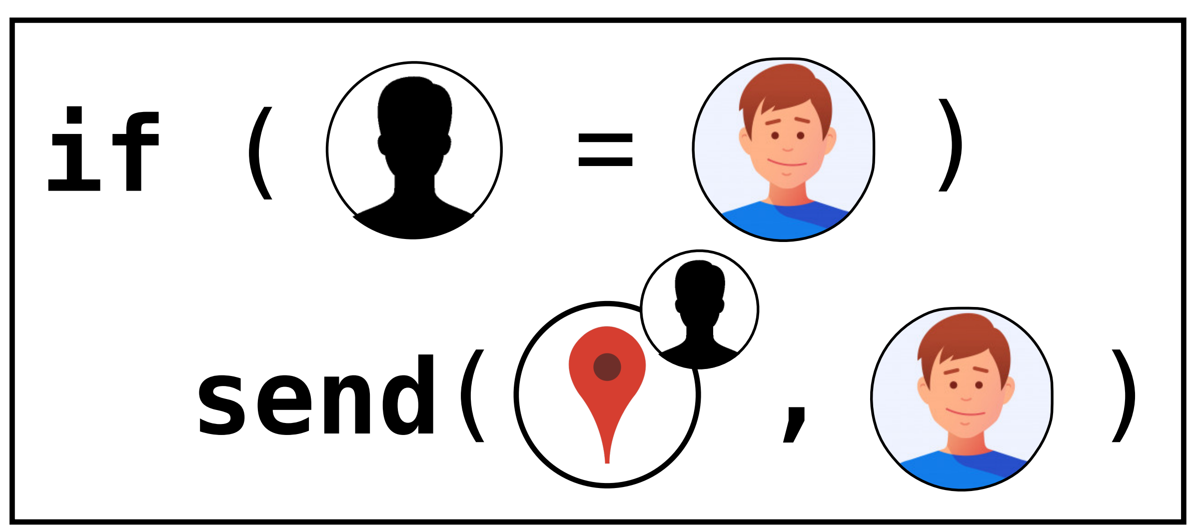


Label Introspection



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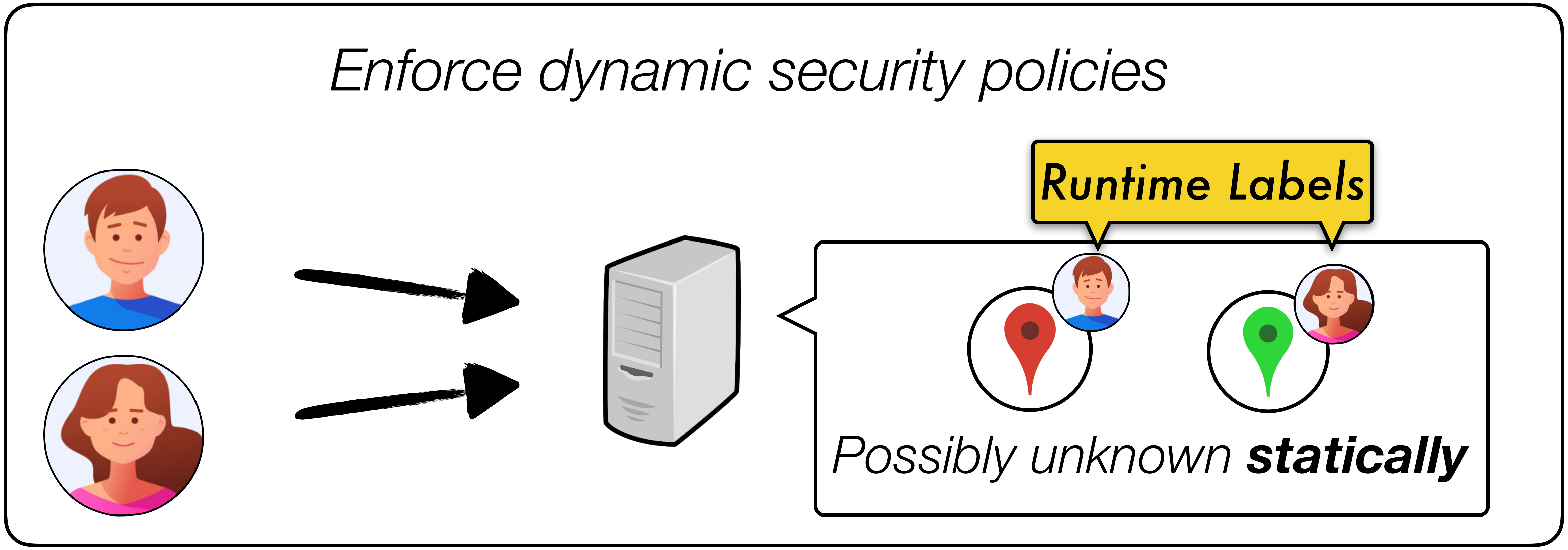

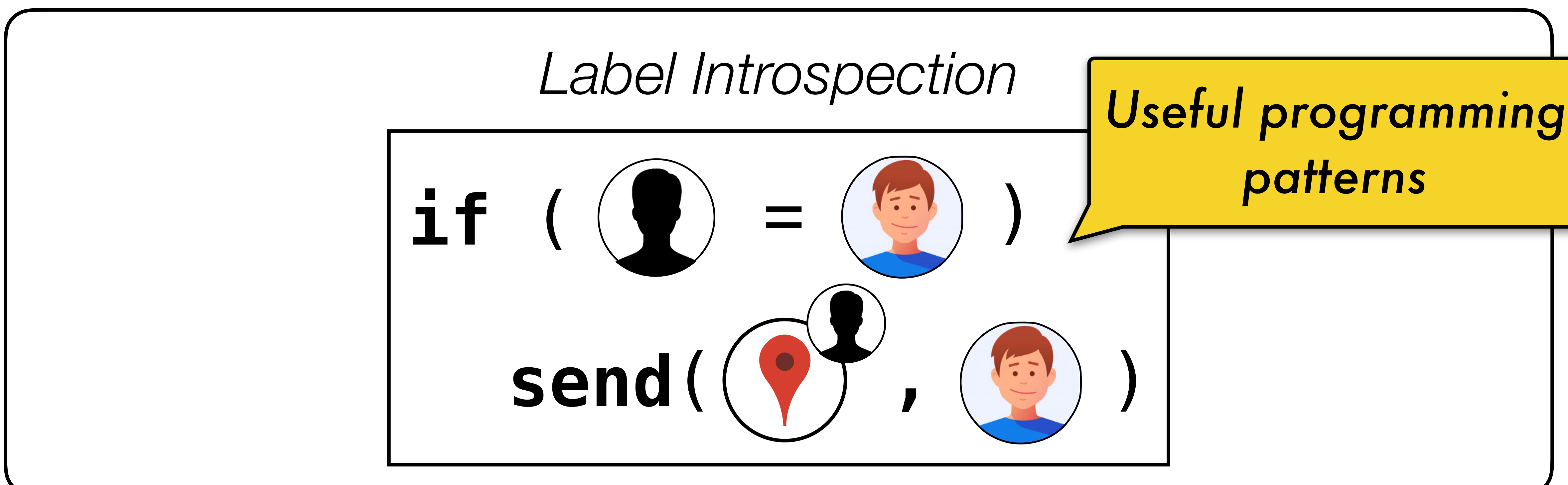

Dynamic Fine-grained IFC

$\lambda^{\mathbf{DFG}}$

Syntax

Types τ ::= **unit** | $\tau \rightarrow \tau$ | $\tau + \tau$ | $\tau \times \tau$ | **Label**

Dynamic Fine-grained IFC

$\lambda^{\mathbf{DFG}}$

Syntax

New!

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Dynamic Fine-grained IFC

$\lambda^{\textbf{DFG}}$

Syntax

New!

Types τ ::= **unit** | τ → τ | τ + τ | τ × τ | **Label**

Labeled Values v ::= r^{ℓ}

Dynamic Fine-grained IFC

λ^{DFG}

Syntax

New!

Types τ ::= **unit** | $\tau \to \tau$ | $\tau + \tau$ | $\tau \times \tau$ | **Label**

Labeled Values v ::= r^{ℓ}

Raw value at security level ℓ

Dynamic Fine-grained IFC

λ^{DFG}

Syntax

New!

Types	τ ::= **unit** | $\tau \to \tau$ | $\tau + \tau$ | $\tau \times \tau$ | **Label**
Labeled Values	v ::= r^{ℓ}
Raw Values	r ::= () | (x.e , θ) | ⟨v , v⟩
	| **inl**(v) | **inr**(v) | ℓ
Environments	θ ∈ Var ⇀ LValue

Raw value at security level ℓ

Dynamic Fine-grained IFC

$\lambda^{\textbf{DFG}}$

Syntax

New!

Types τ ::= **unit** | τ → τ | τ + τ | τ × τ | **Label**

Labeled Values v ::= r^{ℓ}

Raw value at security level ℓ

Raw Values r ::= () | (x.e , θ) | ⟨v , v⟩

| **inl**(v) | **inr**(v) | ℓ

Runtime labels

Environments θ ∈ Var ⇀ LValue

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λ^{DFG}

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New!

Types τ ::= **unit** | $\tau \rightarrow \tau$ | $\tau + \tau$ | $\tau \times \tau$ | **Label**

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Raw Values r ::= () | (x.e , θ) | $\langle$v , v$\rangle$

| **inl**(v) | **inr**(v) | ℓ

Runtime labels

Environments $\theta \in$ Var $\rightharpoonup$ LValue

Expressions e ::= ··· | **labelOf**(e) | **getPC** | e $\sqsubseteq$? e

Dynamic Fine-grained IFC

$\lambda^{\textbf{DFG}}$

Syntax

Types $\tau ::= \textbf{unit} \mid \tau \rightarrow \tau \mid \tau + \tau \mid \tau \times \tau \mid \textbf{Label}$ — *New!*

Labeled Values $v ::= r^{\ell}$ — *Raw value at security level* ℓ

Raw Values $r ::= () \mid (x.e\ ,\ \theta) \mid \langle v\ ,\ v \rangle$

$\mid \textbf{inl}(v) \mid \textbf{inr}(v) \mid \ell$ — *Runtime labels*

Environments $\theta \in \mathrm{Var} \rightharpoonup \mathrm{LValue}$

Label Introspection

Expressions $e ::= \cdots \mid \textbf{labelOf}(e) \mid \textbf{getPC} \mid e \sqsubseteq ?\ e$

Semantics

Static $\Gamma \vdash e : \tau$

Semantics

Standard: no security checks!

Static $\Gamma \vdash e : \tau$

Semantics

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Static $\Gamma \vdash e : \tau$

Dynamic $e \Downarrow^{\theta}_{\mathbf{pc}} v$

λDFG

Semantics

Standard: no security checks!

Static $\Gamma \vdash e : \tau$

Security Monitor

Dynamic $e \Downarrow^{\theta}_{\mathbf{pc}} v$

Semantics

Standard: no security checks!

Static $\Gamma \vdash e : \tau$

Security Monitor

Dynamic $e \Downarrow^{\theta}_{\mathbf{pc}} v$

Program Counter

λDFG

Semantics

Standard: no security checks!

Static $\Gamma \vdash e : \tau$

Security Monitor

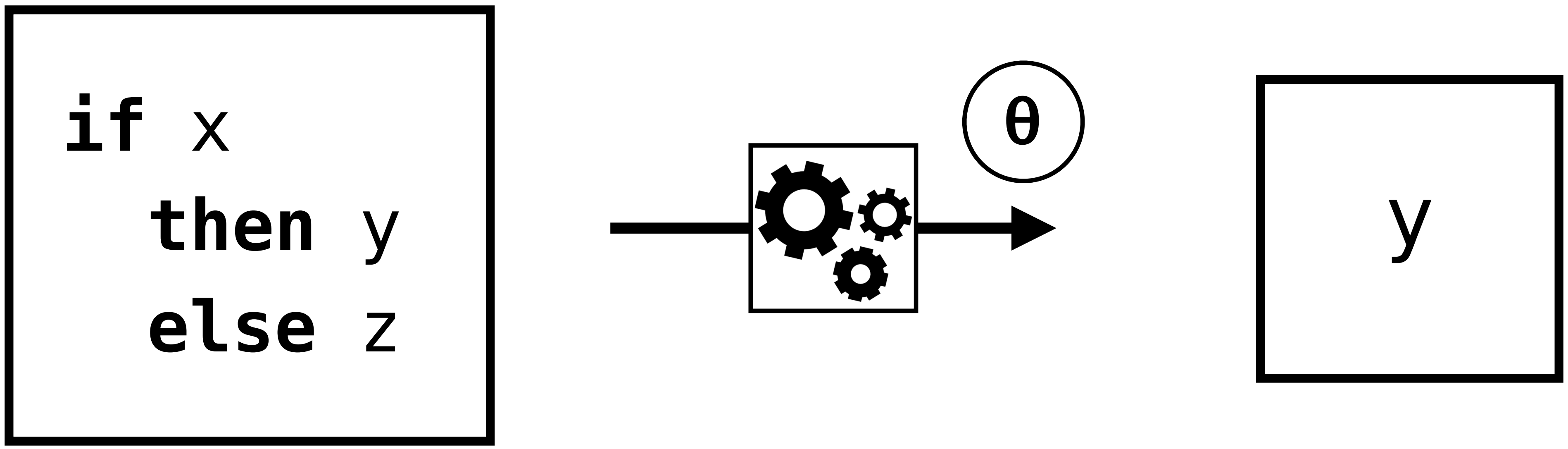
Dynamic $e \Downarrow^{\theta}_{\mathbf{pc}} v$

Program Counter

*The monitor **propagates labels** from inputs to outputs*

Label Propagation

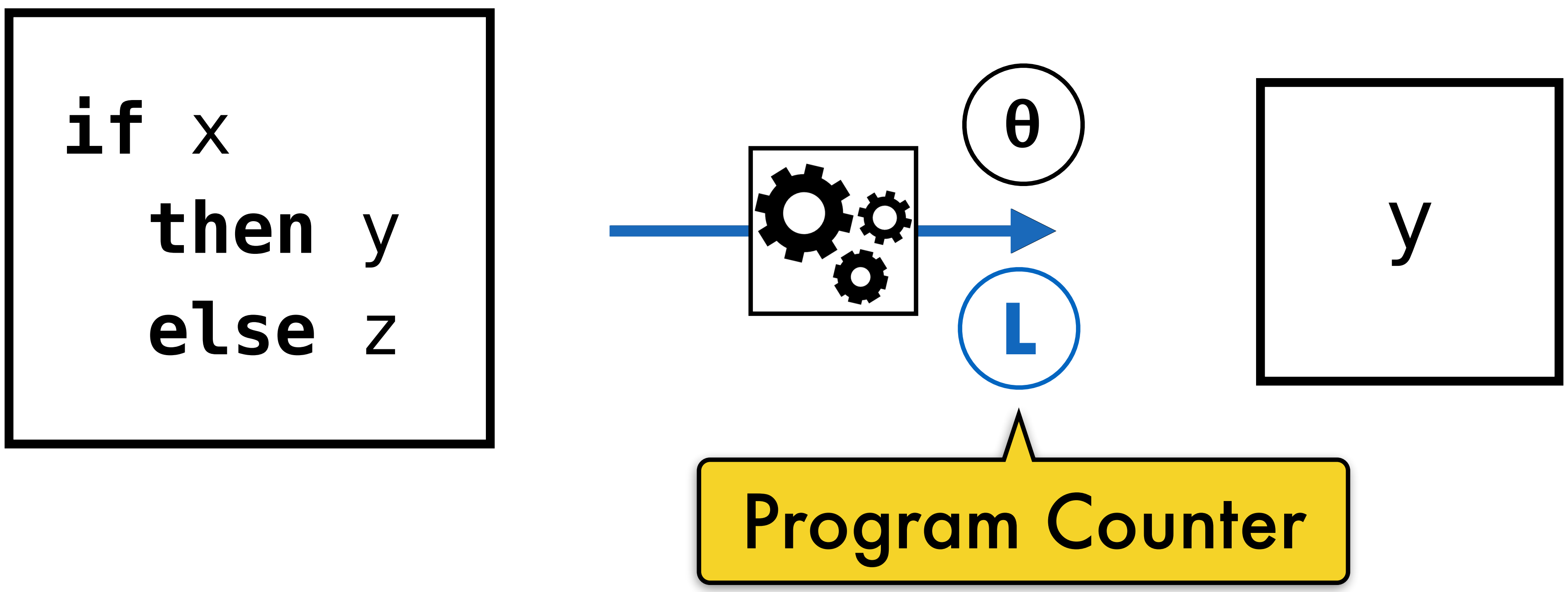
The semantics tracks control-flow dependencies with the ***program counter*** *label.*



$$\theta = [\ x \mapsto \mathbf{true}^{H},\ y \mapsto \mathbf{true}^{L},\ z \mapsto \mathbf{false}^{L}\ ]$$

Label Propagation

The semantics tracks control-flow dependencies with the ***program counter*** *label.*



$$\theta = [\ x \mapsto \mathbf{true}^{H},\ y \mapsto \mathbf{true}^{L},\ z \mapsto \mathbf{false}^{L}\ ]$$

Label Propagation

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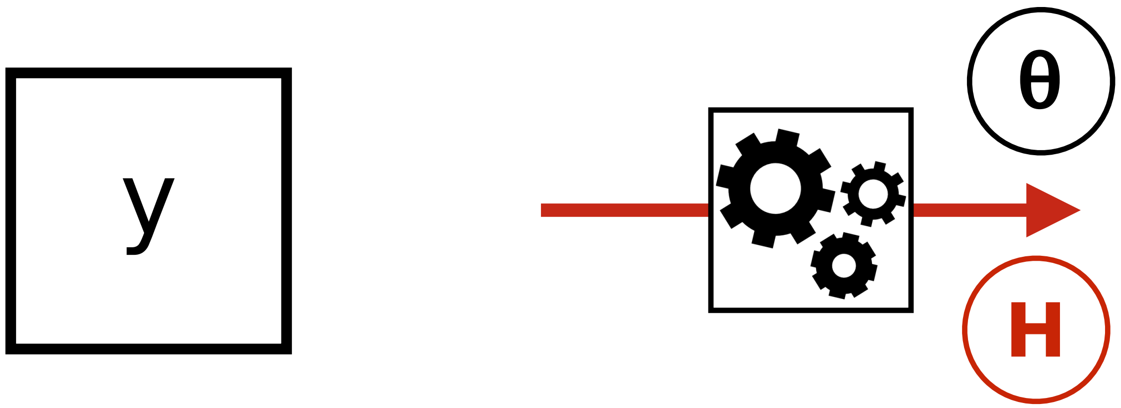

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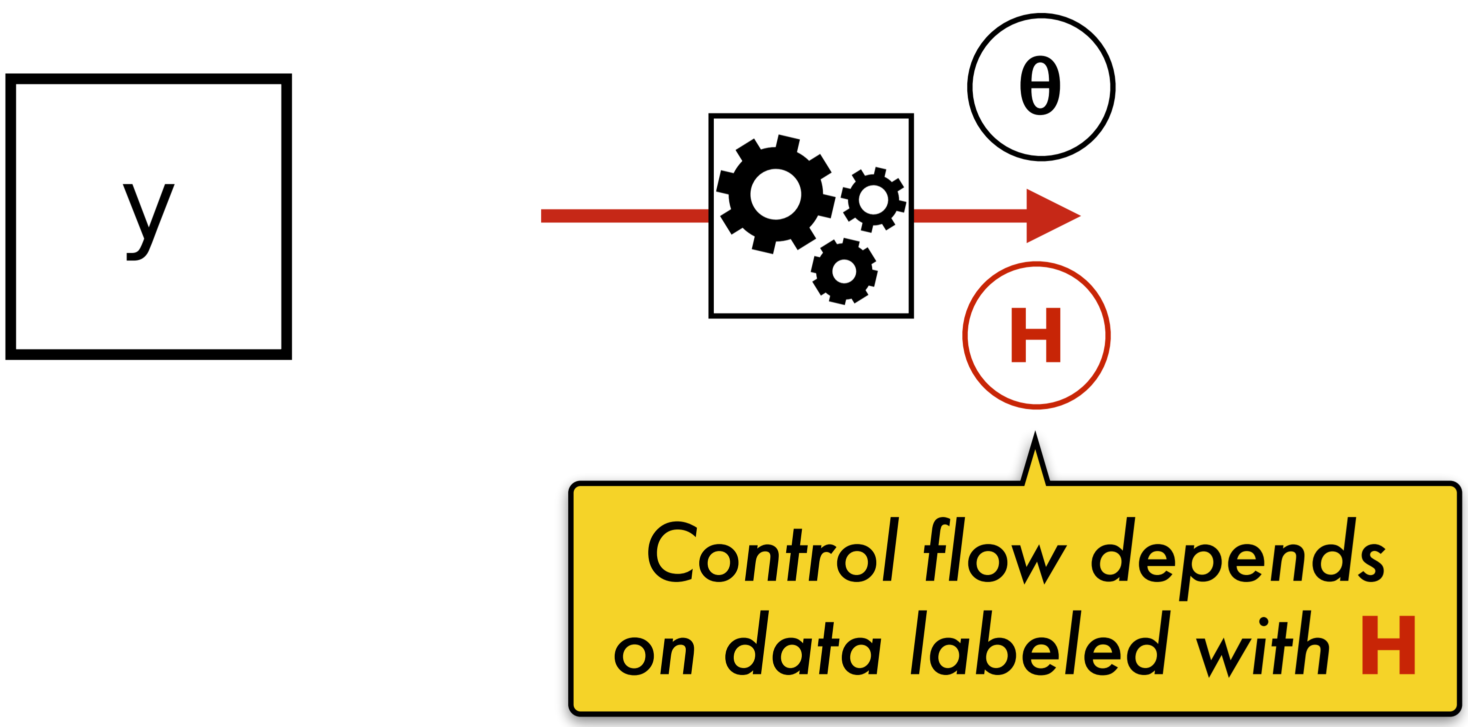

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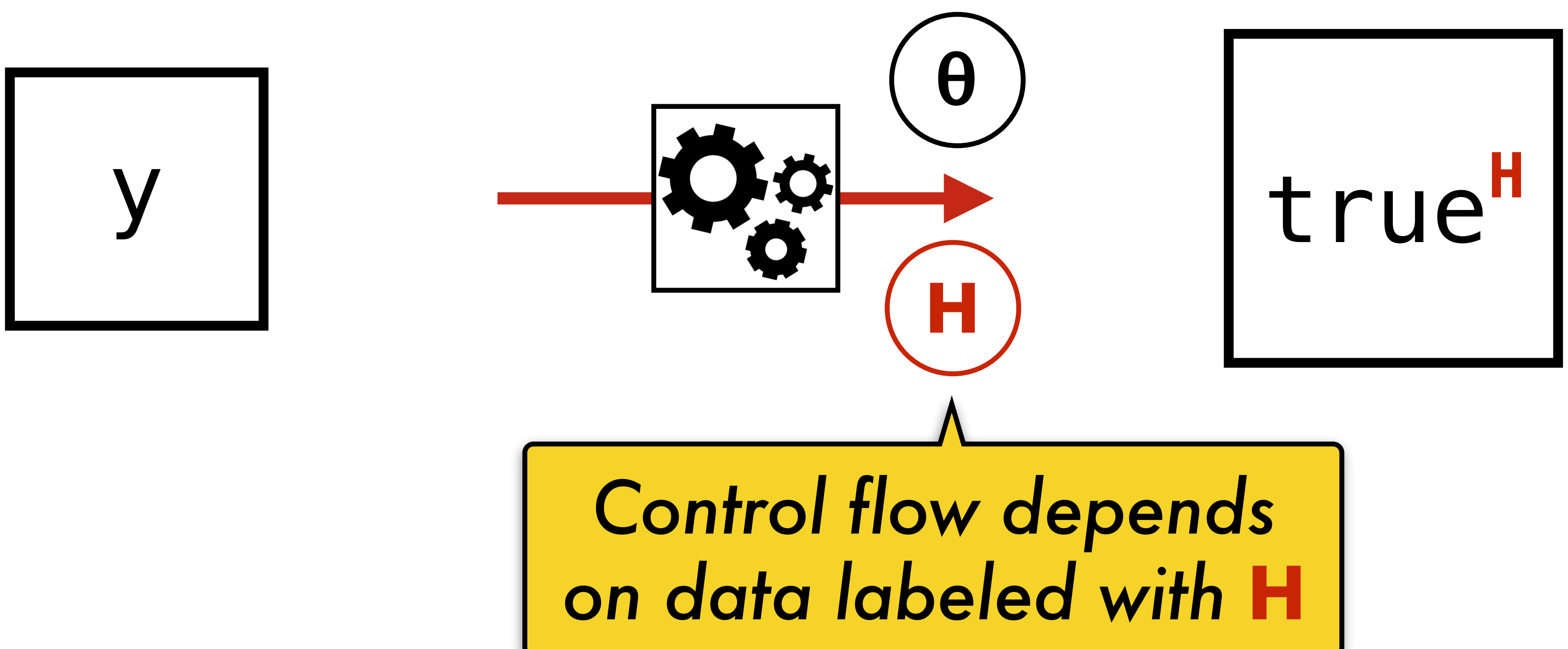

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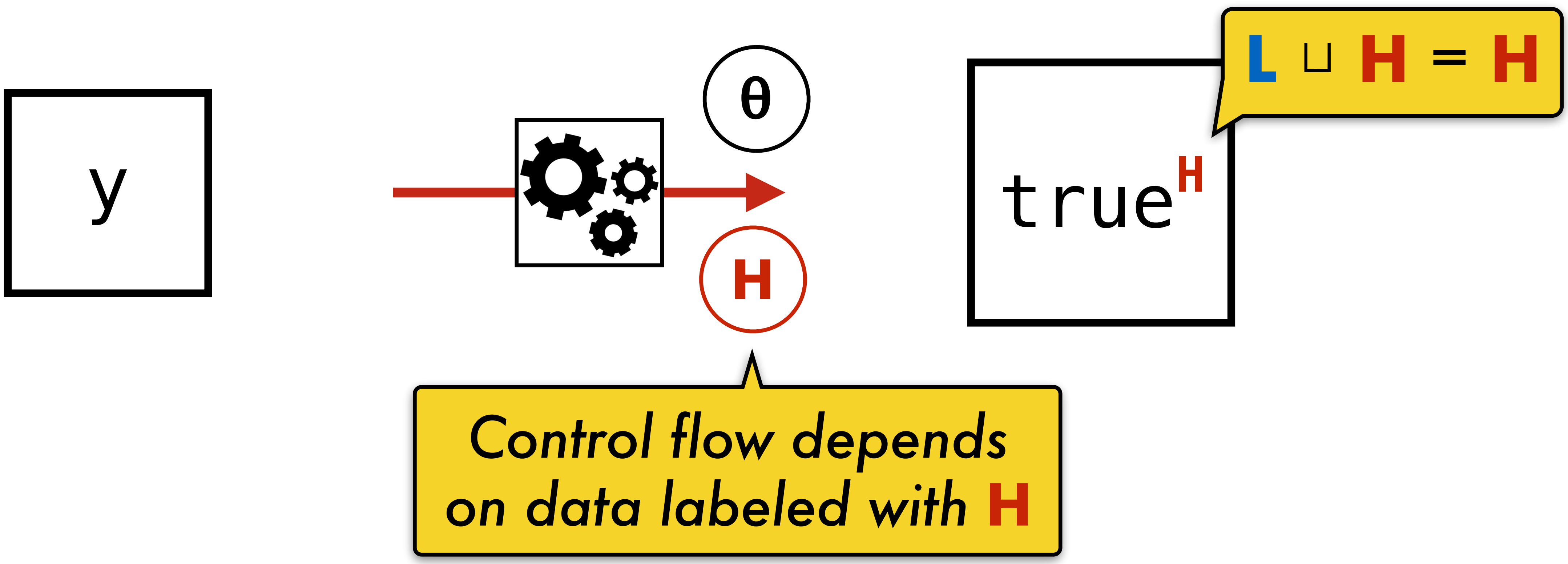
Label Propagation

*The semantics tracks control-flow dependencies with the **program counter** label.*



$$\theta = [\ x \mapsto \mathbf{true}^{H},\ y \mapsto \mathbf{true}^{L},\ z \mapsto \mathbf{false}^{L}\ ]$$

Dynamic Semantics $e \Downarrow^{\theta}_{\mathbf{pc}} v$

$\lambda^{\mathbf{SFG}}$

Dynamic Semantics $e \Downarrow^{\theta}_{\mathbf{pc}} v$

Observations

*Introduction rules label the result with the **program counter***

*Elimination rules **taint** the result with the intermediate value*

λSFG

Dynamic Semantics $e \Downarrow^{\theta}_{\mathbf{pc}} v$

Observations

Introduction rules label the result with the ***program counter***

Elimination rules ***taint*** *the result with the intermediate value*

Invariant

If $e \Downarrow^{\theta}_{pc} r^{\ell}$ *then* $pc \sqsubseteq \ell$

Label Introspection

$$\textbf{labelOf}(e) \Downarrow^{\theta}_{pc}$$

Label Introspection

$$\frac{e \Downarrow^{\theta}_{pc} r^{\ell}}{\mathbf{labelOf}(e) \Downarrow^{\theta}_{pc}}$$

Label Introspection

$$\frac{\texttt{e} \;\Downarrow^{\theta}_{\texttt{pc}}\; \texttt{r}^{\ell}}{\textbf{\texttt{labelOf}}\texttt{(e)} \;\Downarrow^{\theta}_{\texttt{pc}}\; \ell}$$

Label Introspection

$$\frac{e \;\Downarrow^{\theta}_{pc}\; r^{\ell}}{\mathbf{labelOf}(e) \;\Downarrow^{\theta}_{pc}\; \ell^{\,?}}$$

What is the label of the label itself?

Label Introspection

$$\frac{e \ \Downarrow^{\theta}_{pc} \ r^{\ell}}{\mathbf{labelOf}(e) \ \Downarrow^{\theta}_{pc} \ \ell^{\ell}}$$

Label Introspection

The label has the ***same sensitivity*** *of the result!*

$$\frac{e \Downarrow^{\theta}_{pc} r^{\ell}}{\mathbf{labelOf}(e) \Downarrow^{\theta}_{pc} \ell^{\ell}}$$

Label Introspection

The label has the ***same sensitivity*** *of the result!*

$$\frac{e \;\Downarrow^{\theta}_{pc}\; r^{\ell}}{\mathtt{labelOf}(e) \;\Downarrow^{\theta}_{pc}\; \ell^{\ell}}$$

$$\mathtt{getPC} \;\Downarrow^{\theta}_{pc}\; pc^{pc}$$

λ^DFG with References

λ^DFG

Syntax with references

Simple Types τ **::=** ··· | **Ref** τ

$\lambda^{\textbf{DFG}}$ with References

$\lambda^{\textbf{DFG}}$

Syntax with references

Simple Types τ ::= ··· | **Ref** τ

Values v ::= ··· | n_ℓ

λ^{DFG} with References

λ^{DFG}

Syntax with references

Simple Types	τ ::= ··· | **Ref** τ
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Reference to data labeled ℓ

$\lambda^{\textsf{DFG}}$ with References

$\lambda^{\textsf{DFG}}$

Syntax with references

Simple Types	τ ::= ··· | **Ref** τ
Values	v ::= ··· | n_ℓ
Expressions	e ::= ··· | **new** e | !e | e := e
	| **labelOfRef**(e)

Reference to data labeled ℓ

$\lambda^{\mathbf{DFG}}$ with References

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Reference to data labeled ℓ

Label introspection on refs

λ^DFG with References

λ^DFG

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Label introspection on refs

Store Σ ∈ (ℓ : Label) → Memory ℓ

Memory ℓ M ::= [] | r : M

λ^{DFG} with References

λ^{DFG}

Syntax with references

Simple Types τ ::= ··· | **Ref** τ

Values v ::= ··· | n_ℓ

Reference to data labeled ℓ

Expressions e ::= ··· | **new** e | !e | e := e
| **labelOfRef**(e)

Label introspection on refs

Store Σ ∈ (ℓ : Label) → Memory ℓ

Memory ℓ M ::= [] | r : M

The store is partitioned by label

Dynamic Semantics

$\langle \Sigma , e \rangle \Downarrow^{\theta}_{pc} \langle \Sigma' , v \rangle$

$$\frac{}{\langle \Sigma , \mathbf{new}\ e \rangle \Downarrow^{\theta}_{pc} \langle \Sigma'' , (n_{\ell})^{pc} \rangle}\ [\text{New}]$$

λ^{DFG}

Dynamic Semantics

$$\langle \Sigma, e \rangle \Downarrow^{\theta}_{pc} \langle \Sigma', v \rangle$$

$$\frac{\langle \Sigma, e \rangle \Downarrow^{\theta}_{pc} \langle \Sigma', r^{\ell} \rangle}{\langle \Sigma, \mathbf{new}\ e \rangle \Downarrow^{\theta}_{pc} \langle \Sigma'', (n_{\ell})^{pc} \rangle} \text{ [New]}$$

Dynamic Semantics

$\langle \Sigma , e \rangle \Downarrow^{\theta}_{pc} \langle \Sigma' , v \rangle$

Allocate in memory ℓ

$$\frac{\langle \Sigma , e \rangle \Downarrow^{\theta}_{pc} \langle \Sigma' , r^{\ell} \rangle}{\langle \Sigma , \mathbf{new}\ e \rangle \Downarrow^{\theta}_{pc} \langle \Sigma'' , (n_{\ell})^{pc} \rangle}$$

[New]

$\lambda^{\mathbf{DFG}}$

Dynamic Semantics

$\langle \Sigma , e \rangle \Downarrow^{\theta}_{pc} \langle \Sigma' , v \rangle$

Allocate in memory ℓ

$$\frac{\langle \Sigma , e \rangle \Downarrow^{\theta}_{pc} \langle \Sigma' , r^{\ell} \rangle \qquad n = |\Sigma'(\ell)|}{\langle \Sigma , \mathbf{new}\ e \rangle \Downarrow^{\theta}_{pc} \langle \Sigma'' , (n_{\ell})^{pc} \rangle} \text{[New]}$$

λ^{DFG}

Dynamic Semantics

$$\langle \Sigma, e \rangle \Downarrow^{\theta}_{pc} \langle \Sigma', v \rangle$$

Allocate in memory ℓ

Fresh Address

$$\frac{\langle \Sigma, e \rangle \Downarrow^{\theta}_{pc} \langle \Sigma', r^{\ell} \rangle \qquad n = |\Sigma'(\ell)|}{\langle \Sigma, \textbf{new}\ e \rangle \Downarrow^{\theta}_{pc} \langle \Sigma'', (n_{\ell})^{pc} \rangle}\ [\text{New}]$$

Dynamic Semantics

$$\langle \Sigma, e \rangle \Downarrow^{\theta}_{pc} \langle \Sigma', v \rangle$$

Allocate in memory ℓ

Fresh Address

$$\frac{\langle \Sigma, e \rangle \Downarrow^{\theta}_{pc} \langle \Sigma', r^{\ell} \rangle \qquad n = |\Sigma'(\ell)| \qquad \Sigma'' = \Sigma'[\ell \mapsto \Sigma'(\ell)[n \mapsto r]]}{\langle \Sigma, \mathbf{new}\ e \rangle \Downarrow^{\theta}_{pc} \langle \Sigma'', (n_{\ell})^{pc} \rangle} \text{[New]}$$

Dynamic Semantics

$\langle \Sigma , e \rangle \Downarrow^{\theta}_{pc} \langle \Sigma' , v \rangle$

Allocate in memory ℓ

Fresh Address

Update the store

$$\frac{\langle \Sigma , e \rangle \Downarrow^{\theta}_{pc} \langle \Sigma' , r^{\ell} \rangle \qquad n = |\Sigma'(\ell)| \qquad \Sigma'' = \Sigma'[\ell \mapsto \Sigma'(\ell)[n \mapsto r]]}{\langle \Sigma , \mathbf{new}\ e \rangle \Downarrow^{\theta}_{pc} \langle \Sigma'' , (n_{\ell})^{pc} \rangle}\ [\text{New}]$$

Dynamic Semantics

$\langle \Sigma , e \rangle \Downarrow^{\theta}_{pc} \langle \Sigma' , v \rangle$

$$\frac{}{\langle \Sigma , !e \rangle \Downarrow^{\theta}_{pc}}\ [\text{ Read }]$$

Dynamic Semantics

$\langle \Sigma, e \rangle \Downarrow^{\theta}_{pc} \langle \Sigma', v \rangle$

$$\frac{\langle \Sigma, e \rangle \Downarrow^{\theta}_{pc} \langle \Sigma', (n_{\ell})^{\ell'} \rangle}{\langle \Sigma, !e \rangle \Downarrow^{\theta}_{pc}} \quad [\text{ Read }]$$

λDFG

Dynamic Semantics

$$\langle \Sigma, e \rangle \Downarrow^{\theta}_{pc} \langle \Sigma', v \rangle$$

Protects the "identity" of the ref

$$\frac{\langle \Sigma, e \rangle \Downarrow^{\theta}_{pc} \langle \Sigma', (n_{\ell})^{\ell'} \rangle}{\langle \Sigma, !e \rangle \Downarrow^{\theta}_{pc}} \text{[Read]}$$

Dynamic Semantics

λ^{DFG}

$$\langle \Sigma, e\rangle \Downarrow^{\theta}_{pc} \langle \Sigma', v\rangle$$

Protects the "identity" of the ref

$$\frac{\langle \Sigma, e\rangle \Downarrow^{\theta}_{pc} \langle \Sigma', (n_{\ell})^{\ell'}\rangle \quad \Sigma'(\ell)[n] = r}{\langle \Sigma, !e\rangle \Downarrow^{\theta}_{pc}} \text{[Read]}$$

Dynamic Semantics

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Protects the "identity" of the ref

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λDFG

Dynamic Semantics

$$\langle \Sigma, e \rangle \Downarrow^{\theta}_{pc} \langle \Sigma', v \rangle$$

Protects the "identity" of the ref

$$\frac{\langle \Sigma, e \rangle \Downarrow^{\theta}_{pc} \langle \Sigma', (n_{\ell})^{\ell'} \rangle \quad \Sigma'(\ell)[n] = r}{\langle \Sigma, !e \rangle \Downarrow^{\theta}_{pc} \langle \Sigma', r^{\ell \sqcup \ell'} \rangle} \text{[Read]}$$

Tainted with original label + identity of the ref

Dynamic Semantics

$$\langle \Sigma , e \rangle \Downarrow^{\theta}_{pc} \langle \Sigma' , v \rangle$$

$$\frac{}{\langle \Sigma , e_1 := e_2 \rangle \Downarrow^{\theta}_{pc}} \quad [\text{ Write }]$$

Dynamic Semantics

$\langle \Sigma , e \rangle \Downarrow_{pc}^{\theta} \langle \Sigma' , v \rangle$

$$\frac{\langle \Sigma , e_1 \rangle \Downarrow_{pc}^{\theta} \langle \Sigma' , (n_\ell)^{\ell_1} \rangle}{\langle \Sigma , e_1 := e_2 \rangle \Downarrow_{pc}^{\theta}}$$

[Write]

Dynamic Semantics

$\langle \Sigma , e \rangle \Downarrow^{\theta}_{pc} \langle \Sigma' , v \rangle$

$$\frac{\langle \Sigma , e_1 \rangle \Downarrow^{\theta}_{pc} \langle \Sigma' , (n_\ell)^{\ell_1} \rangle \qquad \langle \Sigma' , e_2 \rangle \Downarrow^{\theta}_{pc} \langle \Sigma'' , r^{\ell_2} \rangle}{\langle \Sigma , e_1 := e_2 \rangle \Downarrow^{\theta}_{pc}}$$

[Write]

λ^{DFG}

Dynamic Semantics

$\langle \Sigma , e \rangle \Downarrow_{pc}^{\theta} \langle \Sigma' , v \rangle$

$$\frac{\langle \Sigma , e_1 \rangle \Downarrow_{pc}^{\theta} \langle \Sigma' , (n_\ell)^{\ell_1} \rangle \qquad \ell_1 \sqsubseteq \ell \qquad \langle \Sigma' , e_2 \rangle \Downarrow_{pc}^{\theta} \langle \Sigma'' , r^{\ell_2} \rangle \qquad \ell_2 \sqsubseteq \ell}{\langle \Sigma , e_1 := e_2 \rangle \Downarrow_{pc}^{\theta}} \text{[Write]}$$

Security Checks

λDFG

Dynamic Semantics

$$\langle \Sigma, e \rangle \Downarrow^{\theta}_{pc} \langle \Sigma', v \rangle$$

$$\frac{\langle \Sigma, e_1 \rangle \Downarrow^{\theta}_{pc} \langle \Sigma', (n_\ell)^{\ell_1} \rangle \quad \ell_1 \sqsubseteq \ell \qquad \langle \Sigma', e_2 \rangle \Downarrow^{\theta}_{pc} \langle \Sigma'', r^{\ell_2} \rangle \quad \ell_2 \sqsubseteq \ell}{\langle \Sigma, e_1 := e_2 \rangle \Downarrow^{\theta}_{pc}} \text{[Write]}$$

Security Checks

$\ell_1 \sqsubseteq \ell$ *The decision of writing **this** reference must not depend on data above the label of the reference*

Dynamic Semantics

$\langle \Sigma , e \rangle \Downarrow^{\theta}_{pc} \langle \Sigma' , v \rangle$

$$\langle \Sigma , e_1 \rangle \Downarrow^{\theta}_{pc} \langle \Sigma' , (n_\ell)^{\ell_1} \rangle \qquad \ell_1 \sqsubseteq \ell$$

$$\langle \Sigma' , e_2 \rangle \Downarrow^{\theta}_{pc} \langle \Sigma'' , r^{\ell_2} \rangle \qquad \ell_2 \sqsubseteq \ell$$

Security Checks

[Write]

$$\langle \Sigma , e_1 := e_2 \rangle \Downarrow^{\theta}_{pc}$$

$\ell_1 \sqsubseteq \ell$ *The decision of writing* ***this*** *reference must not depend on data above the label of the reference*

$\ell_2 \sqsubseteq \ell$ *Must not write data above the label of the reference*

Dynamic Semantics

λ^{DFG}

$$\langle \Sigma , e \rangle \Downarrow^{\theta}_{pc} \langle \Sigma' , v \rangle$$

$$\dfrac{\langle \Sigma , e_1 \rangle \Downarrow^{\theta}_{pc} \langle \Sigma' , (n_{\ell})^{\ell_1} \rangle \quad \ell_1 \sqsubseteq \ell \quad \langle \Sigma' , e_2 \rangle \Downarrow^{\theta}_{pc} \langle \Sigma'' , r^{\ell_2} \rangle \quad \ell_2 \sqsubseteq \ell \quad \Sigma''' = \Sigma''[\ell \mapsto \Sigma''(\ell)[n \mapsto r]]}{\langle \Sigma , e_1 := e_2 \rangle \Downarrow^{\theta}_{pc} \langle \Sigma''' , ()^{pc} \rangle} \text{[Write]}$$

Security Checks

Update store

$\ell_1 \sqsubseteq \ell$ *The decision of writing **this** reference must not depend on data above the label of the reference*

$\ell_2 \sqsubseteq \ell$ *Must not write data above the label of the reference*

Proof Technique

1 *Define the **low-equivalence** relation* $v_1 \approx^{\tau}_{L} v_2$

Proof Technique

v_1 and v_2 are indistinguishable at security level L

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v_1 *and* v_2 *are indistinguishable at security level* **L**

1. *Define the* ***low-equivalence*** *relation* $v_1 \approx^{\tau}_{L} v_2$

2. *Prove that the semantics* ***preserves*** *the relation:*

$$\left.\begin{array}{l} \theta_1 \approx \theta_2 \\ c_1 \approx c_2 \end{array}\right\}$$

Proof Technique

v_1 *and* v_2 *are indistinguishable at security level* **L**

① *Define the* ***low-equivalence*** *relation* $v_1 \approx^{\tau}_{L} v_2$

② *Prove that the semantics* ***preserves*** *the relation:*

$$\left.\begin{array}{l} \theta_1 \approx \theta_2 \\ c_1 \approx c_2 \end{array}\right\} \textit{ if } \left\{\begin{array}{l} c_1 \Downarrow^{\theta_1}_{pc} c_1' \\ c_2 \Downarrow^{\theta_2}_{pc} c_2' \end{array}\right\}$$

Proof Technique

v_1 *and* v_2 *are indistinguishable at security level* **L**

① *Define the* ***low-equivalence*** *relation* $v_1 \approx^{\tau}_{L} v_2$

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Proof Technique

*v_1 and v_2 are indistinguishable at security level **L***

1. *Define the **low-equivalence** relation* $v_1 \approx^{\tau}_{L} v_2$

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$$\left.\begin{array}{l} \theta_1 \approx \theta_2 \\ c_1 \approx c_2 \end{array}\right\} \textit{if} \quad \left.\begin{array}{l} c_1 \Downarrow^{\theta_1}_{pc} c_1' \\ c_2 \Downarrow^{\theta_2}_{pc} c_2' \end{array}\right\} \quad \textit{then} \quad c_1' \approx c_2'$$

3. *Derive non-interference as a **corollary***

Outline

Overview of different language-based IFC approaches

- Non Interference
- 4 IFC Languages

	Static	*Dynamic*
Fine-grained	$\lambda^{\textbf{SFG}}$	$\lambda^{\textbf{DFG}}$
Coarse-grained	$\lambda^{\textbf{SCG}}$	$\lambda^{\textbf{DCG}}$

Outline

Overview of different language-based IFC approaches

- **Non Interference** ✓
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Outline

Overview of different language-based IFC approaches

- **Non Interference** ✓
- **4 IFC Languages**

	Static	*Dynamic*	
Fine-grained	$\lambda^{\textbf{SFG}}$	$\lambda^{\textbf{DFG}}$	✓
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Introduction and Surveys

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