Evidence-based Audit

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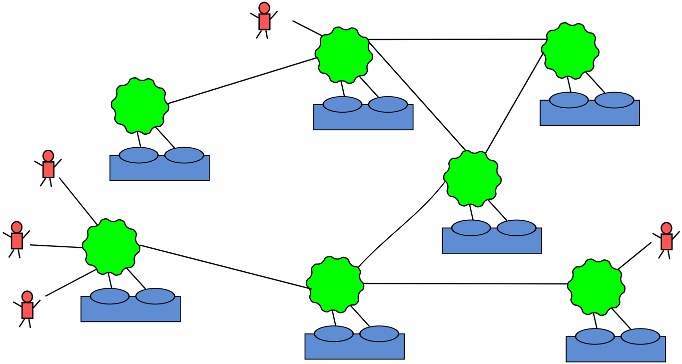
Our Setting: Distributed Access Control



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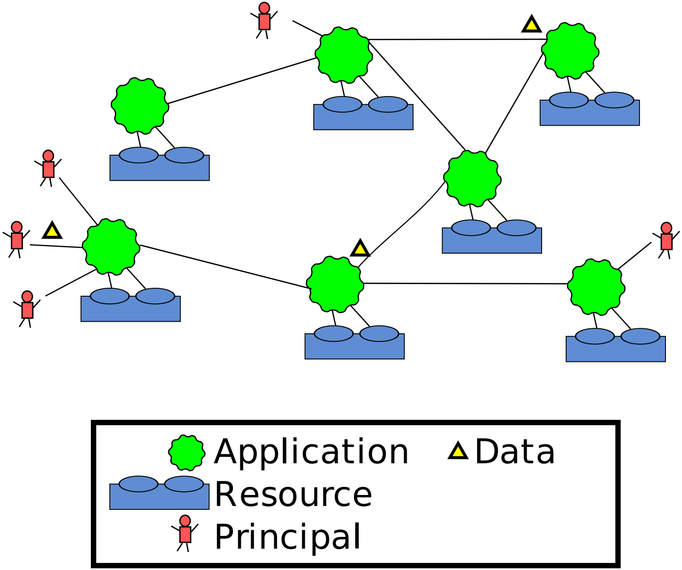

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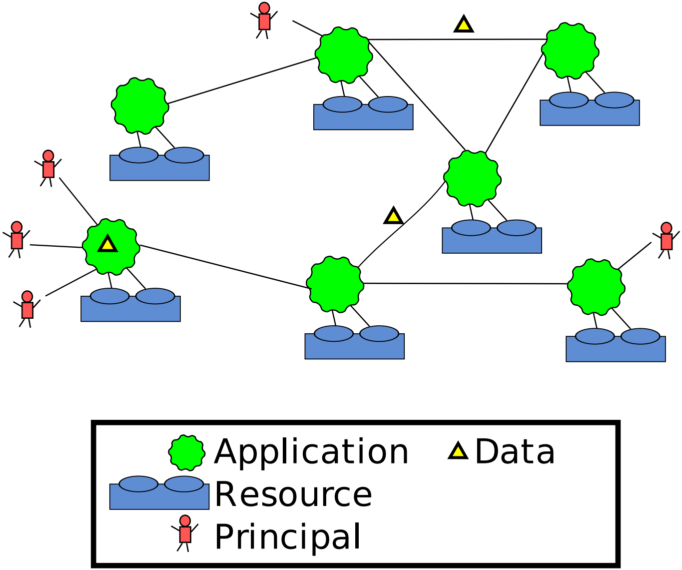

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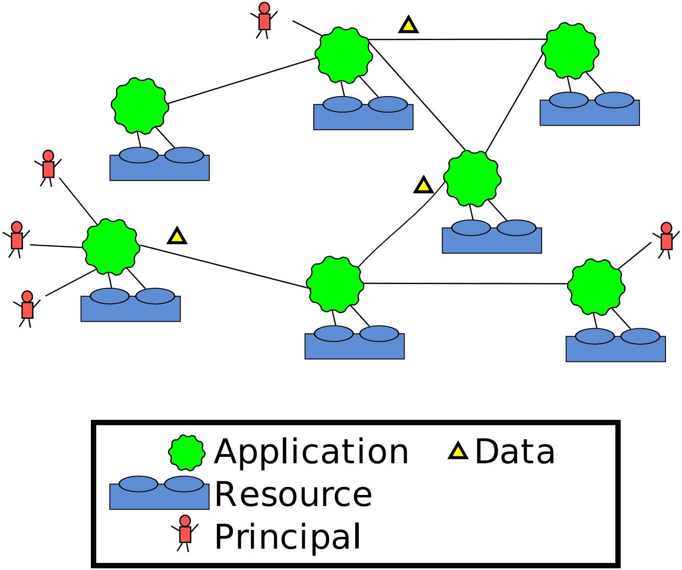
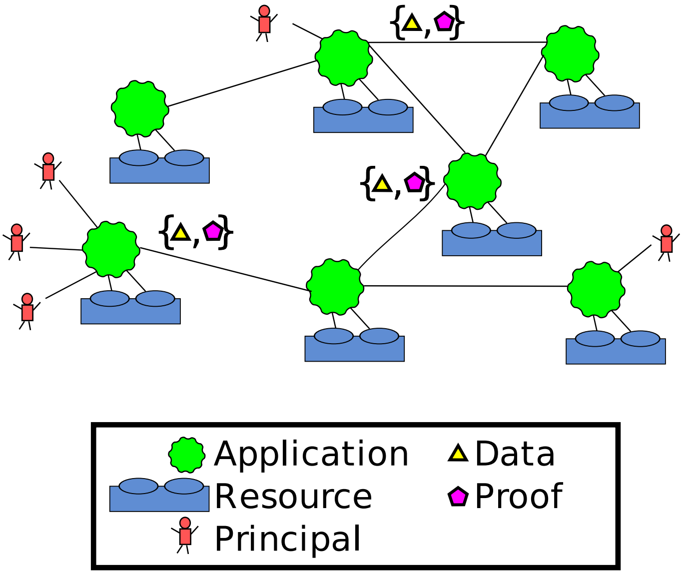


Key Idea: Proofs attest to data integrity.



[Necula+ 98]

The Aura Project

- A programming language called Aura
  - A propositional fragment, modeled here by Aura_0
  - An ML-like computation language [Jia+ 08]
- A security aware programming model
  - active, potentially malicious principals
  - mutual distrust between applications and principals
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Today's Talk

Analyzing the local security of Aura applications.

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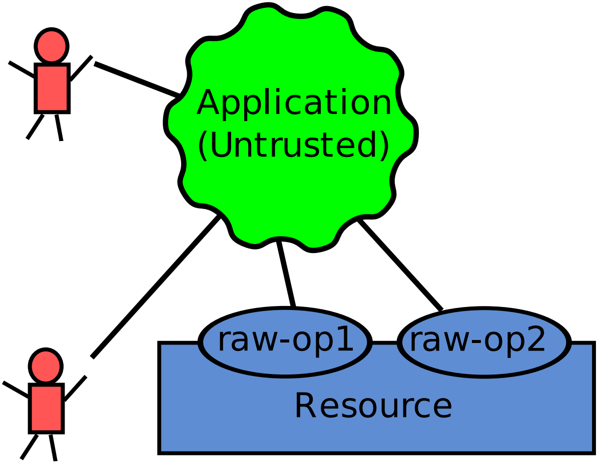

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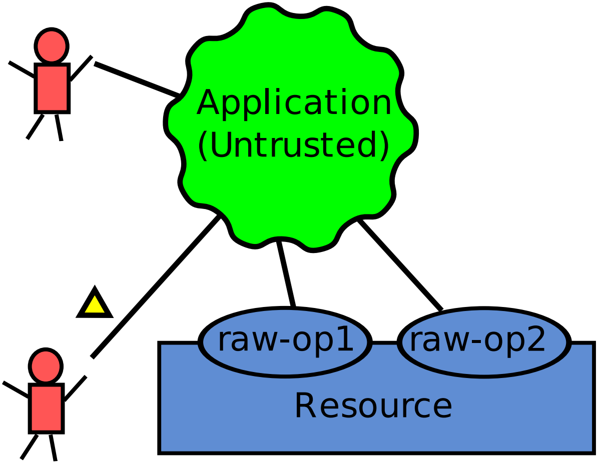

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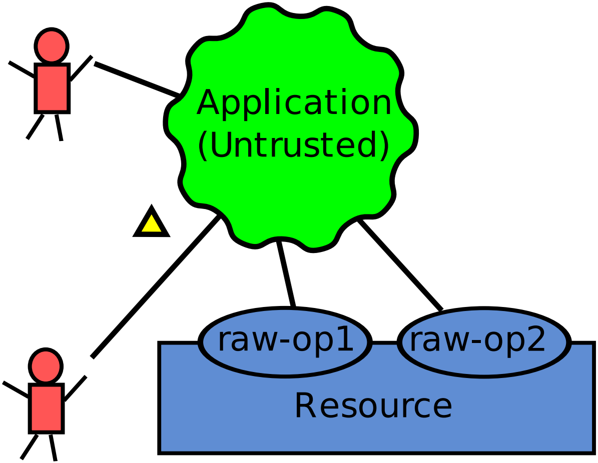

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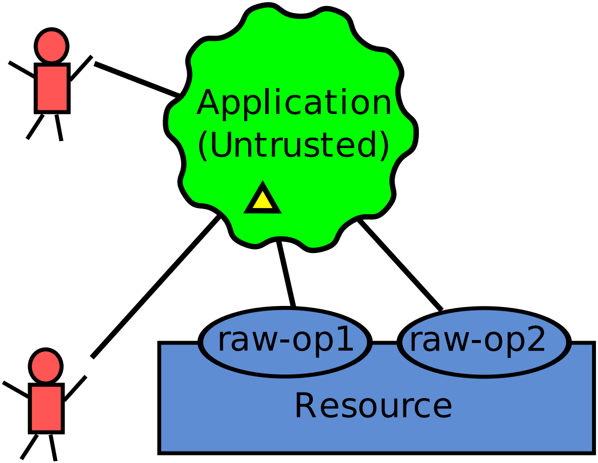

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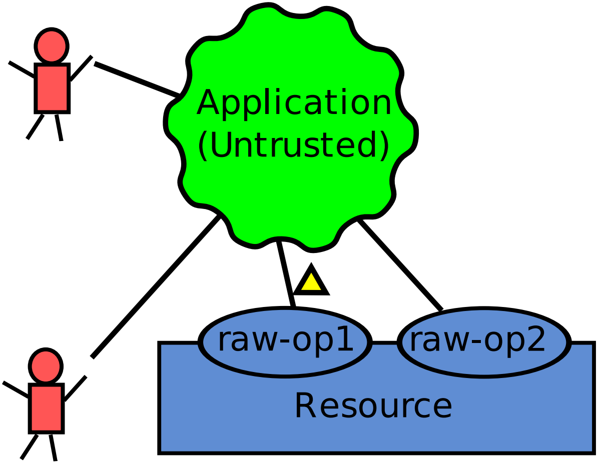

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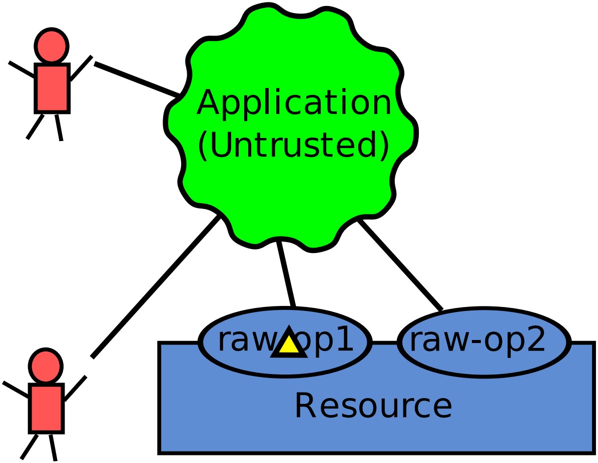

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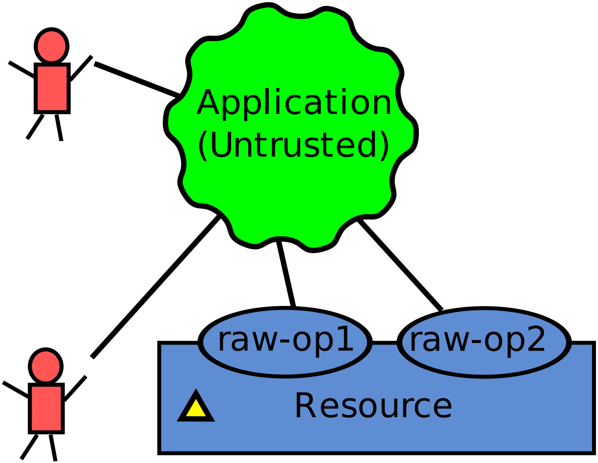

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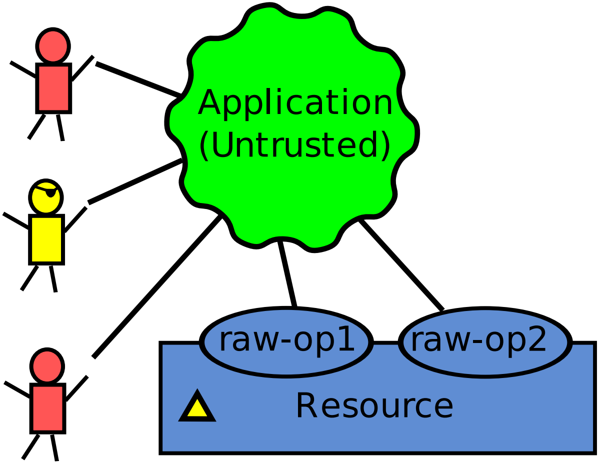

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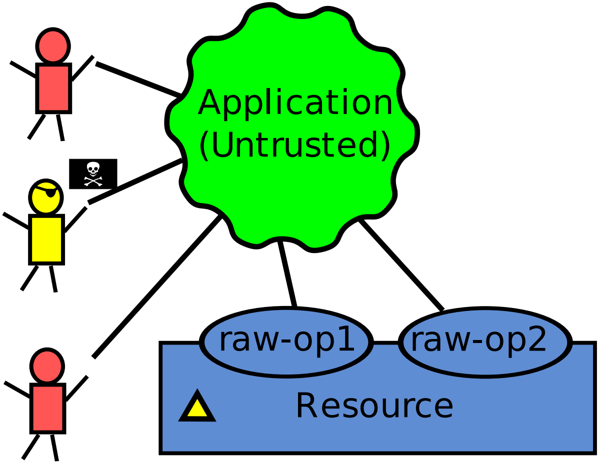

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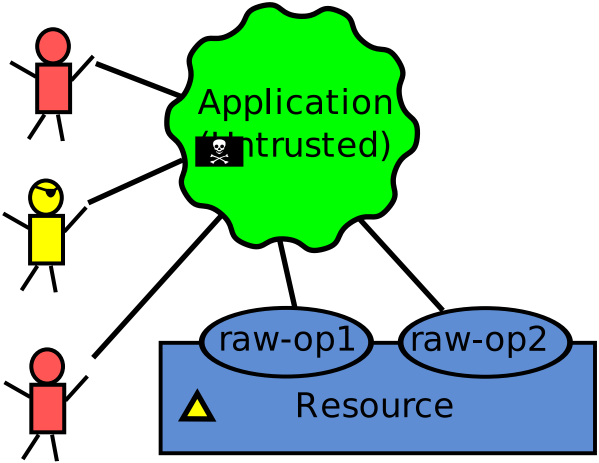

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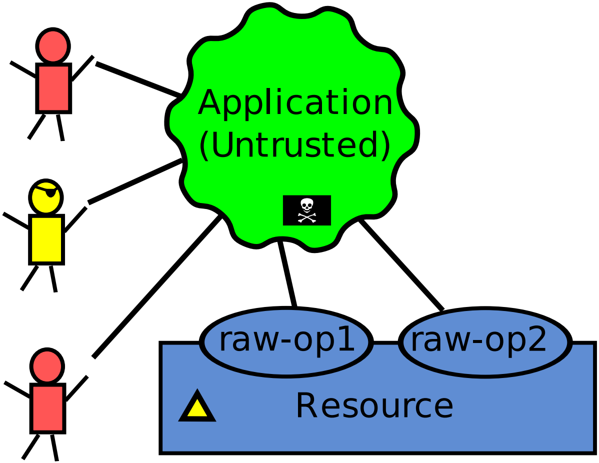

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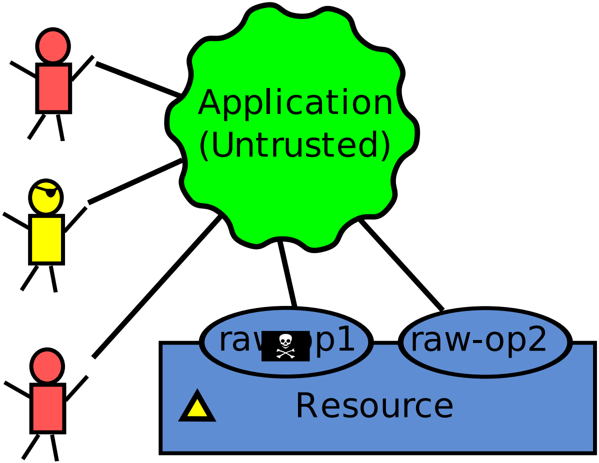

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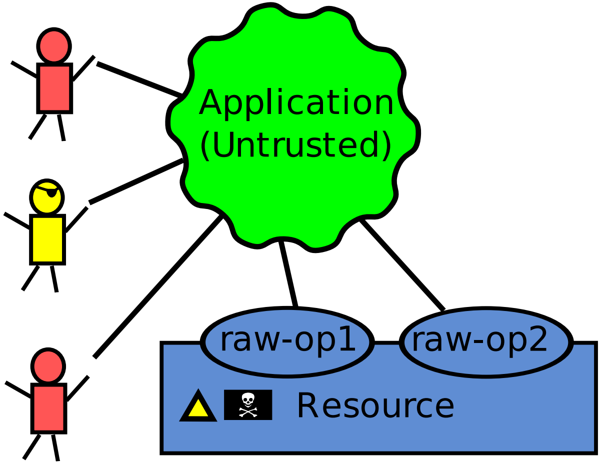

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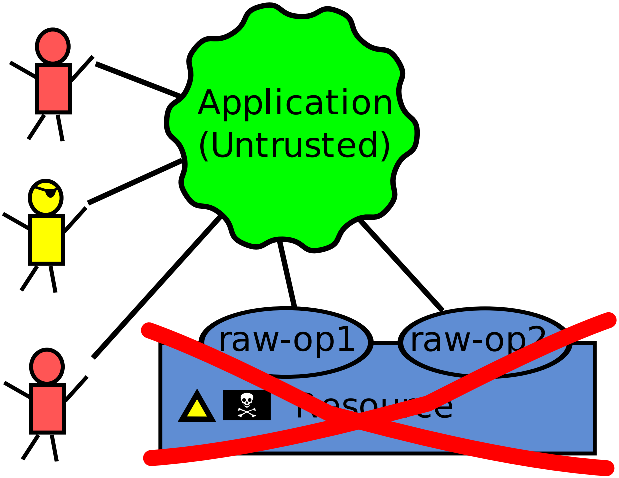

Jargon needed for this talk

Institutional Policy Human-level rules about principals, data values, and resources.

Bad Access A system state change violating institutional policy.

Formal Rules Machine-level encoding of policy.

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Institutional Policy: Human-level rules about principals, data values, and resources.

Bad Access: A system state change violating institutional policy.

Formal Rules: Machine-level encoding of policy.

Foreshadowing

Users care about *institutional policy*, but technology tries to enforces *formal rules*.

Why do reference monitors allow bad accesses to occur?

Problem 1

The trusted computing base's implementation may be buggy.

Problem 2

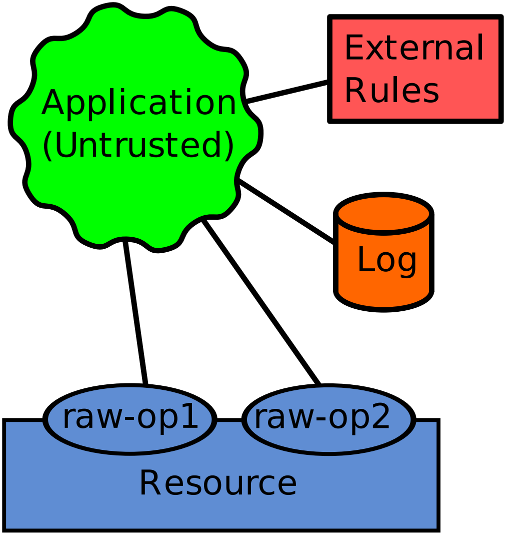
The formal rules language may be too impoverished to express institutional policy.

Problem 3

The system may be configured with incorrect formal rules.

And many other reasons not addressed here...

Common application design exacerbates these problems.



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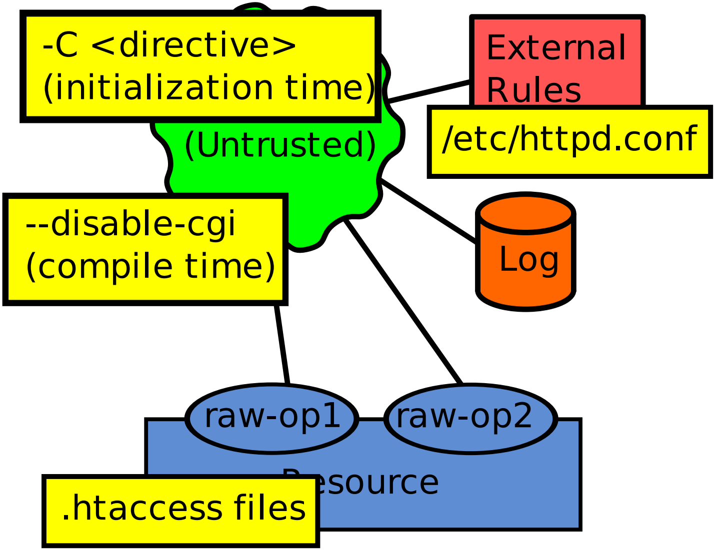

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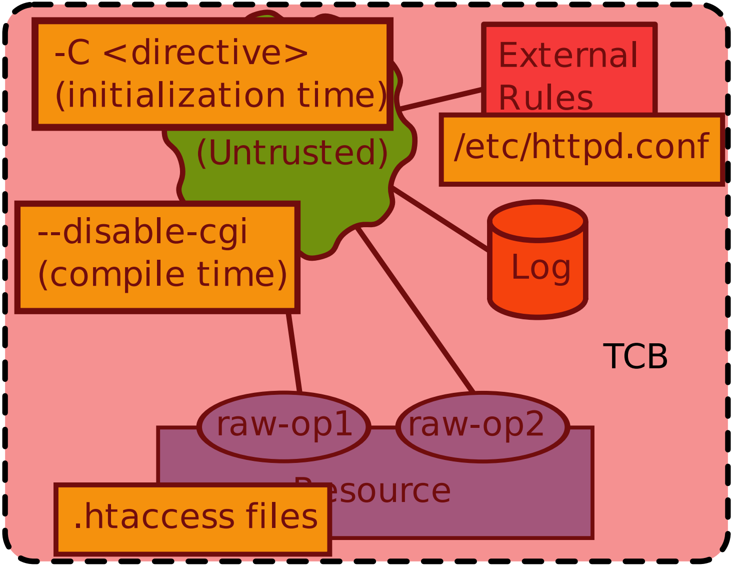


Problem 1

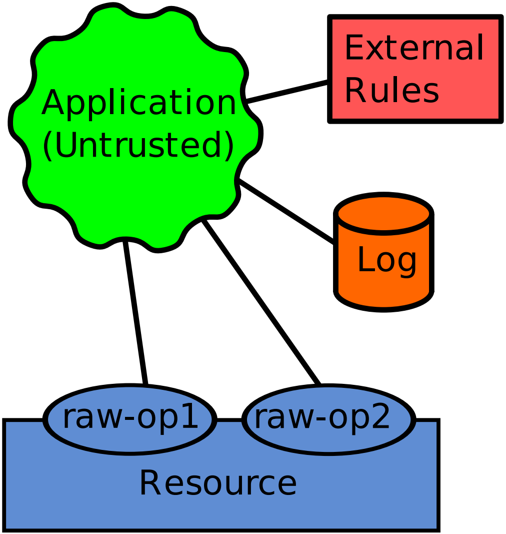
The trusted computing base's implementation may be buggy.

Aura Solution

Trust only a small, generic *kernel* that has no application-specific functionality.

[Saltzer+ 75], [Bauer+ 99], [Jia+ 08]

In Aura, a lightweight kernel protects resources.



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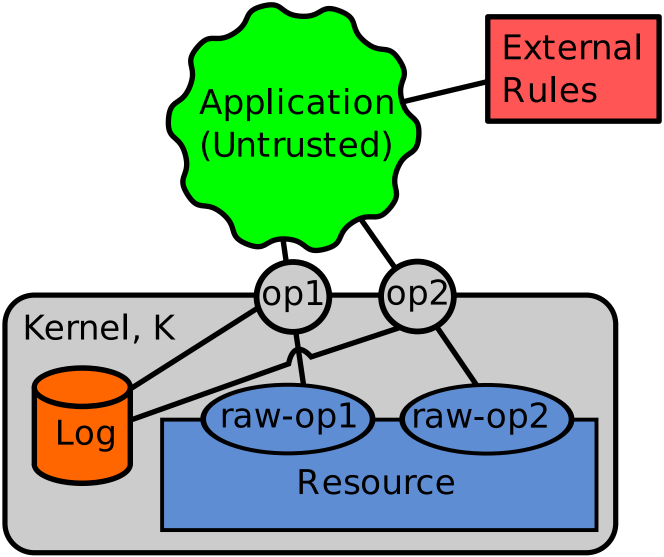

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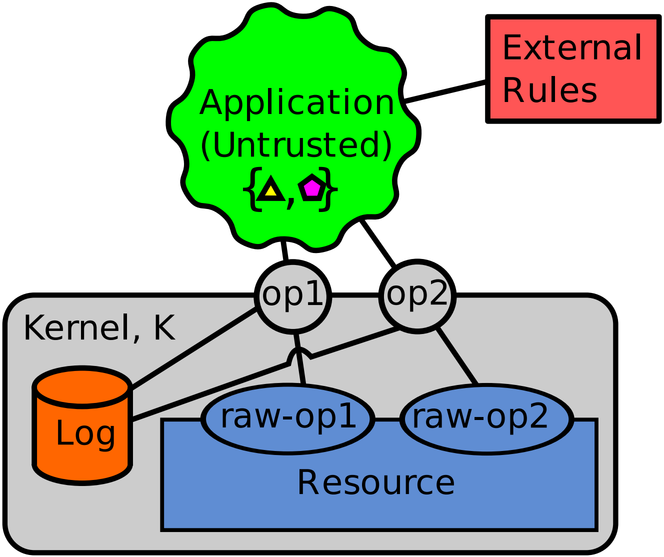

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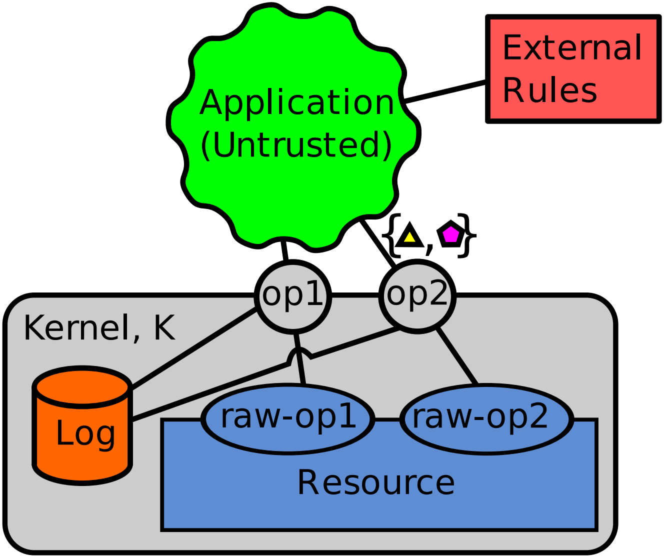

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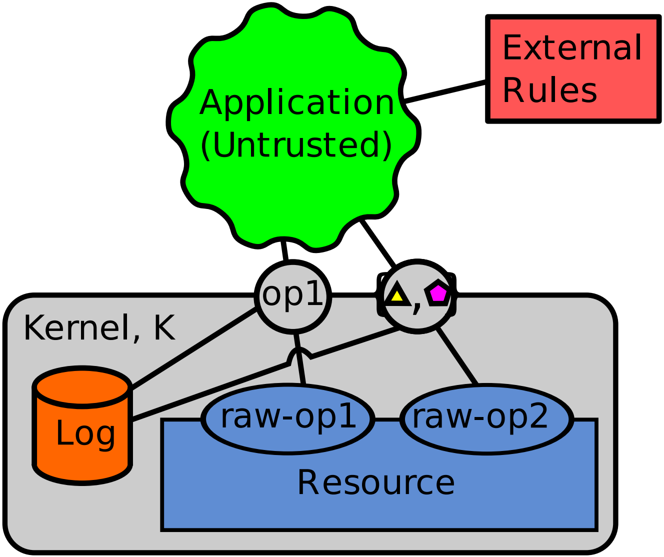

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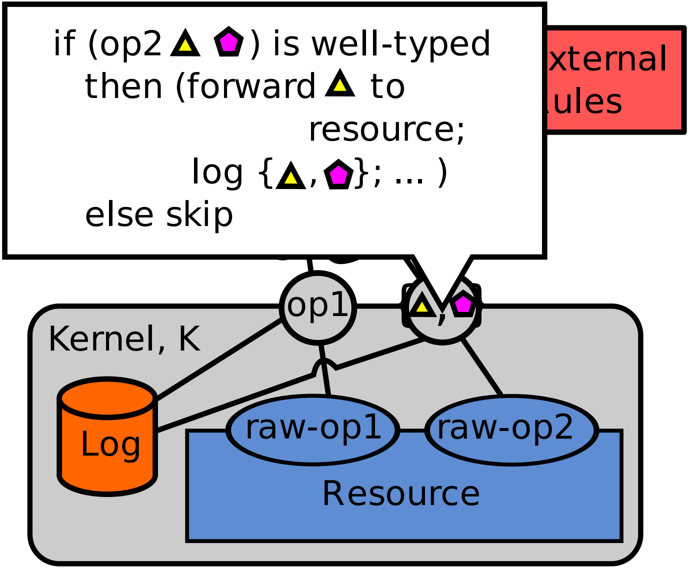

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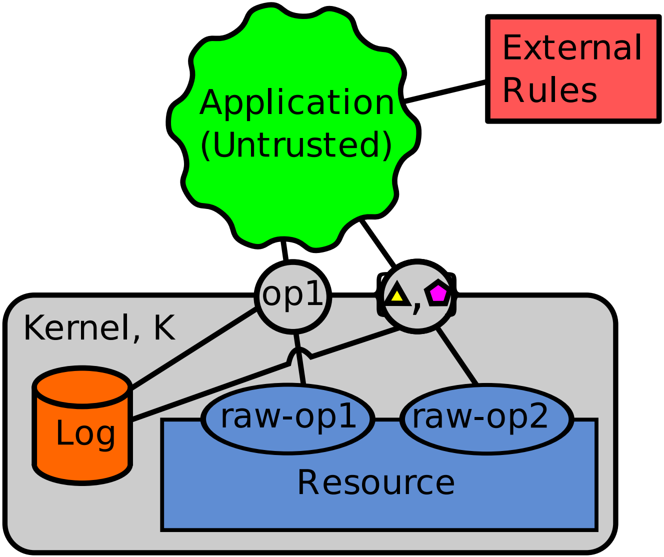

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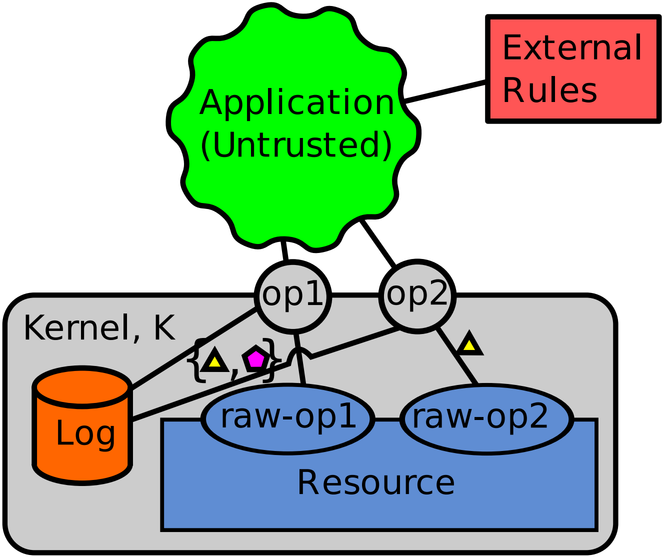

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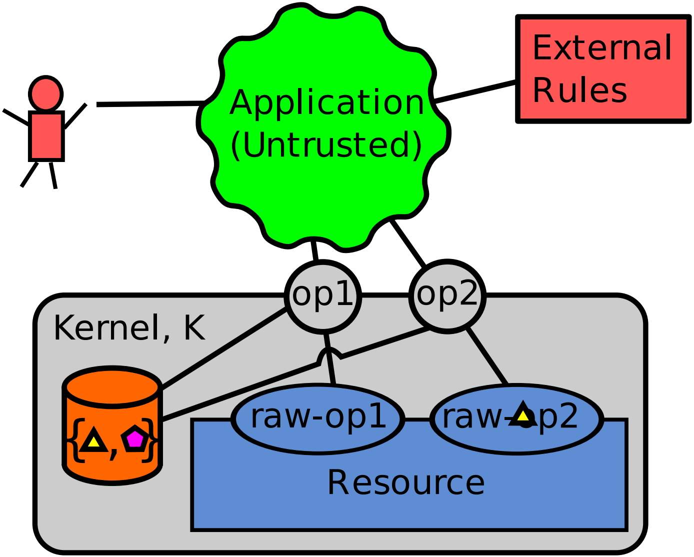

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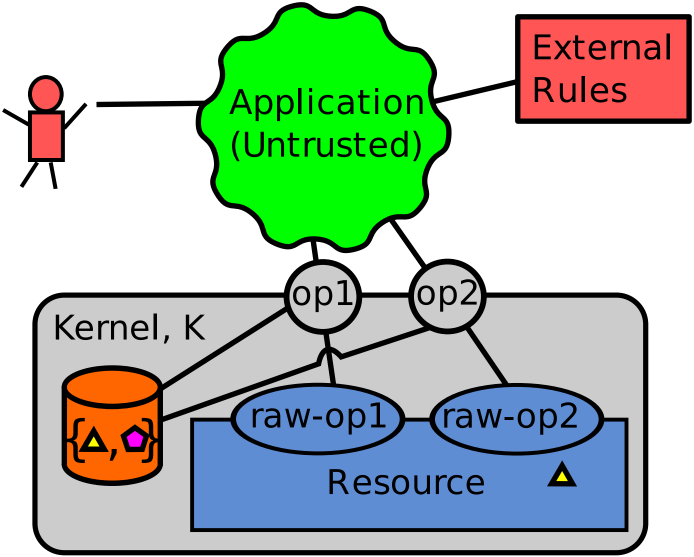

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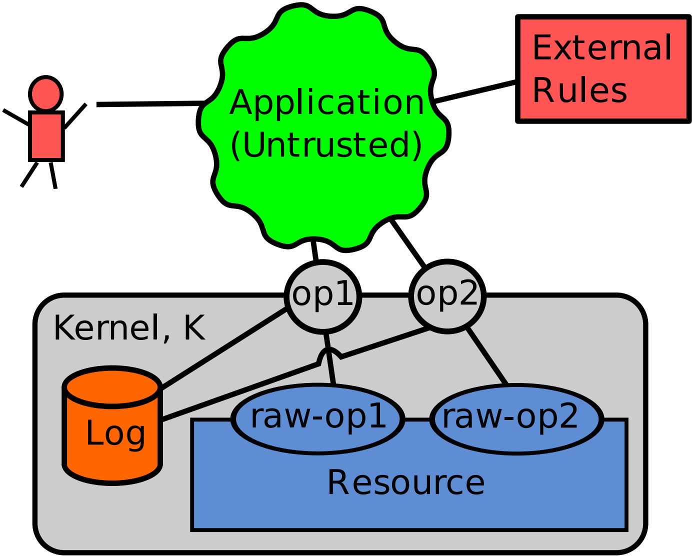

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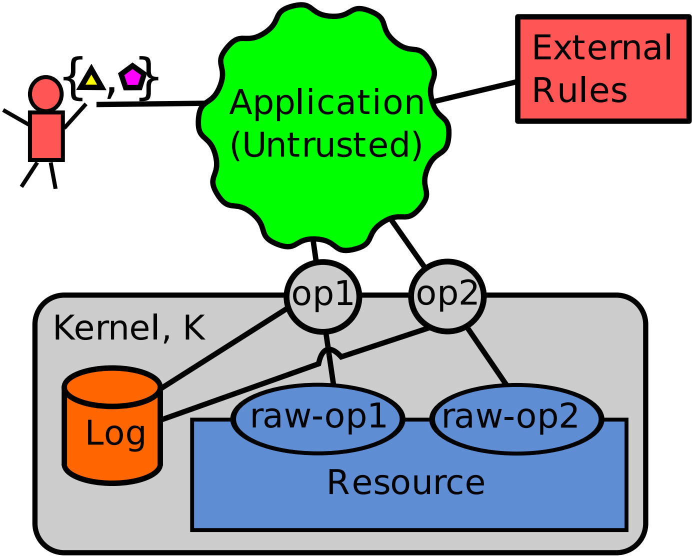

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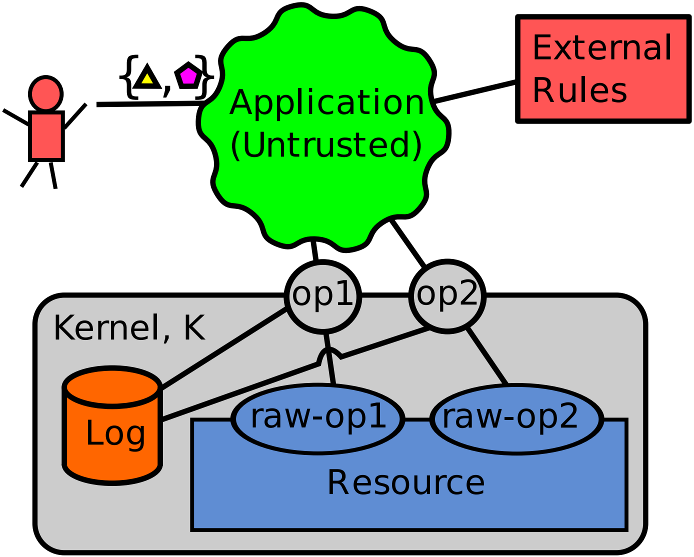

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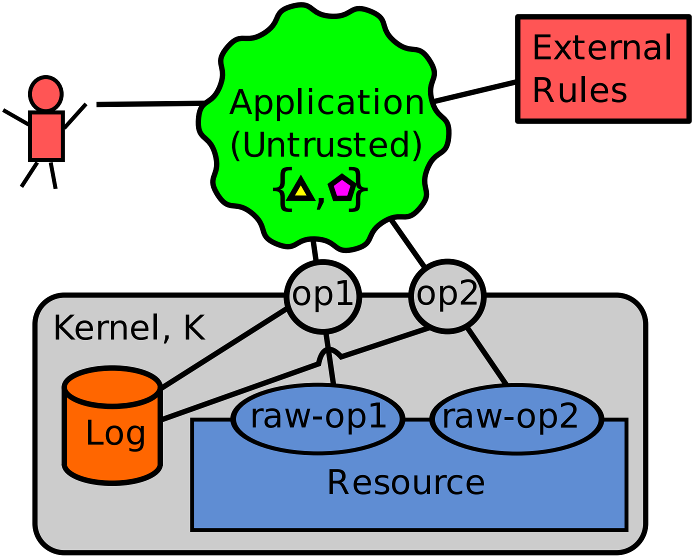

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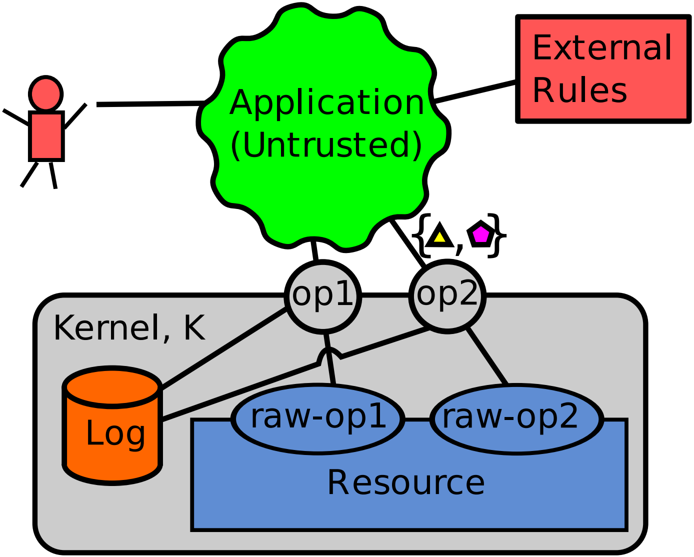

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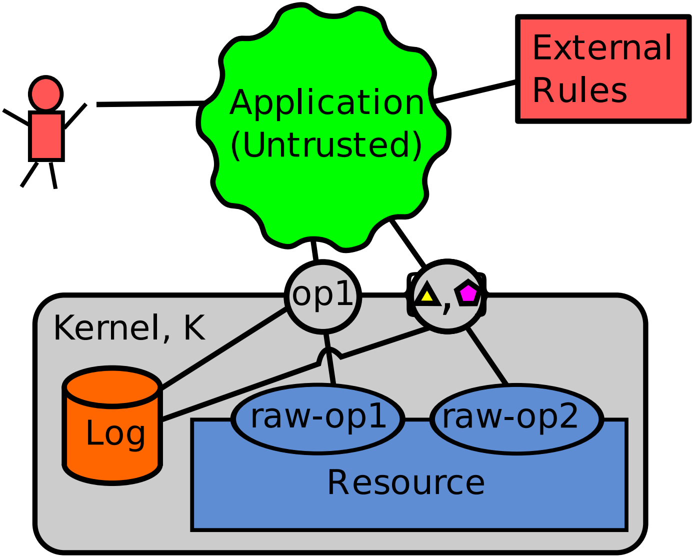

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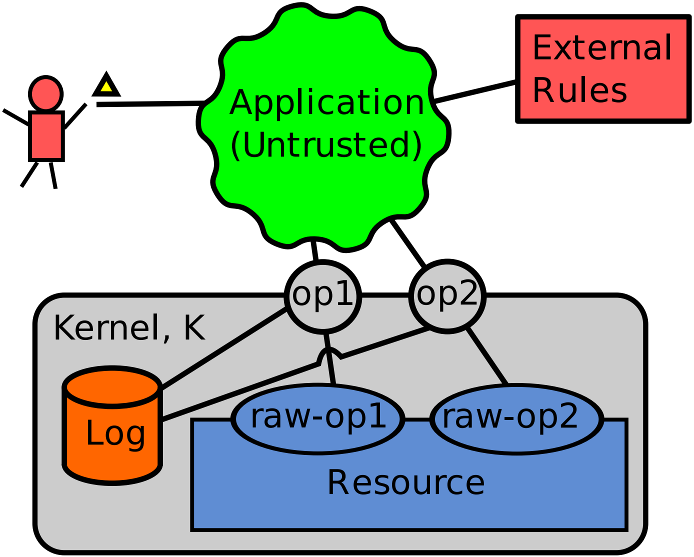

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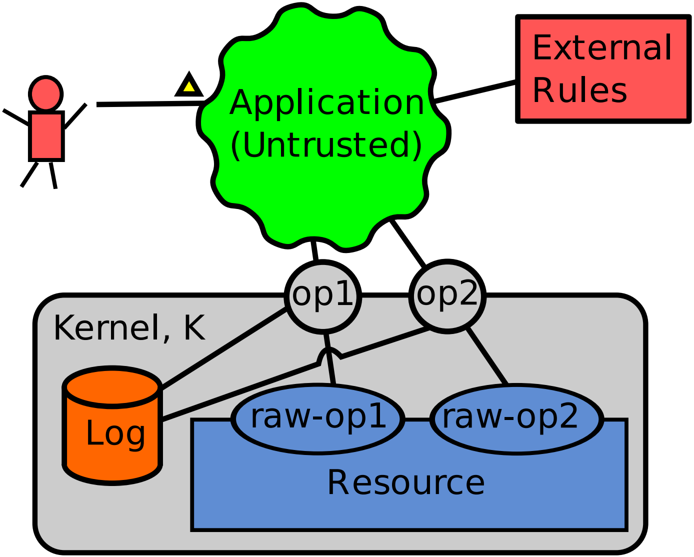

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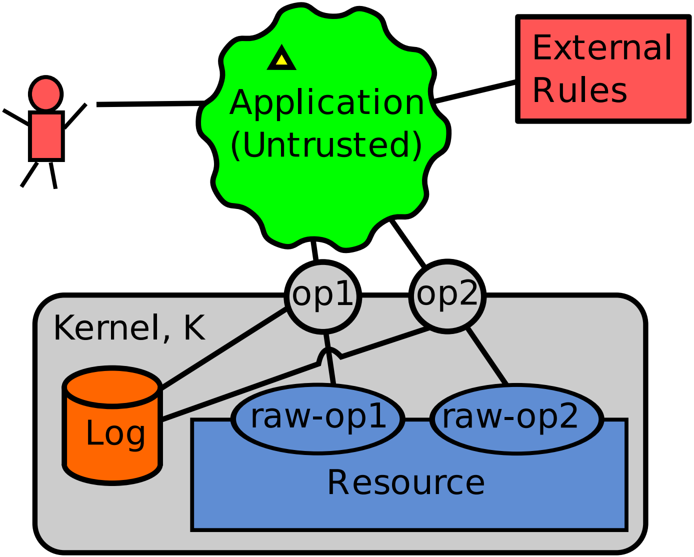

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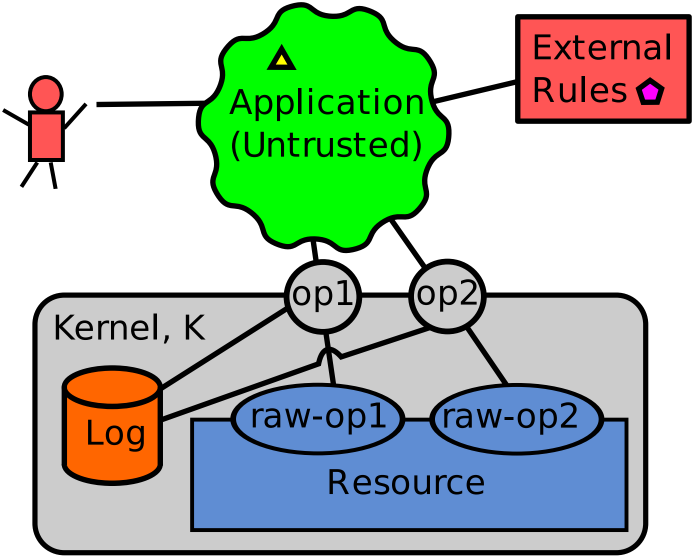

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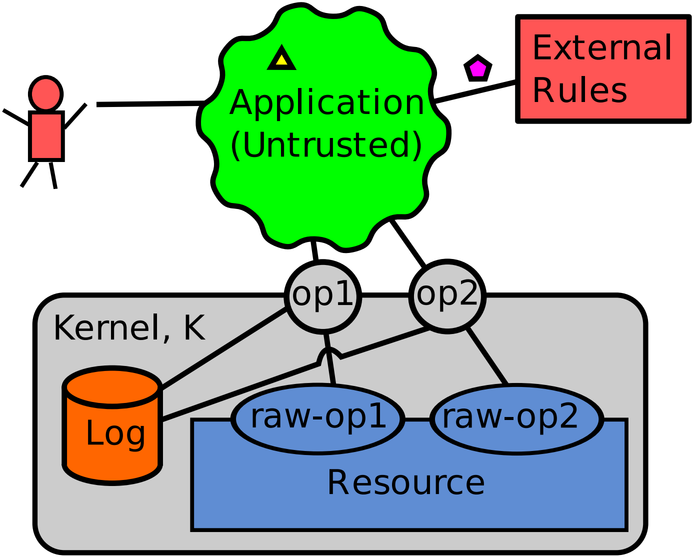

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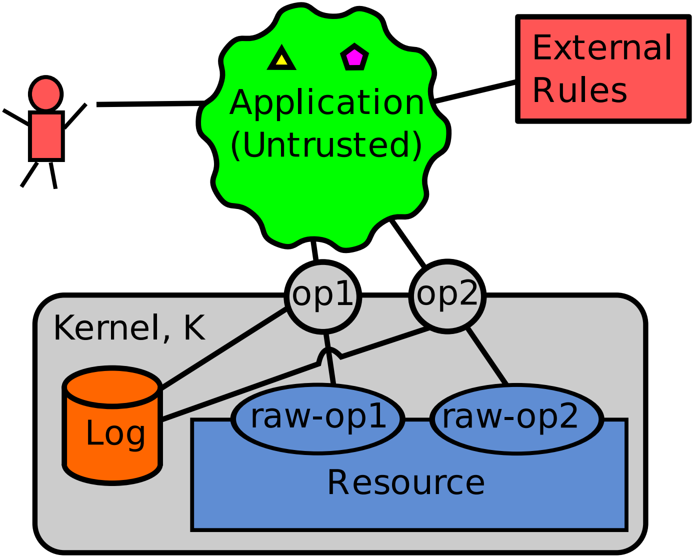

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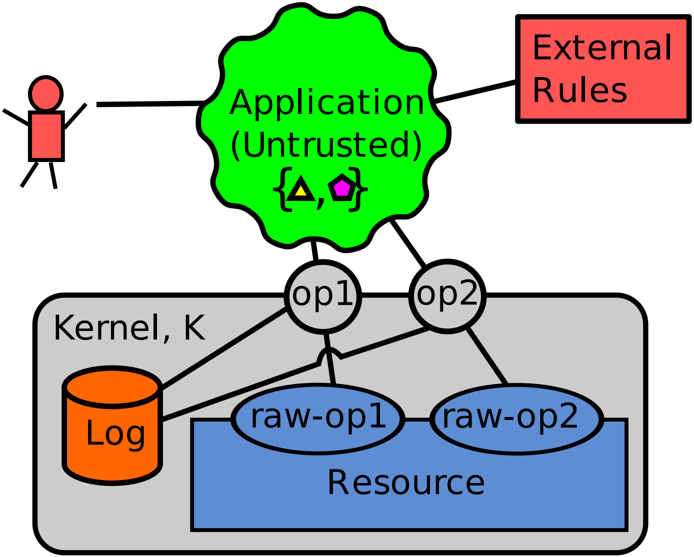

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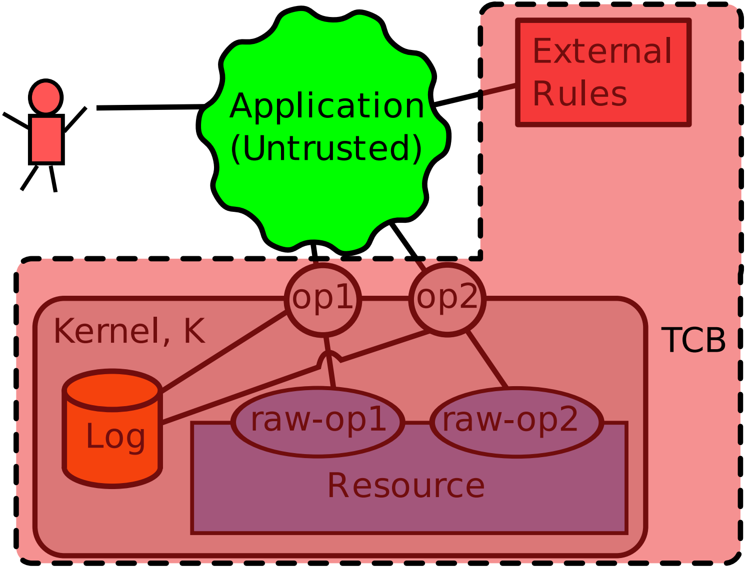

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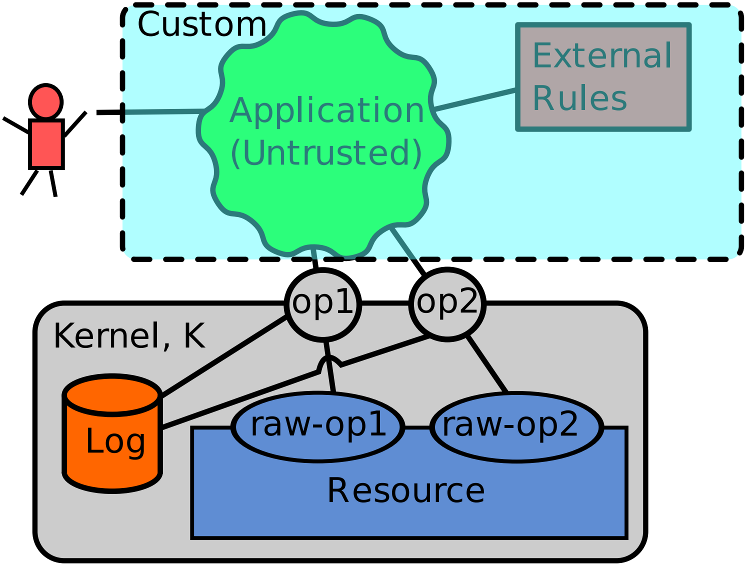

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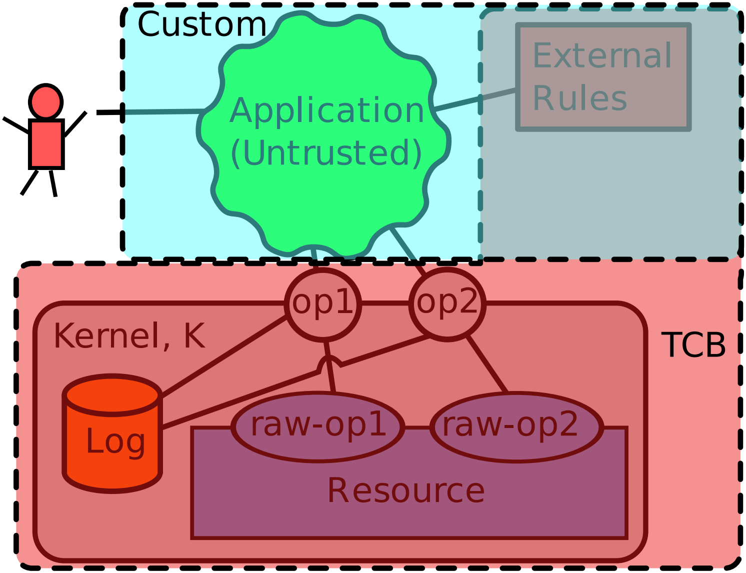

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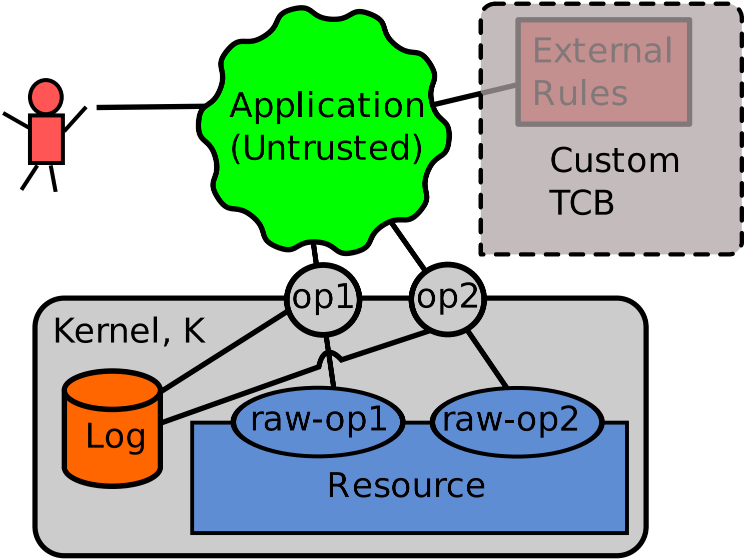

Example: Types for a remote procedure call server.

The RPC server resource has a single raw operation

$$\text{raw-rpc} : \textbf{string} \Rightarrow \textbf{string}$$

The kernel exposes an *extended signature* of propositions.

$$\begin{aligned} \text{OkToRPC} &: \textbf{string} \rightarrow \textbf{Prop} \\ \text{DidRPC} &: \textbf{string} \rightarrow \textbf{string} \rightarrow \textbf{Prop} \end{aligned}$$

Applications are written against the *kernel interface*.

$$\begin{aligned} \text{rpc} \;:\; & (x : \textbf{string}) \Rightarrow (\text{Kernel } \textbf{says } \text{OkToRPC } x) \\ & \Rightarrow \{y : \textbf{string}; \text{Kernel } \textbf{says } \text{DidRPC } x\ y\} \end{aligned}$$

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The kernel interface and extended signature
may be mechanically generated.

Problem 2

The formal rules language may be too impoverished to express institutional policy.

Aura Solution

Use dependent DCC with signature objects to specify rules.

[Abadi+ 06], [Fournet+ 07], [Bengtson+ 08] ...

Aura's **says** modality represents affirmation. (1/2)

$$\frac{\Gamma \vdash P : \textbf{Prop}}{\Gamma \vdash A \ \textbf{says} \ P : \textbf{Prop}}$$

The proposition "Principal A affirms proposition P."

$$\frac{\Gamma \vdash P : \textbf{Prop}}{\Gamma \vdash \textbf{sign}(A, P) : A \ \textbf{says} \ P}$$

A's signature on P. P might be unprovable.

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Aura's **says** modality represents affirmation. (2/2)

$$\frac{\Gamma \vdash p : P}{\Gamma \vdash \textbf{return@}[A]p : A \ \textbf{says} \ P}$$

A affirms proven propositions.

$$\frac{\Gamma \vdash p : A \ \textbf{says} \ P \qquad \Gamma, x : P \vdash q : A \ \textbf{says} \ Q}{\Gamma \vdash \textbf{bind} \ x = p \ \textbf{in} \ q : A \ \textbf{says} \ Q}$$

A affirms the result of hypothetical reasoning. We can "reason from A's point of view."

(These are standard monad rules.)

Aura$_0$'s syntax supports restricted dependent types.

Partial syntax

$$
\begin{array}{lcll}
t & ::= & \textbf{string} \mid \textbf{prin} & \text{Base types} \\
 & \mid & x \mid a & \text{Variables and constants} \\
 & \mid & t \ \textbf{says} \ t & \text{Says modality} \\
 & \mid & (x{:}\, t) \rightarrow \ t & \text{Logical implication/quantification} \\
 & \mid & (x{:}\ t) \ \Rightarrow \ t & \text{Computational arrows} \\
 & \mid & \{x{:}\, t; t\} & \text{Dependent pair type} \\
 & \mid & t \ t & \text{Application} \\
 & & \vdots &
\end{array}
$$

Syntactic separation of computation and logical arrows stop arbitrary resource-effects from polluting the logic.

Dependent types allow for expressive rules.

Example (Bob acts for Alice)

$$\text{Alice } \textbf{says } ((P\colon \textbf{Prop}) \rightarrow \text{ Bob } \textbf{says } P \rightarrow P)$$

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Example (Bob acts for Alice)

$$\text{Alice } \textbf{says } ((P\colon \textbf{Prop}) \to \text{ Bob } \textbf{says } P \to P)$$

Example (Bob acts for Alice only regarding validity)

$$\text{Alice } \textbf{says } ((x\colon \textbf{string}) \to \text{ Bob } \textbf{says } \text{valid } x \to \text{valid } x)$$

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Example (Kernel allows RPC calls on strings endorsed by Alice)

$$\text{Kernel } \textbf{says } ((x\colon \textbf{string}) \rightarrow \text{ Alice } \textbf{says } \text{valid } x \rightarrow \text{OkToRPC } x)$$

Problem 3

The system may be configured with incorrect formal rules.

Aura Solution

Consistently log runtime proof objects for later analysis.

[Wee 95], [Cederquist+ 05]

When something unexpected happens: look at the log.

- System design guarantees a one-to-one correspondence between log entries and resource state changes.
- If a Alice's signature does not appear in a log entry, she could not have caused the associated action.
- Proofs get convoluted, but *proof reduction* can restore clarity.

Example (A convoluted proof)

$$(\lambda x.\lambda y.y)\ (\mathbf{sign}(\mathsf{Alice}, P))\ (\mathbf{sign}(\mathsf{Bob}, Q))$$

Here Alice's signature is "irrelevant."

Reduction relation includes special cases for **bind**.

R-Bind-Specious

$$\frac{x \notin fv(t_2)}{\textbf{bind}\ x = t_1\ \textbf{in}\ t_2 \longrightarrow t_2}$$

Drops unused hypotheses. Most interesting when t_1 is a signature.

R-Bind-Commute

$$\frac{y \notin fv(t_3)}{\begin{array}{c}\textbf{bind}\ x = (\textbf{bind}\ y = t_1\ \textbf{in}\ t_2)\ \textbf{in}\ t_3 \longrightarrow \\ \textbf{bind}\ y = t_1\ \textbf{in}\ \textbf{bind}\ x = t_2\ \textbf{in}\ t_3\end{array}}$$

Commutation rule that can enable further reductions.

. . . plus standard β and structural rules.

Proof reduction

Example (The same convoluted proof)

$$(\lambda x.\lambda y.y)\ (\mathbf{sign}(\mathsf{Alice}, P))\ (\mathbf{sign}(\mathsf{Bob}, Q)) \longrightarrow^{*} \mathbf{sign}(\mathsf{Bob}, Q)$$

Example (Reducing by special bind rules)

$$\begin{aligned}
&\mathbf{bind}\ x = \big(\mathbf{bind}\ y = (f\ \mathbf{sign}(\mathsf{Bob}, Q)) \\
&\qquad\qquad\quad \mathbf{in}\ \mathbf{sign}(\mathsf{Alice}, P)\big) \\
&\quad \mathbf{in}\ x \\
&\longrightarrow^{*} \mathbf{sign}(\mathsf{Alice}, P)
\end{aligned}$$

Logical properties of Aura_0

Theorem (Subject Reduction)

If $p \longrightarrow p'$ and $\Gamma \vdash p : s$ then $\Gamma \vdash p' : s$.

Theorem (Confluence)

If $p \longrightarrow^* p_1$, and $p \longrightarrow^* p_2$, then there exists p_3 such that $p_1 \longrightarrow^* p_3$ and $p_2 \longrightarrow^* p_3$.

Theorem (Strong Normalization)

If $\Gamma \vdash p : s$, then p is strongly normalizing (SN). That is, all reduction sequences starting with p halt.

Aura$_0$ is strongly normalizing.

Fact

The Calculus of Constructions with dependent pairs (CoC) is SN.

[Geuvers 95]

Proof Idea

Show Aura reductions can be simulated in terminating system based on CoC.

$$\begin{array}{ccccccccc}
p_0 & \longrightarrow & p_1 & \longrightarrow & & \longrightarrow & p_2 & \longrightarrow & \cdots \\
\downarrow [\![\cdot]\!] & & \downarrow [\![\cdot]\!] & & & & \downarrow [\![\cdot]\!] & & \\
t_0 & \longrightarrow_{cc} & t_1 & \longrightarrow_{cc} & t_1' & \longrightarrow_{cc} & t_2 & \longrightarrow_{cc} & \cdots
\end{array}$$

Take home message

Aura is a framework for proof carrying authorization and audit.

Aura includes

- a small and generic trusted computing base,
- an expressive authorization logic, and
- a principled audit methodology.

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Code and technical reports available from
`http://www.cis.upenn.edu/~stevez/sol/aura.html`

Or ask us for a demo!

Bonus Slides

- Typing Rules for Pair and Arrow
- Strong Normalization Proof

Typing rules for arrow and pair.

$$\frac{\Sigma;\Gamma \vdash t_1 : k_1 \qquad \Sigma;\Gamma, x : t_1 \vdash t_2 : k_2 \qquad k_1 \in \{\mathbf{Kind}^{\mathrm{P}}, \mathbf{Prop}, \mathbf{Type}\} \qquad k_2 \in \{\mathbf{Prop}, \mathbf{Type}\}}{\Sigma;\Gamma \vdash (x{:}\, t_1) \to\ t_2 : k_2}$$

$$\frac{\Sigma;\Gamma \vdash t_1 : k_1 \qquad \Sigma;\Gamma, x : t_1 \vdash t_2 : k_2 \qquad k_1, k_2 \in \{\mathbf{Prop}, \mathbf{Type}\}}{\Sigma;\Gamma \vdash \{x{:}\, t_1; t_2\} : k_1}$$

Translation from Aura to CoC erases **says**

Definition

$$
\begin{aligned}
[\![A \ \textbf{says} \ P]\!] &\approx [\![P]\!] \\[2em]
[\![\textbf{return@}[A]p]\!] &\approx [\![p]\!] \\
[\![\textbf{bind}\ x = p{:}\ P\ \textbf{in}\ q]\!] &\approx (\lambda x{:}[\![P]\!] \ .\ [\![q]\!] \ )\ [\![p]\!] \\
[\![\textbf{sign}(A, P)]\!] &\approx x \quad \text{fresh}
\end{aligned}
$$

Translation from Aura to CoC erases **says**

Definition

$$[\![A \ \textbf{says} \ P]\!]_\Delta \approx [\![P]\!]_\Delta$$

$$\begin{aligned}
[\![\textbf{return@}[A]p]\!]_\Delta &\approx [\![p]\!]_\Delta \\
[\![\textbf{bind } x = p{:}\ P \textbf{ in } q]\!]_\Delta &\approx (\lambda x{:}[\![P]\!]_\Delta.\ [\![q]\!]_\Delta)\ [\![p]\!]_\Delta \\
[\![\textbf{sign}(A, P)]\!]_\Delta &\approx \Delta(\textbf{sign}(A, P))
\end{aligned}$$

Where Δ maps signatures to unique fresh variables.
(We'll treat the Δ's implicitly from now on.)

Translation from Aura to CoC erases **says**

Definition

$$\llbracket A \ \textbf{says} \ P \rrbracket_\Delta \quad \approx \quad \llbracket P \rrbracket_\Delta$$

$$\begin{aligned}
\llbracket \textbf{return@}[A]p \rrbracket_\Delta &\quad \approx \quad \llbracket p \rrbracket_\Delta \\
\llbracket \textbf{bind } x = p \text{: } P \textbf{ in } q \rrbracket_\Delta &\quad \approx \quad (\lambda x{:}\llbracket P \rrbracket_\Delta .\, \llbracket q \rrbracket_\Delta)\ \llbracket p \rrbracket_\Delta \\
\llbracket \textbf{sign}(A, P) \rrbracket_\Delta &\quad \approx \quad \Delta(\textbf{sign}(A, P))
\end{aligned}$$

Where Δ maps signatures to unique fresh variables.
(We'll treat the Δ's implicitly from now on.)

Lemma

If p is a well typed term in $Aura_0$, then—for an appropriate context—$\llbracket p \rrbracket$ is well typed in CoC.

Constructions needs a new reduction to simulate **bind**.

Definition (CC′ reduction)

The CC′ reduction relation augments the standard Calculus of Construction reduction relation with

$$\frac{}{(\lambda x{:}t.\, t_1)((\lambda y{:}s.\, t_2)u) \longrightarrow (\lambda y{:}s.\, ((\lambda x{:}t.\, t_1)t_2))u}\ \beta'$$

β' reductions simulate R-Bind-Commute reductions:

$$\frac{y \notin fv(t_3)}{\begin{array}{c}\textbf{bind } x = (\textbf{bind } y = t_1 \textbf{ in } t_2) \textbf{ in } t_3 \longrightarrow \\ \textbf{bind } y = t_1 \textbf{ in bind } x = t_2 \textbf{ in } t_3\end{array}}$$

Aura$_0$ is strongly normalizing.

Lemma

Well typed CoC terms are SN under CC$'$ reduction.

[Lindley 05]

Lemma

If p is a well typed Aura$_0$ term and $p \longrightarrow p'$. Then $[\![p]\!] \longrightarrow^{+}_{CC'} [\![p']\!]$ using one or more steps.

Proof of strong normalization.

Imagine p is an looping Aura$_0$ term. Then by the second lemma we can build a term which loops according to CC$'$. This contradicts the first lemma. $\square$