A Conceptual Framework for Safe Object Initialization

Clément Blaudeau, Inria & Université de Paris Cité, France

Fengyun Liu, Oracle Labs, Switzerland

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Celsius

Examples

Examples

```
class A {
  var y = 42 :: this.x
  var x = List()
}
```

Initialization errors

- Early field access

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```
class A {
  var x : List[Int] = this.m()

  def m() = 42::this.x
 }
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- Early method call

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  def m() = 42::this.x
 }
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```
class A {
  var b = new B(this)
  var x = List()
}
class B (a:A) {
  var y = 42 :: a.x
}
```

Initialization errors

- Early field access
- Early method call
- Incorrect escaping

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Initialization errors

- Early field access
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Key issue

Objects *under initialization* do not fulfill their class specification yet

Complex initializations

Cyclic data structures

```
class A () {
  var b = new B(this)
  var c = this.b.c
}
class B (arg:A) {
  var a = arg
  var c = new C(this)
}
class C (arg:B) {
  var a = arg.a
  var b = arg
}
```

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class C (arg:B) {
  var a = arg.a
  var b = arg
}
```

Early method call

```
class Server (a: Address) {
  var address = a
  var _ = this.broadcast("Init")
  ... // other fields

  def broadcast(m: String) = {
   ... // sends a message
  }
}
```

Design space

Design space

Sound

- No access to uninitialized field

Design space

strict initialization

proof of program

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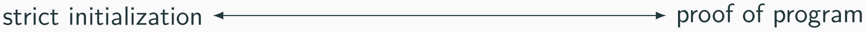
- No access to uninitialized field

Design space



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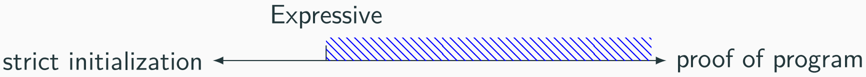

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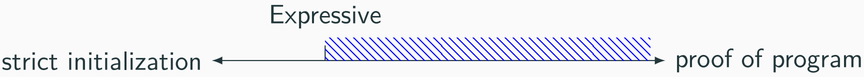

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Modular

- Class by class analysis
- Limited footprint

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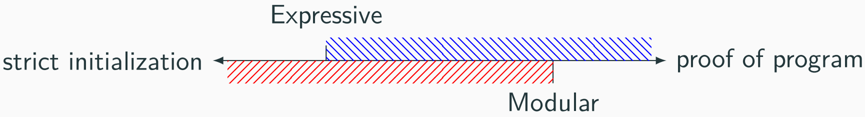

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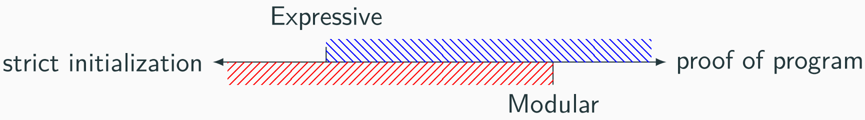

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- Understandable annotations
- Inference

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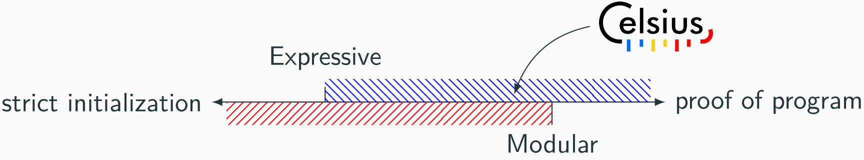

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Plan

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In this presentation

1. The Celsius model of initialization

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2. The Core principles

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    - High-level, language agnostic

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   - High-level, language agnostic
   - Design choices for the minimal calculus

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3. Local reasoning and soundness (overview)

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- The minimal calculus
- The semantic interpretation of the principles

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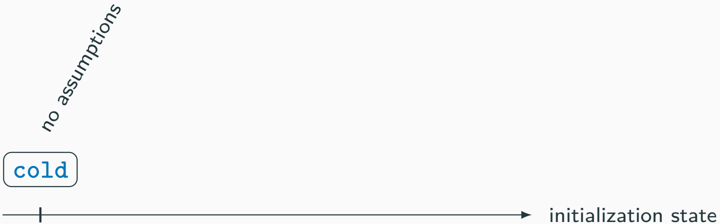
The Celsius Model

The Celsius model

initialization state

The Celsius model



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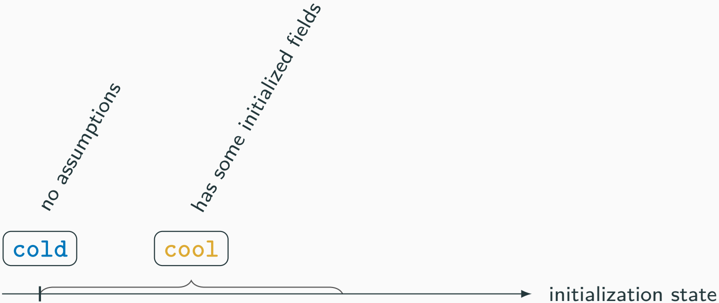

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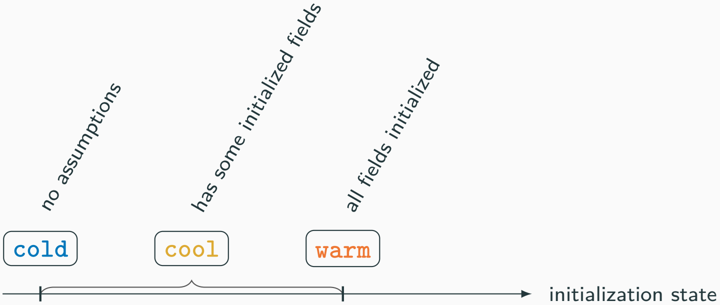

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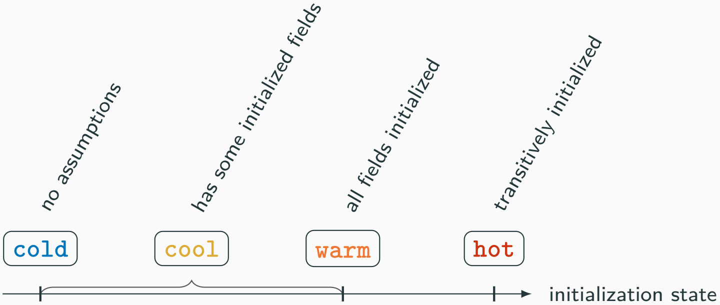

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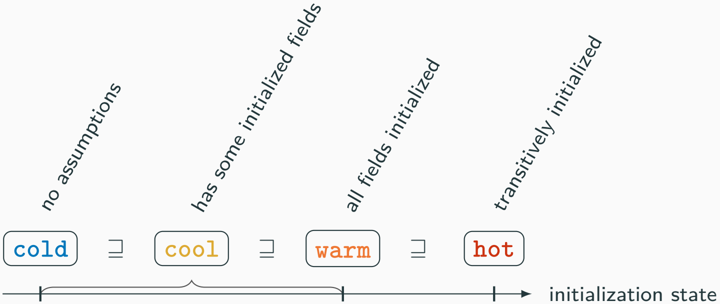
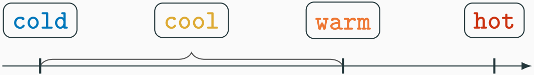


The core principles

Principle 1/4: Monotonicity



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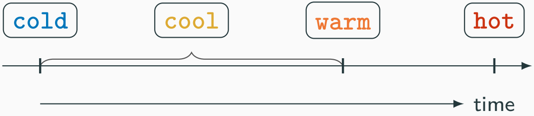

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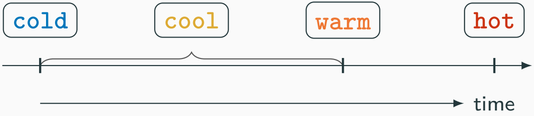
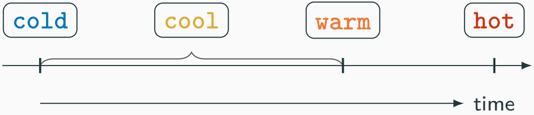


Partial monotonicity $\preceq$

Fields cannot be un-initialized

Principle 1/4: Monotonicity



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Perfect monotonicity $\preccurlyeq$

Initialization state *of every field* cannot decrease

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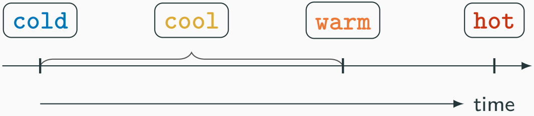

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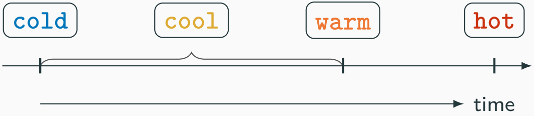

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Design choices (for the calculus)

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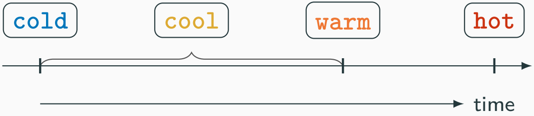

Partial monotonicity $\preceq$

Fields cannot be un-initialized

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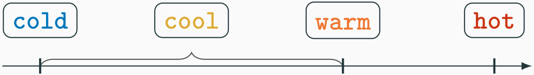
Initialization state *of every field* cannot decrease

Design choices (for the calculus)

- No de-initialization
- Update fields only with hot values

Principle 2/4: Authority



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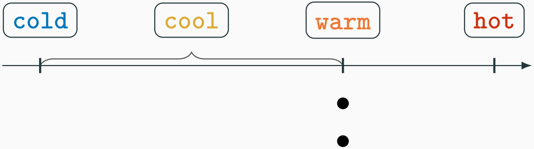

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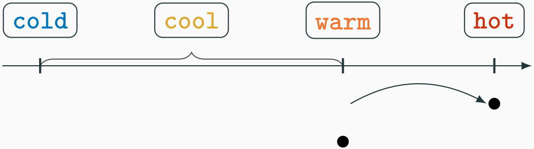

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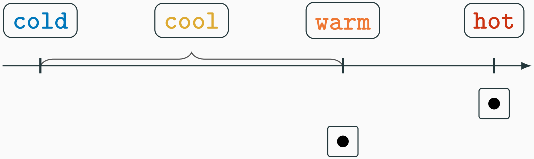
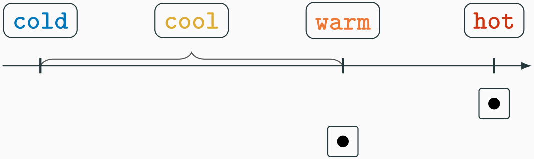


Local vision of the initialization state might differ between aliases

Principle 2/4: Authority



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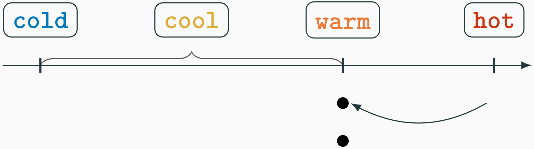

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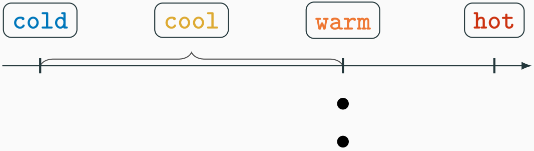

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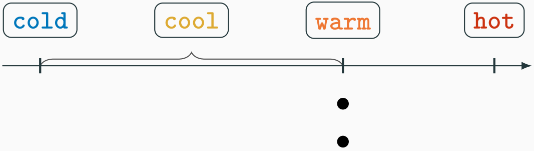
Authority

State updates are only authorized on a distinguished alias

Principle 2/4: Authority



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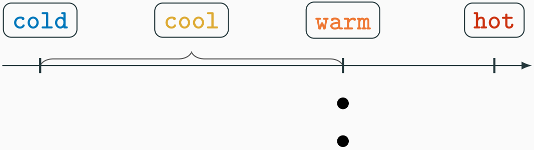

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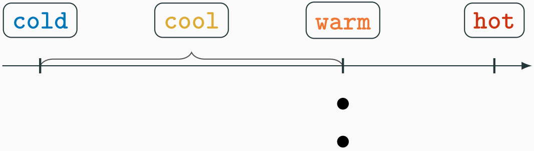
Design choices

Principle 2/4: Authority



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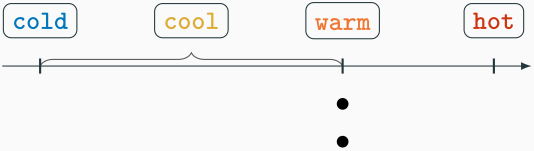


Local vision of the initialization state might differ between aliases

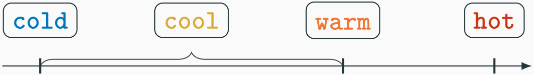
Authority

State updates are only authorized on a distinguished alias : **`this`**

Design choices

- Distinguish 1$^{\text{fst}}$ assignment / update
- Type updates (up to warm) only inside the constructor

Principle 3/4: Stackability



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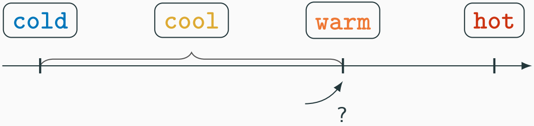

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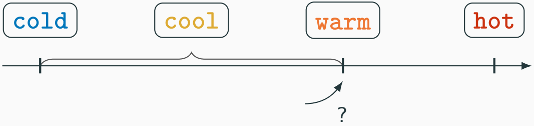

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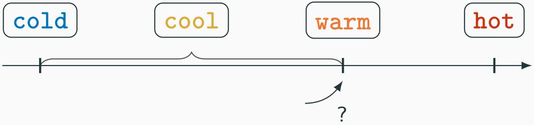
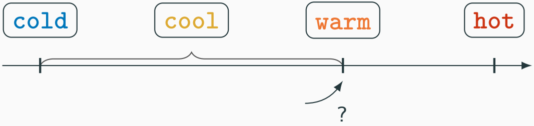


Stackability

All fields must be initialized at the end of their constructor
→ constructors form a *call stack*

Principle 3/4: Stackability



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Design choices

- Mandatory field initializers

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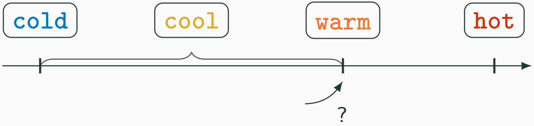

Stackability

All fields must be initialized at the end of their constructor
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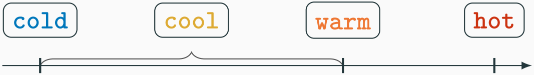
Design choices

- Mandatory field initializers
- No control effects

Principle 4/4: Scopability



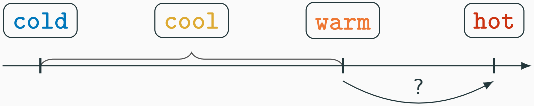
cold

cool

warm

hot

Principle 4/4: Scopability



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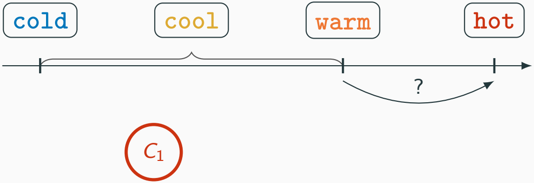

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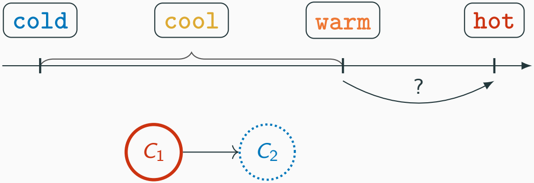

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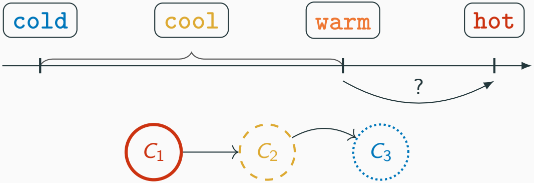

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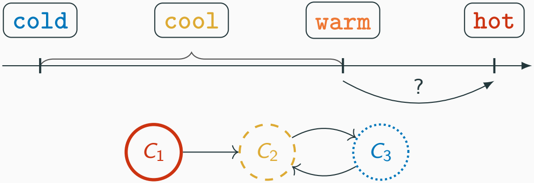

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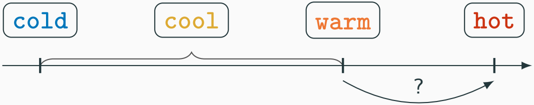

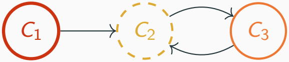

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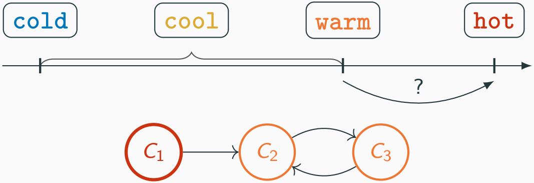

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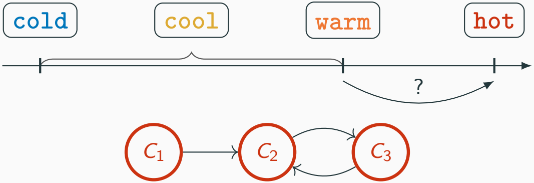

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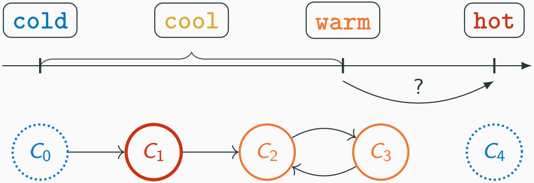
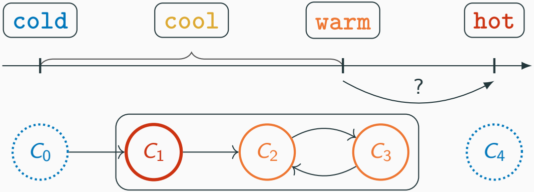


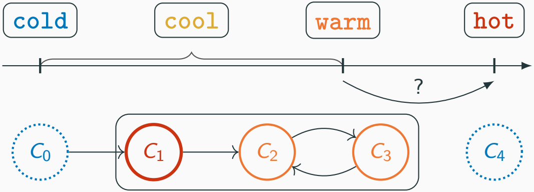
Nested/parallel initializations

Principle 4/4: Scopability



Nested/parallel initializations → Control the accessible part of the heap

Principle 4/4: Scopability



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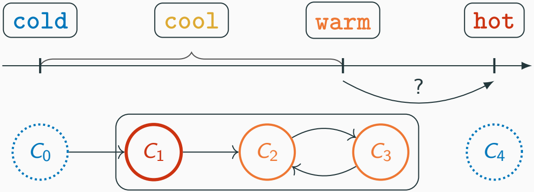
Scopability

Principle 4/4: Scopability

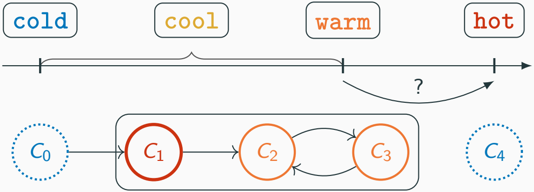


Nested/parallel initializations → Control the accessible part of the heap

Scopability

Access to *objects under initialization* must go through controlled channels, i.e. be controlled by static scoping

Principle 4/4: Scopability



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Design choices

- No global variables (see Liu 2023)

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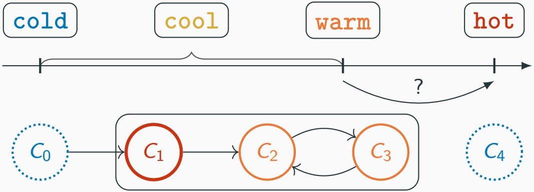

Nested/parallel initializations → Control the accessible part of the heap

Scopability

Access to *objects under initialization* must go through controlled channels, i.e. be controlled by static scoping

Design choices

- No global variables (see Liu 2023)
- Over-approximate reachable objects

Local reasoning

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Theorem (Local reasoning)

Executing an expression in an hot environment results in an hot object

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→ gives rises to a typing system with *hot-bypasses*:

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- old, so already accessible in the execution environment (by scopability), and therefore still hot (by monotonicity)

□

→ gives rises to a typing system with *hot-bypasses*:you can safely ignore initialization issues when handling hot objects

Take away

Take away

A **conceptual framework** for safe initialization based on four principles

- the Celsius model (`cold`, `cool`, `warm`, `hot`)

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A **conceptual framework** for safe initialization based on four principles

- the Celsius model (`cold`, `cool`, `warm`, `hot`)
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See the paper for precise definitions, typing system and soundness proof!

The Celsius calculus

Grammar

Grammar

Expressions

$$\begin{array}{rlr} e ::= & x & \text{(Local variable)} \\ \mid & \text{this} & \text{(Self-reference)} \\ \mid & e.f & \text{(Field access)} \\ \mid & e.m(\overline{e}) & \text{(Method call)} \\ \mid & \text{new } C(\overline{e}) & \text{(Instance creation)} \\ \mid & e.f \leftarrow e; e & \text{(Assignment)} \end{array}$$

Mode

$$\mu ::= \text{cold} \mid \text{cool}\,\overline{f} \mid \text{warm} \mid \text{hot}$$

Grammar

Expressions

$$\begin{aligned} e ::= {} & x && \text{(Local variable)} \\ \mid {} & \text{this} && \text{(Self-reference)} \\ \mid {} & e.f && \text{(Field access)} \\ \mid {} & e.m(\overline{e}) && \text{(Method call)} \\ \mid {} & \text{new } C(\overline{e}) && \text{(Instance creation)} \\ \mid {} & e.f \leftarrow e; e && \text{(Assignment)} \end{aligned}$$

Mode

$$\mu ::= \text{cold} \mid \text{cool } \overline{f} \mid \text{warm} \mid \text{hot}$$

Type

$$T ::= C^{\mu}$$

Class

$$\begin{aligned} \mathbb{C} ::= {} & \text{class } C(\overline{x : T})\{ \\ & \quad \text{fields} = \overline{\mathbb{F}}, \text{methods} = \overline{\mathbb{M}}\} \end{aligned}$$

Field

$$\mathbb{F} ::= \text{var } f : T = e$$

Method

$$\mathbb{M} ::= \texttt{@}\mu \text{ def } m(\overline{x : T}) : T = \{e\}$$

Program

$$\mathbb{P} ::= \{\text{ct} = \overline{\mathbb{C}}, \text{entry} = \mathbb{C}\}$$

Examples in Celsius syntax

```
class A () {
  var b: B@warm = new B(this)
  var c: C@warm = this.b.c
}
```

Examples in Celsius syntax

```
class A () {
  var b: B@warm = new B(this)
  var c: C@warm = this.b.c
}
class B (arg: A@cold) {
  var a: A@cold = arg
  var c: C@warm = new C(this)
}
```

Examples in Celsius syntax

```
class A () {
  var b: B@warm = new B(this)
  var c: C@warm = this.b.c
}
class B (arg: A@cold) {
  var a: A@cold = arg
  var c: C@warm = new C(this)
}
class C (arg: B@cool(a)) {
  var a: A@cold = arg.a
  var b: B@cool(a) = arg
}
```

Examples in Celsius syntax

```
class A () {
  var b: B@warm = new B(this)
  var c: C@warm = this.b.c
}
class B (arg: A@cold) {
  var a: A@cold = arg
  var c: C@warm = new C(this)
}
class C (arg: B@cool(a)) {
  var a: A@cold = arg.a
  var b: B@cool(a) = arg
}
```

```
class Server (a: Address@hot) {
  var address : Address@hot = a
  var _ = this.broadcast("Init");
  ... // other fields

  @cool(address)
    def broadcast(m: String) = {
   ... // sends a message
  }
}
```

Semantics - Big steps

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Store

$$\sigma : I \mapsto (C, \omega)$$

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Expressions

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$$\sigma : l \mapsto (C, \omega)$$

Expressions

$$[\![e]\!](\sigma, \rho, \psi) \longrightarrow (v, \sigma')$$

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e expression

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Expressions

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e	expression
σ	store
ρ	local environment (fields)
ψ	current object (`this`)

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Initialization

$$\text{init}_C(\psi, i, \rho, \sigma) \longrightarrow \sigma'$$

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i	number of initialized fields

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$$\text{init}_C(\psi, i, \rho, \sigma) \longrightarrow \sigma'$$

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Semantic rules

E-NEW

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E-New

$$\frac{}{[\![\mathsf{new}\ C\ (\overline{e_a})]\!](\sigma, \rho, \psi) \longrightarrow (\quad , \quad)}$$

Semantic rules

$$\frac{\llbracket \overline{e_a} \rrbracket(\sigma, \rho, \psi) \longrightarrow (\overline{l_a}, \sigma_1)}{\llbracket \mathsf{new}\ C\ (\overline{e_a}) \rrbracket(\sigma, \rho, \psi) \longrightarrow (\quad , \quad)}\ \textsc{E-New}$$

Semantic rules

E-NEW

$$\frac{[\![\overline{e_a}]\!](\sigma, \rho, \psi) \longrightarrow (\overline{l_a}, \sigma_1) \qquad l_{\mathsf{fresh}} \notin dom\,(\sigma_1)}{[\![\mathsf{new}\; C\,(\overline{e_a})]\!](\sigma, \rho, \psi) \longrightarrow (\qquad , \quad)}$$

Semantic rules

$$\dfrac{\textsc{E-New}\quad [\![\overline{e_a}]\!](\sigma,\rho,\psi) \longrightarrow (\overline{l_a},\sigma_1) \qquad l_{\mathsf{fresh}} \notin dom\,(\sigma_1) \qquad \mathsf{args}(C) = \overline{(x : T)}}{[\![\mathsf{new}\ C\,(\overline{e_a})]\!](\sigma,\rho,\psi) \longrightarrow (\qquad,\quad)}$$

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E-Init-End

$$\text{init}_C(\psi, \text{length}(\text{fields}(C)), \rho, \sigma) \longrightarrow \sigma$$

Typing and soundness

Soundness (1/3)

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Definitional interpreter [Amin and Rompf(2017)]

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$$
\begin{aligned}
[\![e]\!](\sigma, \rho, \psi, n) = r \quad &\textit{with} \quad r \coloneqq \mathsf{success}(v, \sigma') \mid \mathsf{error} \mid \mathsf{timeout} \\
\mathsf{init}_C(\psi, i, \rho, \sigma, n) = r \quad &\textit{with} \quad r \coloneqq \mathsf{success}(\sigma') \quad\ \mid \mathsf{error} \mid \mathsf{timeout}
\end{aligned}
$$

Soundness (1/3)

Definitional interpreter [Amin and Rompf(2017)]

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$$[\![e]\!](\sigma,\rho,\psi) \longrightarrow (v,\sigma') \iff \exists n.\, [\![e]\!](\sigma,\rho,\psi,n) = \mathsf{success}(v,\sigma') \tag{1}$$

$$\mathsf{init}_C(\psi,i,\rho,\sigma) \longrightarrow \sigma' \iff \exists n.\, \mathsf{init}_C(\psi,i,\rho,\sigma,n) = \mathsf{success}(\sigma') \tag{2}$$

Soundness (1/3)

Definitional interpreter [Amin and Rompf(2017)]

$$\begin{aligned} [\![e]\!](\sigma, \rho, \psi, n) = r \quad & \textit{with} \quad r \coloneqq \mathsf{success}(v, \sigma') \mid \mathsf{error} \mid \mathsf{timeout} \\ \mathsf{init}_C(\psi, i, \rho, \sigma, n) = r \quad & \textit{with} \quad r \coloneqq \mathsf{success}(\sigma') \quad\ \mid \mathsf{error} \mid \mathsf{timeout} \end{aligned}$$

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Soundness invariant (structure)

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Soundness invariant (structure)

$$\left.\begin{aligned} &[\![e]\!](\sigma, \rho, \psi, n) = r \\ &r \neq \mathsf{timeout} \\ & \end{aligned}\right\} \qquad \left\{ \begin{aligned} & \\ & \\ & \end{aligned}\right.$$

Soundness (1/3)

Definitional interpreter [Amin and Rompf(2017)]

$$
\begin{array}{rll}
[\![e]\!](\sigma, \rho, \psi, n) = r & \textit{with} & r \coloneqq \mathsf{success}(v, \sigma') \mid \mathsf{error} \mid \mathsf{timeout} \\
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\end{array}
$$

$$
[\![e]\!](\sigma, \rho, \psi) \longrightarrow (v, \sigma') \iff \exists n.\, [\![e]\!](\sigma, \rho, \psi, n) = \mathsf{success}(v, \sigma') \tag{1}
$$

$$
\mathsf{init}_C(\psi, i, \rho, \sigma) \longrightarrow \sigma' \iff \exists n.\, \mathsf{init}_C(\psi, i, \rho, \sigma, n) = \mathsf{success}(\sigma') \tag{2}
$$

Soundness invariant (structure)

$$
\left.
\begin{array}{l}
[\![e]\!](\sigma, \rho, \psi, n) = r \\
r \neq \mathsf{timeout} \\
\vdash e : T
\end{array}
\right\}
\qquad\qquad
\left\{
\begin{array}{l}
\\
\\
\\
\\
\end{array}
\right.
$$

Soundness (1/3)

Definitional interpreter [Amin and Rompf(2017)]

$$
\begin{aligned}
[\![e]\!](\sigma, \rho, \psi, n) = r \quad & \textit{with} \quad r \coloneqq \mathsf{success}(v, \sigma') \mid \mathsf{error} \mid \mathsf{timeout} \\
\mathsf{init}_C(\psi, i, \rho, \sigma, n) = r \quad & \textit{with} \quad r \coloneqq \mathsf{success}(\sigma') \quad \mid \mathsf{error} \mid \mathsf{timeout}
\end{aligned}
$$

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$$[\![e]\!](\sigma,\rho,\psi) \longrightarrow (v,\sigma') \iff \exists n.\, [\![e]\!](\sigma,\rho,\psi,n) = \mathsf{success}(v,\sigma') \tag{1}$$

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\\
\\
\\
\end{cases}$$

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\text{Authority} \\
\\
\\
\end{cases}$$

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r = \text{success}(v, \sigma') \\
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Reachability and Scopability

Reachability and Scopability

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Reachability - $\sigma \models l \rightsquigarrow l'$

Reachability and Scopability

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Transitive closure of field access

Reachability and Scopability

Reachability - $\sigma \vDash l \rightsquigarrow l'$

Transitive closure of field access

Scopability - $(\sigma, L) \lessdot (\sigma', L')$

Reachability and Scopability

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Scopability - $(\sigma, L) \lessdot (\sigma', L')$

Every location reachable from L' in σ' is either new or already reachable from L in σ:

$$\forall l \in dom(\sigma), \sigma' \vDash L' \rightsquigarrow l \implies \sigma \vDash L \rightsquigarrow l$$

Reachability and Scopability

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Scopability theorem

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Every location reachable from L' in σ' is either new or already reachable from L in σ:

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Scopability theorem

The heap reachable from the result location v is scoped in the result store σ' by the *execution environment* ($codom(\rho) \cup \{\psi\}$) in the starting store σ:

$$[\![e]\!](\sigma, \rho, \psi) \longrightarrow (v, \sigma') \implies (\sigma, \rho \cup \{\psi\}) \lessdot (\sigma', \{v\})$$

Typing (1/2) - typing rules

Mode lattice - $\mu \sqsubseteq \mu'$

cold $\sqsubseteq$ cool $\overline{f}$ $\sqsubseteq$ warm $\sqsubseteq$ hot

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Typing - $(\Gamma, T_{\texttt{this}}) \vdash e : T$

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Typing - $(\Gamma, T_{\texttt{this}}) \vdash e : T$

- Local environment

$$\textsc{T-E-Var}\quad \frac{\Gamma(x) = T}{(\Gamma, T_{\texttt{this}}) \vdash x : T}$$

$$\textsc{T-E-This}\quad (\Gamma, T_{\texttt{this}}) \vdash \text{this} : T_{\texttt{this}}$$

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- Local environment
- Ambient subtyping

$$\textsc{T-E-Sub}\quad \frac{(\Gamma, T_{\mathtt{this}}) \vdash e : C^{\mu} \qquad \mu \sqsubseteq \mu'}{(\Gamma, T_{\mathtt{this}}) \vdash e : C^{\mu'}}$$

Typing (1/2) - typing rules

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$$\text{cold} \sqsubseteq \text{cool}\ \overline{f} \sqsubseteq \text{warm} \sqsubseteq \text{hot}$$

Typing - $(\Gamma, T_{\texttt{this}}) \vdash e : T$

- Local environment
- Ambient subtyping
- Stackability (T-E-New)

T-E-Fld

$$\frac{(\Gamma, T_{\texttt{this}}) \vdash e : D^{\text{cool}\ \overline{f}} \qquad f \in \overline{f} \qquad \text{fieldType}(D, f) = T}{(\Gamma, T_{\texttt{this}}) \vdash e.f : T}$$

T-E-Call

$$\frac{(\Gamma, T_{\texttt{this}}) \vdash e : C^{\mu} \qquad \text{lookup}(C, m) = @\mu\ \text{def}\ m : \overline{(x : T)} \to T \qquad (\Gamma, T_{\texttt{this}}) \vdash \overline{e_a} : \overline{T}}{(\Gamma, T_{\texttt{this}}) \vdash e.m(\overline{e_a}) : T}$$

T-E-New

$$\frac{\text{ct}(C) = \text{class}\ C(\overline{x : T})\ \{\ldots\} \qquad (\Gamma, T_{\texttt{this}}) \vdash \overline{e} : \overline{T}}{(\Gamma, T_{\texttt{this}}) \vdash \text{new}\ C\,(\overline{e}) : C^{\text{warm}}}$$

Typing (1/2) - typing rules

Mode lattice - $\mu \sqsubseteq \mu'$

$$\text{cold} \sqsubseteq \text{cool}\ \overline{f} \sqsubseteq \text{warm} \sqsubseteq \text{hot}$$

Typing - $(\Gamma, T_{\texttt{this}}) \vdash e : T$

- Local environment
- Ambient subtyping
- Stackability (T-E-New)
- Hot shortcuts

T-E-Fld-Hot

$$\frac{\begin{array}{c}(\Gamma, T_{\texttt{this}}) \vdash e : D^{\text{hot}} \\ \text{fieldType}(D, f) = C^{\mu}\end{array}}{(\Gamma, T_{\texttt{this}}) \vdash e.f : C^{\text{hot}}}$$

T-E-Call-Hot

$$\frac{\begin{array}{c}(\Gamma, T_{\texttt{this}}) \vdash e : C_0^{\text{hot}} \\ \text{lookup}(C_0, m) = @\mu\ \text{def}\ m : \overline{(x : D^{\mu})} \to C^{\mu} \\ (\Gamma, T_{\texttt{this}}) \vdash \overline{e_a} : \overline{D^{\text{hot}}}\end{array}}{(\Gamma, T_{\texttt{this}}) \vdash e.m(\overline{e_a}) : C^{\text{hot}}}$$

T-E-New-Hot

$$\frac{\begin{array}{c}\text{ct}(C) = \text{class}\ C(\overline{x : D^{\mu}})\ \{\ldots\} \\ (\Gamma, T_{\texttt{this}}) \vdash \overline{e} : \overline{D^{\text{hot}}}\end{array}}{(\Gamma, T_{\texttt{this}}) \vdash \text{new}\ C(\overline{e}) : C^{\text{hot}}}$$

Typing (1/2) - typing rules

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Typing - $(\Gamma, T_{\texttt{this}}) \vdash e : T$

- Local environment
- Ambient subtyping
- Stackability (T-E-New)
- Hot shortcuts
- Monotonicity (T-E-Block)

$$\textsc{T-E-Block}\quad \frac{\begin{array}{c}(\Gamma, T_{\texttt{this}}) \vdash e_1.f : C^{\mu} \\ (\Gamma, T_{\texttt{this}}) \vdash e_2 : C^{\text{hot}} \\ (\Gamma, T_{\texttt{this}}) \vdash e_3 : T\end{array}}{(\Gamma, T_{\texttt{this}}) \vdash e_1.f \leftarrow e_2; e_3 : T}$$

Typing (2/2) - Store typing

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Store typing - $\Sigma : l \mapsto T$

Prevent cyclic dependencies

Typing (2/2) - Store typing

Store typing - $\Sigma : l \mapsto T$

Prevent cyclic dependencies

Object typing - $\Sigma \models (C, \omega) : (C, \mu)$

Lower bound of actual initialization state

Typing (2/2) - Store typing

Store typing - $\Sigma : l \mapsto T$

Prevent cyclic dependencies

Abstraction of the store - $\Sigma \vDash \sigma$

Object typing - $\Sigma \vDash (C, \omega) : (C, \mu)$

Lower bound of actual initialization state

Typing (2/2) - Store typing

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Lower bound of actual initialization state

Abstraction of the store - $\Sigma \vDash \sigma$

$$\frac{dom\,(\sigma) = dom\,(\Sigma) \qquad \forall l \in dom\,(\sigma)\,.\,\Sigma \vDash \sigma(l) : \Sigma(l)}{\Sigma \vDash \sigma}$$

Typing (2/2) - Store typing

Store typing - $\Sigma : l \mapsto T$

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Environment typing - $\Sigma \vDash \rho : \Gamma$

Typing (2/2) - Store typing

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Prevent cyclic dependencies

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Lower bound of actual initialization state

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$$\frac{dom(\sigma) = dom(\Sigma) \qquad \forall l \in dom(\sigma) \,.\, \Sigma \vDash \sigma(l) : \Sigma(l)}{\Sigma \vDash \sigma}$$

Environment typing - $\Sigma \vDash \rho : \Gamma$

$$\Sigma \vDash \varnothing : \varnothing \qquad\qquad \frac{\Sigma \vDash \rho : \Gamma \qquad \Sigma \vDash l : T}{\Sigma \vDash (x \mapsto l) \cup \rho : (x \mapsto T) \cup \Gamma}$$

Soundness (2/3)

$$\left.\begin{array}{l} [\![e]\!](\sigma, \rho, \psi, n) = r \\ r \neq \text{timeout} \\ \\ \\ \\ \\ \vdash e : T \end{array}\right\} \implies \exists \sigma', v \quad . \begin{cases} r = \text{success}(v, \sigma') \\ \models v : T \\ \\ \text{Monotonicity} \\ \text{Authority} \\ \text{Stackability} \\ \cancel{\text{Scopability}} \end{cases}$$

Soundness (2/3)

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Soundness (2/3)

$$\left.\begin{array}{l} [\![e]\!](\sigma,\rho,\psi,n) = r \\ r \neq \text{timeout} \\ \Sigma \vDash \sigma \\ \Sigma \vDash \rho : \Gamma \\ \\ \vdash e : T \end{array}\right\} \implies \exists \sigma', v \quad . \left\{\begin{array}{l} r = \text{success}(v,\sigma') \\ \vDash v : T \\ \\ \text{Monotonicity} \\ \text{Authority} \\ \text{Stackability} \end{array}\right.$$

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$$\left.\begin{array}{l} [\![e]\!](\sigma, \rho, \psi, n) = r \\ r \neq \text{timeout} \\ \Sigma \vDash \sigma \\ \Sigma \vDash \rho : \Gamma \\ \Sigma \vDash \psi : T_{\texttt{this}} \\ (\Gamma, T_{\texttt{this}}) \vdash e : T \end{array}\right\} \implies \exists \sigma', v \quad . \left\{\begin{array}{l} r = \text{success}(v, \sigma') \\ \vDash v : T \\ \\ \text{Monotonicity} \\ \text{Authority} \\ \text{Stackability} \end{array}\right.$$

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$$\left.\begin{array}{l} [\![e]\!](\sigma, \rho, \psi, n) = r \\ r \neq \text{timeout} \\ \Sigma \vDash \sigma \\ \Sigma \vDash \rho : \Gamma \\ \Sigma \vDash \psi : T_{\texttt{this}} \\ (\Gamma, T_{\texttt{this}}) \vdash e : T \end{array}\right\} \implies \exists \sigma', v, \Sigma'. \left\{\begin{array}{l} r = \text{success}(v, \sigma') \\ \Sigma' \vDash v : T \\ \Sigma' \vDash \sigma' \\ \text{Monotonicity} \\ \text{Authority} \\ \text{Stackability} \end{array}\right.$$

Core principles for typing

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Monotonicity

$$\Sigma \preccurlyeq \Sigma' \coloneqq \forall l \in dom\,(\Sigma)\,.\,\Sigma'(l) <: \Sigma(l)$$

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Authority

$$\Sigma \triangleright \Sigma' \coloneqq \forall l.\, \Sigma(l) = C^{\,\text{cool}\,\overline{f}} \implies \Sigma'(l) = \Sigma(l)$$

Soundness (3/3)

$$\left.\begin{aligned}
&[\![e]\!](\sigma, \rho, \psi, n) = r \\
&r \neq \text{timeout} \\
&\Sigma \vDash \sigma \\
&\Sigma \vDash \rho : \Gamma \\
&\Sigma \vDash \psi : T_{\texttt{this}} \\
&(\Gamma, T_{\texttt{this}}) \vdash e : T
\end{aligned}\right\} \implies \exists \sigma',\, v,\, \Sigma'.\; \begin{cases}
r = \text{success}(v, \sigma') \\
\Sigma' \vDash \sigma' \\
\Sigma' \vDash v : T \\
\Sigma \preccurlyeq \Sigma' \\
\Sigma \triangleright \Sigma' \\
\Sigma \ll \Sigma'
\end{cases} \tag{3}$$

Soundness (3/3)

$$\left.\begin{array}{l}
\llbracket e \rrbracket(\sigma, \rho, \psi, n) = r \\
r \neq \text{timeout} \\
\Sigma \models \sigma \\
\Sigma \models \rho : \Gamma \\
\Sigma \models \psi : T_{\texttt{this}} \\
(\Gamma, T_{\texttt{this}}) \vdash e : T
\end{array}\right\} \implies \exists \sigma',\, v,\, \Sigma'.\, \left\{\begin{array}{l}
r = \text{success}(v, \sigma') \\
\Sigma' \models \sigma' \\
\Sigma' \models v : T \\
\Sigma \preccurlyeq \Sigma' \\
\Sigma \triangleright \Sigma' \\
\Sigma \ll \Sigma'
\end{array}\right. \tag{3}$$

$$\left.\begin{array}{l}
\text{init}_C(\psi, i, \rho, \sigma, n) = r \\
r \neq \text{timeout} \\
\Sigma \models \sigma \\
\Sigma \models \rho : \Gamma \\
\Sigma(\psi) = \text{cool}\,\{f_0, \ldots, f_{i-1}\} \\
\Gamma <: \Gamma_a
\end{array}\right\} \implies \exists \sigma',\, \Sigma'.\, \left\{\begin{array}{l}
r = \text{success}(\sigma') \\
\Sigma' \models \sigma' \\
\Sigma \preccurlyeq \Sigma' \\
\Sigma \ll \Sigma' \\
\left[\psi \mapsto C^{\,\text{cool}(\text{fields}(C))}\right] \Sigma \triangleright \Sigma'
\end{array}\right. \tag{4}$$

Program Soundness

Theorem (Program Soundness)

A well typed program cannot run into an error

$$\vdash \mathbb{P} \implies \forall n, [\![\mathbb{P}]\!](n) \neq \mathit{error} \tag{5}$$

Conclusion

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- A minimal calculus to illustrate the principles
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References i

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