Relax!

The Semilenient Core of Choreographic Programming

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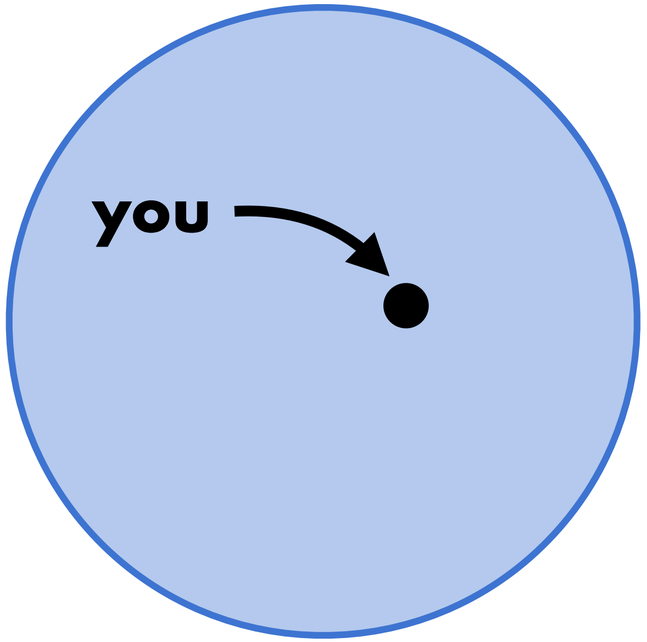
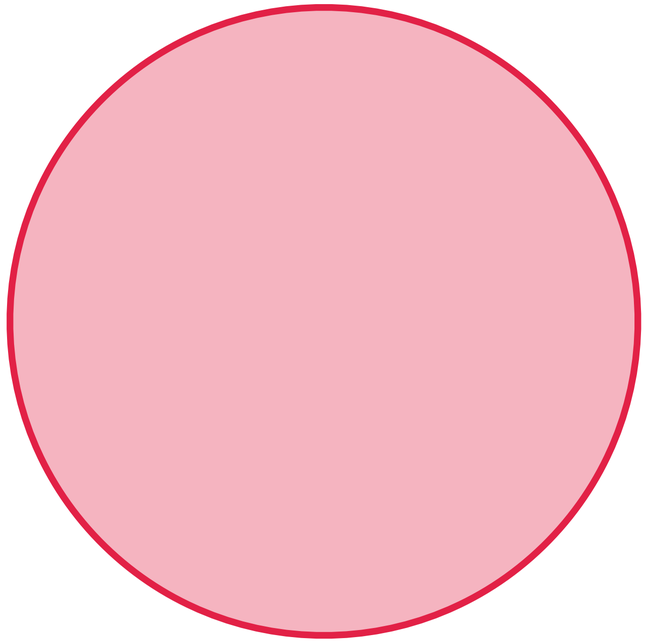
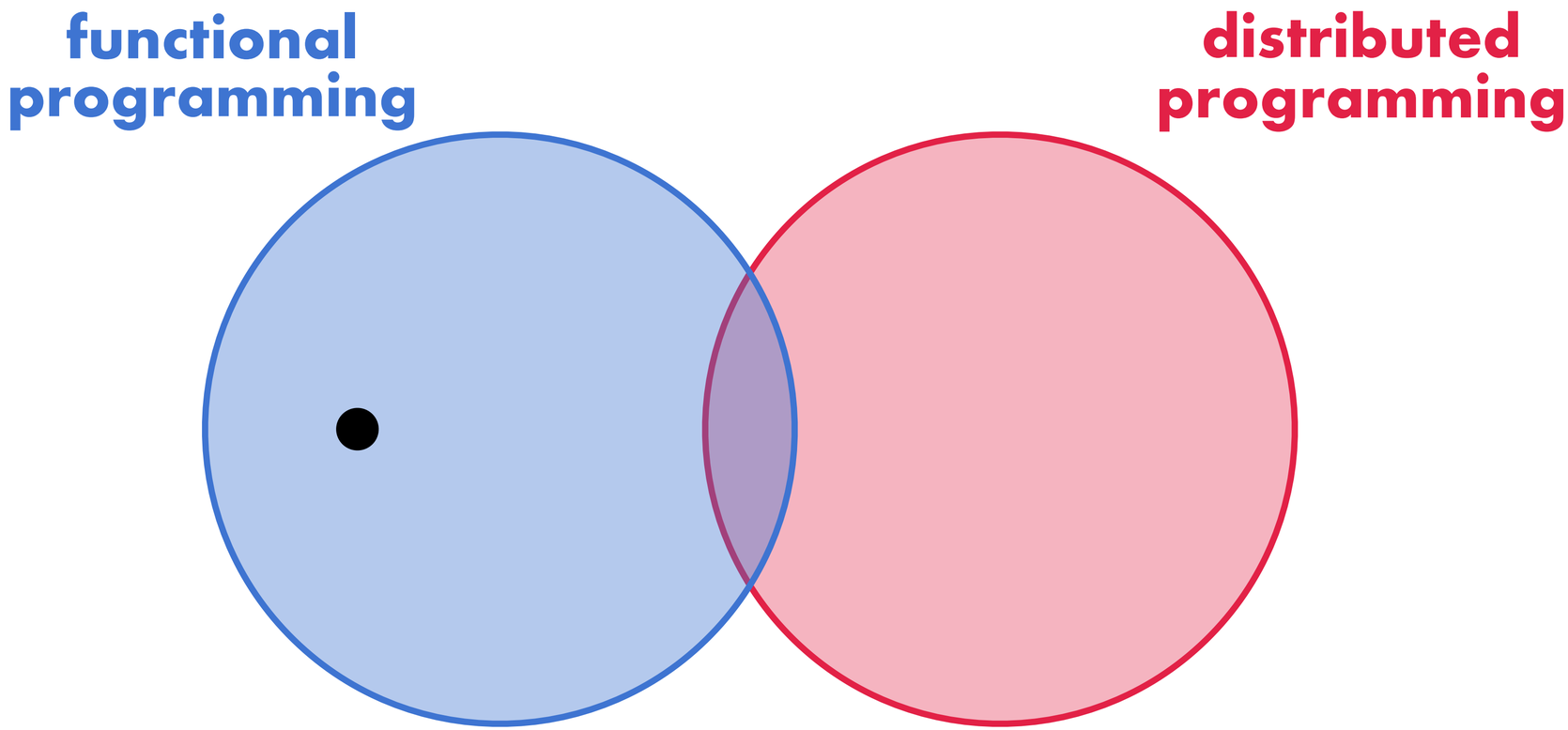
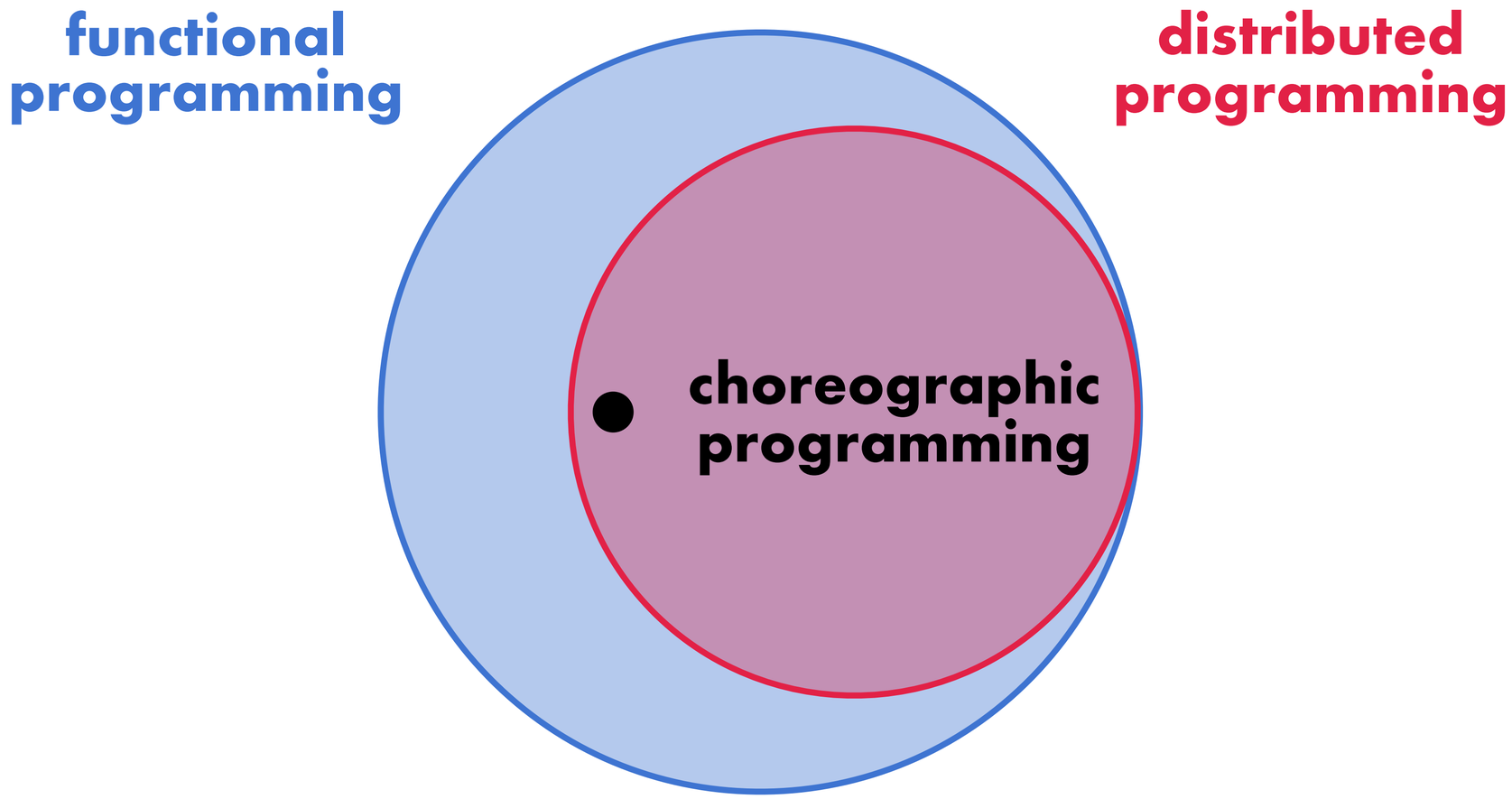
functional programmers



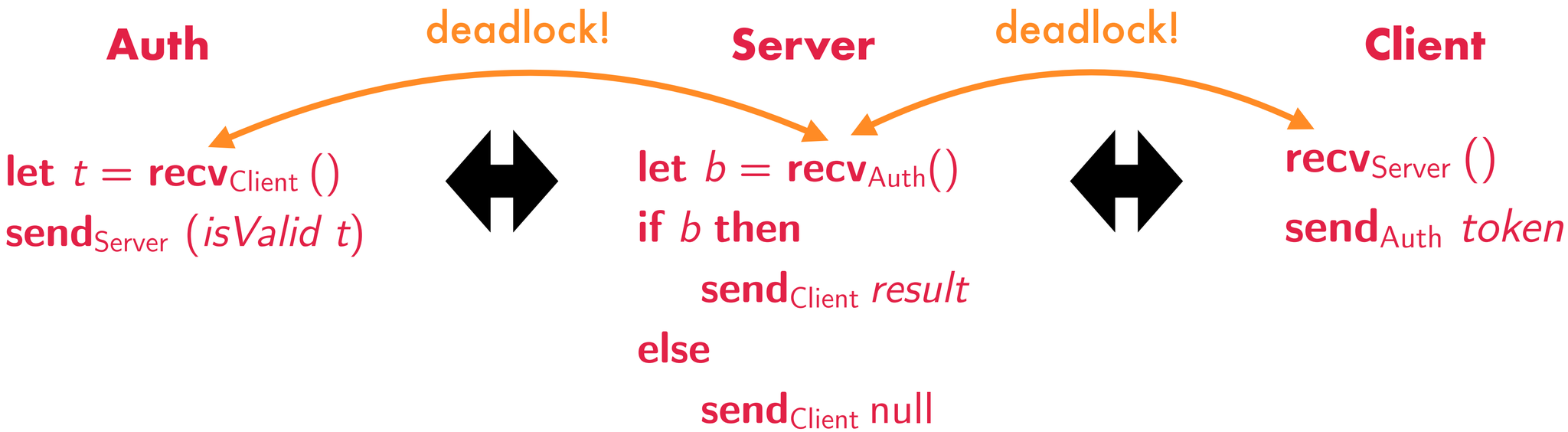
distributed programmers




functional
programming
distributed
programming


functional
programming
distributed
programming
choreographic
programming

the problem with
distributed programming



the problem with
distributed programming

Auth

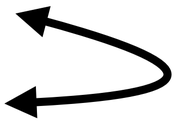
$\textbf{let } t = \textbf{recv}_{\text{Client}}\ ()$
$\textbf{send}_{\text{Server}}\ (\mathit{isValid}\ t)$

Server

$\textbf{let } b = \textbf{recv}_{\text{Auth}}()$
$\textbf{if } b \textbf{ then}$
$\quad \textbf{send}_{\text{Client}}\ \mathit{result}$
$\textbf{else}$
$\quad \textbf{send}_{\text{Client}}\ \text{null}$

Client

$\textbf{send}_{\text{Auth}}\ \mathit{token}$
$\textbf{recv}_{\text{Server}}\ ()$



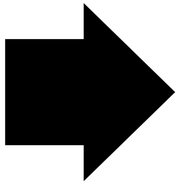
the problem with
distributed programming

that sounds like...
...multitier?
...program partitioning?
...*macroprogramming*?

"choreography"

??????
??????
??????
??????

"projection"



Auth

let $t =$ **recv**$_{\text{Client}}$ ()
send$_{\text{Server}}$ (*isValid t*)

Server

let $b =$ **recv**$_{\text{Auth}}$()
if b **then**
    send$_{\text{Client}}$ *result*
else
    send$_{\text{Client}}$ null

Client

send$_{\text{Auth}}$ *token*
recv$_{\text{Server}}$ ()

baby's first
choreographic program

1. start local

```
let t = getToken()
let b = isValid t
let r =
    if b then
        newResult()
    else
        null
printLine r
```

baby's first
choreographic program

1. start local
2. add locations

```
def myChoreo(Client, Auth, Server) =
    let t = getToken(Client)
    let b = isValid@Auth t
    let r =
        if b then
            newResult(Server)
        else
            null@Server
    printLine@Client r
```

baby's first
choreographic program

1. start local
2. add locations

```
def myChoreo(Client, Auth, Server) =
  let t = getToken(Client)
  let b = isValid@Auth t
  let r =
    if b then
      newResult(Server)
    else
      null@Server
  printLine@Client r
```

Token@**Client**

Bool@**Auth**

⚠ can't apply isValid at **Auth** to token at **Client**

baby's first
choreographic program

```
def myChoreo(Client, Auth, Server) =
  let t = com_{Client,Auth} getToken(Client)
  let b = com_{Auth,Server} (isValid@Auth t)
  let r =
    if b then
      newResult(Server)
    else
      null@Server
  printLine@Client (com_{Server,Client} r)
```

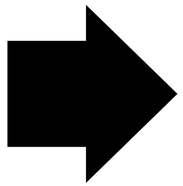
Token@**Auth**

Token@**Client**

1. start local
2. add locations
3. add communications

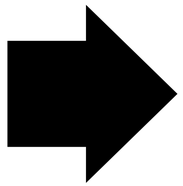
grow your own
choreographic programming language

```
let t = com_{Client,Auth} getToken(Client)
let b = com_{Auth,Server} (isValid@Auth t)
let r =
    if b then
        newResult(Server)
    else
        null@Server
printLine@Client (com_{Server,Client} r)
```



grow your own
choreographic programming language

```
let t = com_{Client,Auth} getToken(Client)
let b = com_{Auth,Server} (isValid@Auth t)
let r =
    if b then
        newResult(Server)
    else
        null@Server
printLine@Client (com_{Server,Client} r)
```

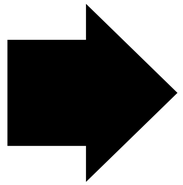


Client

```
send_{Auth} getToken()
printLine (recv_{Server}())
```

grow your own
choreographic programming language

```
let t = com_{Client,Auth} getToken(Client)
let b = com_{Auth,Server} (isValid@Auth t)
let r =
    if b then
        newResult(Server)
    else
        null@Server
printLine@Client (com_{Server,Client} r)
```



Client

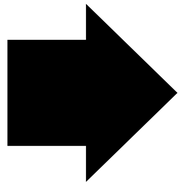
```
send_{Auth} getToken()
printLine (recv_{Server}())
```

Auth

```
let t = recv_{Client}()
send_{Server} (isValid t)
```

grow your own
choreographic programming language

```
let t = com_{Client,Auth} getToken(Client)
let b = com_{Auth,Server} (isValid@Auth t)
let r =
    if b then
        newResult(Server)
    else
        null@Server
printLine@Client (com_{Server,Client} r)
```



Client

```
send_{Auth} getToken()
printLine (recv_{Server}())
```

Auth

```
let t = recv_{Client}()
send_{Server} (isValid t)
```

Server

```
let b = recv_{Auth}()
let r =
    if b then newResult()
    else null
send_{Client} r
```

✅ deadlock-free
✅ type-safe

we don’t agree on the semantics!

(in higher-order models)

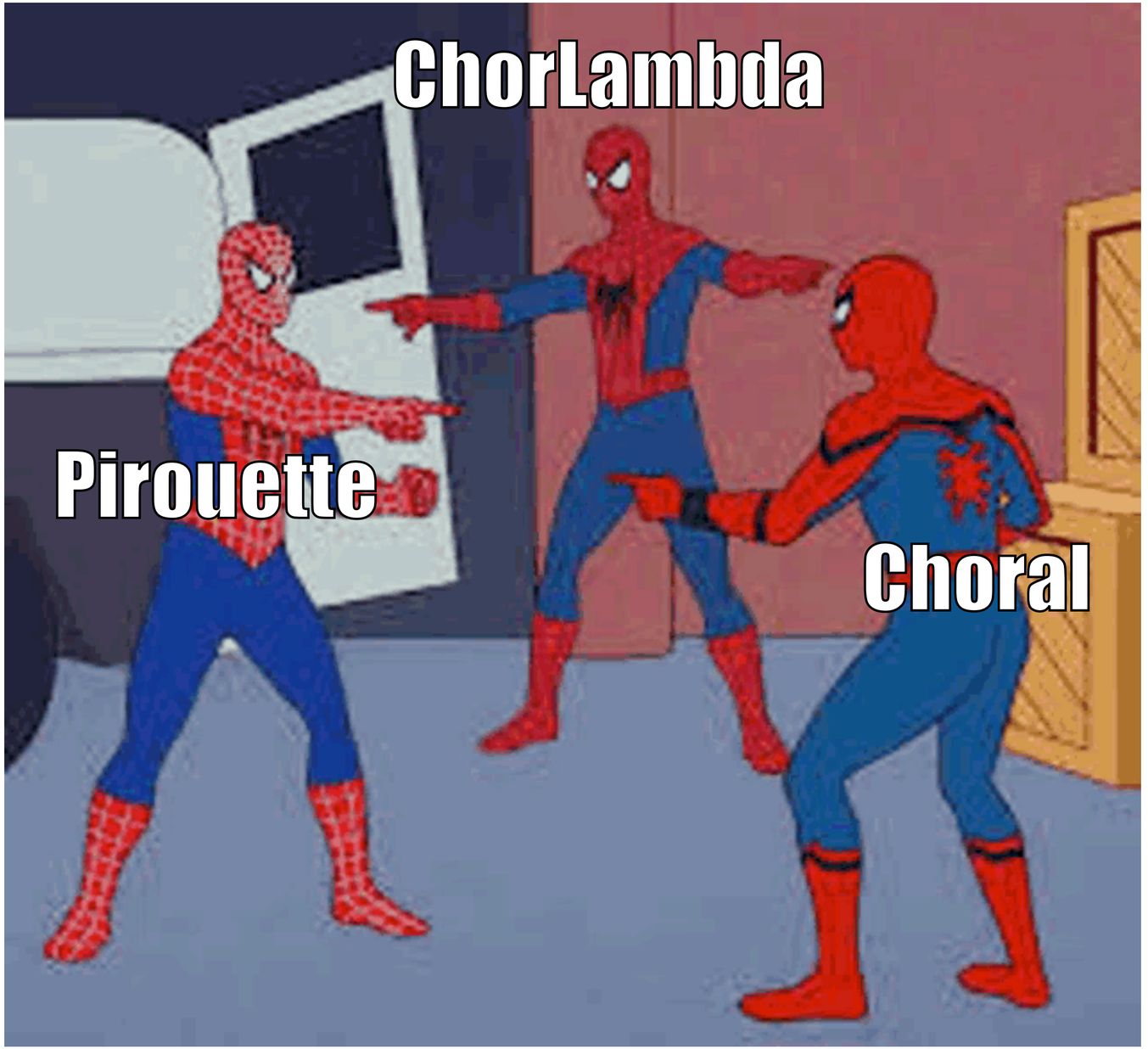
```
void main() {
  println@A(helper());
}

String@A helper() {
  loop(0@C);
  return "hello"@A;
}
```

```
void main() {
  if (helper()) {
    println@A("hello"@A);
  }
}

bool@A helper() {
  loop(0@C);
  return true@A;
}
```

Choral (Java impl.):	✅ print “hello”	✅ print “hello”
Chorλ (ICTAC 2022):	✅ print “hello”	⛔ no effects
Pirouette (POPL 2022):	⛔ no effects	⛔ no effects



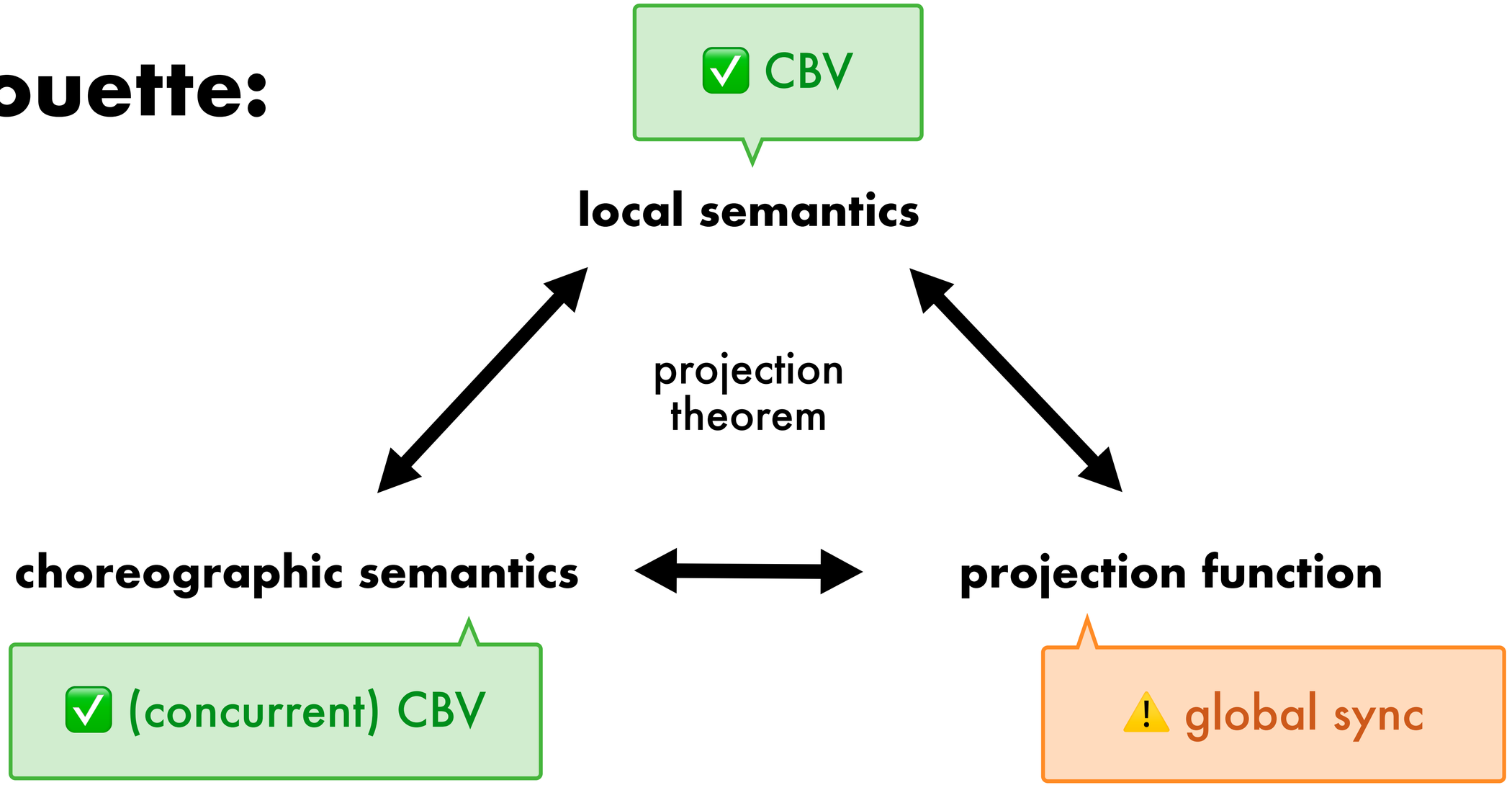
who cares?

🦺 type safety

🚧 refactoring

🏎️ optimization

Pirouette:


✅ CBV
local semantics
projection
theorem
choreographic semantics
projection function
✅ (concurrent) CBV
⚠ global sync

Chorλ:

✅ CBV

local semantics

projection theorem

choreographic semantics ⟷ **projection function**

⚠️ **looks weird:**
evaluation under lambda
ad-hoc commuting conversions

$$\frac{M \xrightarrow{\ell,\mathsf{P}}_D M'}{\lambda x : T.M \xrightarrow{\lambda,\mathsf{P}}_D \lambda x : T.M'}\ [\textsc{InAbs}]$$

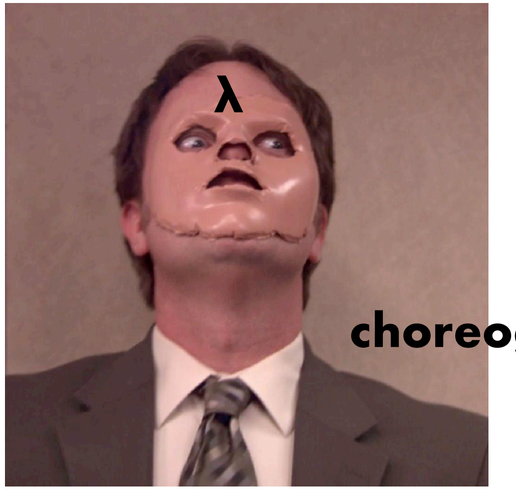
✅ no global sync

$$\frac{x \notin \mathrm{fv}(M') \quad \mathrm{spn}(M') \cap \mathrm{pn}(N) = \varnothing}{M'\ ((\lambda x : T.M)\ N) \rightsquigarrow (\lambda x : T.(M'\ M))\ N)}\ [\text{R-}\textsc{AbsL}]$$

choreographies
(first-order)

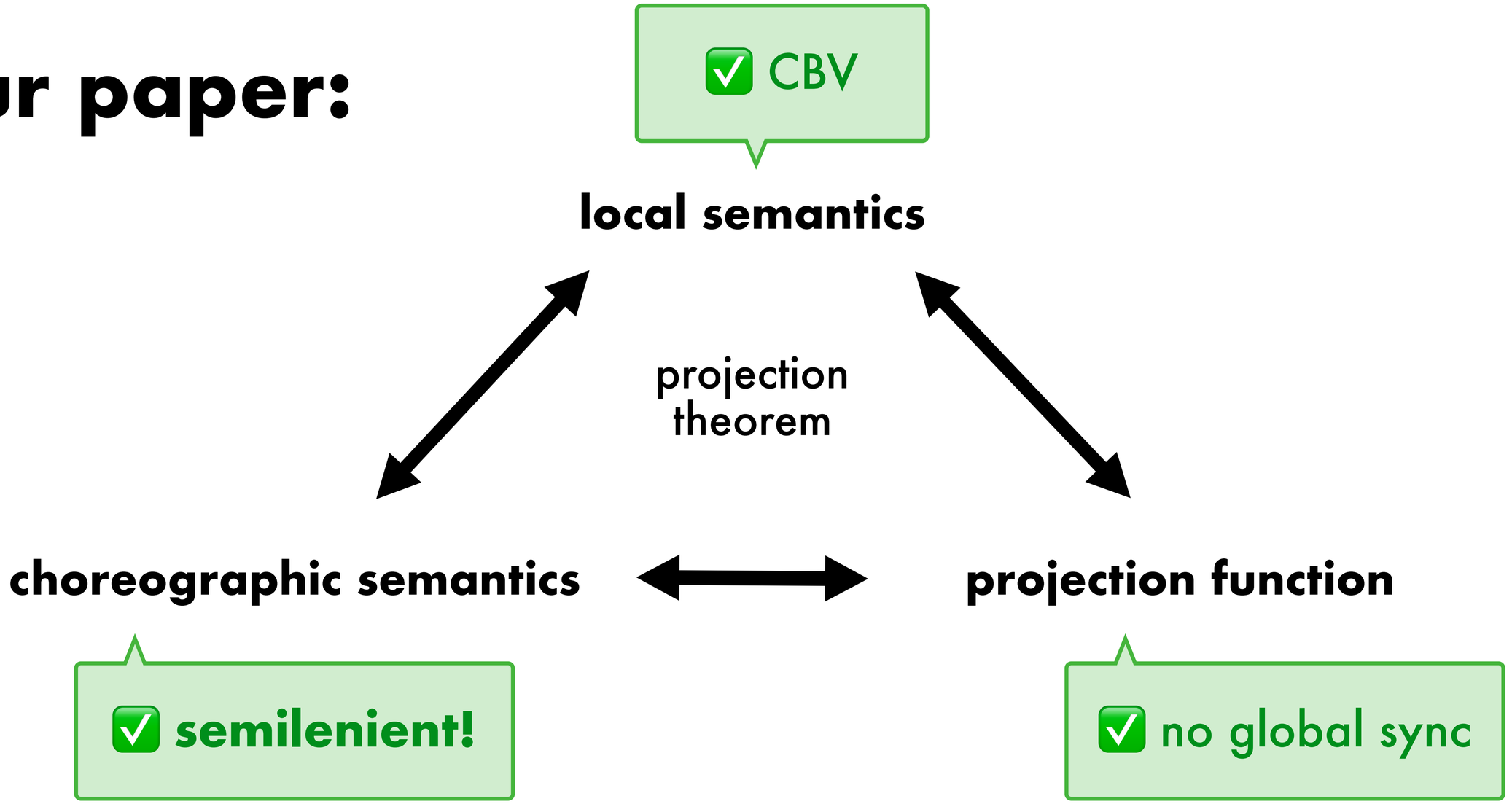
λ-calculus
(higher-order)

how it looks to **CP fans**



how it looks to **FP fans**

our paper:


✅ CBV
local semantics
projection
theorem
choreographic semantics
projection function
✅ semilenient!
✅ no global sync

operational semantics

notion of reduction: redexes

evaluation strategy: evaluation contexts

notion of reduction: redexes

evaluation strategy: evaluation contexts

$$\textbf{if true@A then } M_1 \textbf{ else } M_2 \longrightarrow M_1$$

$$\textbf{if false@A then } M_1 \textbf{ else } M_2 \longrightarrow M_2$$

$$\textbf{com}_{A,\,B}\ \mathit{const}@A \longrightarrow \mathit{const}@B$$

$$\textbf{let } x = V \textbf{ in } M \longrightarrow M[x := V]$$

$$(\lambda\, x.\ M)\ N \longrightarrow \textbf{let } x = N \textbf{ in } M$$

Call-by-Value:

notion of reduction: redexes

evaluation strategy: evaluation contexts

$$E ::= \bullet \mid E\ M \mid V\ E \mid \textbf{if } E \textbf{ then } M \textbf{ else } M \mid \textbf{let } x = E \textbf{ in } M$$

let x = *print*@A “hello”@A
let y = *print*@B “foo”@B
print@A “world”@A

$E =$ **let** x = •
let y = *print*@B “foo”@B
print@A “world”@A

Δ = *print*@A “hello”@A

Call-by-Value:

notion of reduction: redexes

evaluation strategy: evaluation contexts

$$E \quad ::= \quad \bullet \;\mid\; E\ M \;\mid\; V\ E \;\mid\; \textbf{if } E \textbf{ then } M \textbf{ else } M \;\mid\; \textbf{let } x = E \textbf{ in } M$$

let x = *print*@A “hello”@A
let y = *print*@B “foo”@B
print@A “world”@A

determinism:
at most one decomposition $M = E[\Delta]$

prints “hello” “foo” “world”

Call-by-Value:

notion of reduction: redexes

evaluation strategy: evaluation contexts

$$E \quad ::= \quad \bullet \;\mid\; E\ M \;\mid\; V\ E \;\mid\; \textbf{if } E \textbf{ then } M \textbf{ else } M \;\mid\; \textbf{let } x = E \textbf{ in } M$$

let x = *print*@A “hello”@A
let y = *print*@B “foo”@B
print@A “world”@A

what’s the projection?

Call-by-Value:

notion of reduction: redexes

evaluation strategy: evaluation contexts

$$E \quad ::= \quad \bullet \;\mid\; E\ M \;\mid\; V\ E \;\mid\; \textbf{if } E \textbf{ then } M \textbf{ else } M \;\mid\; \textbf{let } x = E \textbf{ in } M$$

let x = *print*@A “hello”@A
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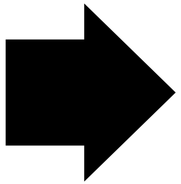


process A

let x = *print* “hello”
print “world”

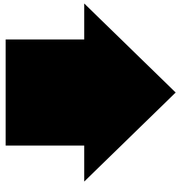
Call-by-Value:

notion of reduction: redexes

evaluation strategy: evaluation contexts

$$E \quad ::= \quad \bullet \;\mid\; E\ M \;\mid\; V\ E \;\mid\; \textbf{if } E \textbf{ then } M \textbf{ else } M \;\mid\; \textbf{let } x = E \textbf{ in } M$$

let x = *print*@A “hello”@A
let y = *print*@B “foo”@B
print@A “world”@A



process A

let x = *print* “hello”
print “world”

process B

print “foo”

Call-by-Value:

notion of reduction: redexes

evaluation strategy: evaluation contexts

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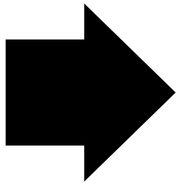
print@A “world”@A



process A

let x = *print* “hello”
print “world”

process B

print “foo”

1. rewrites are **nondeterministic**
2. rewrites can **evaluate under “let”**

1. “hello” “foo” “world”
2. “hello” “world” “foo”
3. “foo” “hello” “world”

Lenient:

1. rewrites are **nondeterministic**
2. rewrites can **evaluate under "let"**

E ::= $\bullet$ | $E\ M$ | $V\ E$ | **if** E **then** M **else** M | **let** x = E **in** M | **let** x = M **in** E

let x = *print*@A "hello"@A
let y = *print*@B "foo"@B
print@A "world"@A

E = **let** x = $\bullet$
let y = *print*@B "foo"@B
print@A "world"@A

Δ = *print*@A "hello"@A

Lenient:

1. rewrites are **nondeterministic**
2. rewrites can **evaluate under "let"**

E ::= • | E M | V E | **if** E **then** M **else** M | **let** x = E **in** M | **let** x = M **in** E

let x = *print*@A "hello"@A
let y = *print*@B "foo"@B
print@A "world"@A

let x = *print*@A "hello"@A
E = **let** y = •
print@A "world"@A

Δ = *print*@B "foo"@B

Lenient:

1. rewrites are **nondeterministic**
2. rewrites can **evaluate under "let"**

$E ::= \bullet \mid E\ M \mid V\ E \mid \textbf{if } E \textbf{ then } M \textbf{ else } M \mid \textbf{let } x = E \textbf{ in } M \mid \textbf{let } x = M \textbf{ in } E$

let x = *print*@A "hello"@A
let y = *print*@B "foo"@B
print@A "world"@A

$E =$ **let** x = *print*@A "hello"@A
let y = *print*@B "foo"@B
$\bullet$

Δ = *print*@A "world"@A

Lenient:

1. rewrites are **nondeterministic**
2. rewrites can **evaluate under "let"**

$E ::= \bullet \mid E\ M \mid V\ E \mid \textbf{if } E \textbf{ then } M \textbf{ else } M \mid \textbf{let } x = E \textbf{ in } M \mid \textbf{let } x = M \textbf{ in } E$

let x = *print*@A "hello"@A
let y = *print*@B "foo"@B
print@A "world"@A

1. "hello" "foo" "world"
2. "hello" "world" "foo"
3. "foo" "hello" "world"
4. ⛔"world" "hello" "foo"

3. rewrites are **deterministic per process**

SemiLenient:

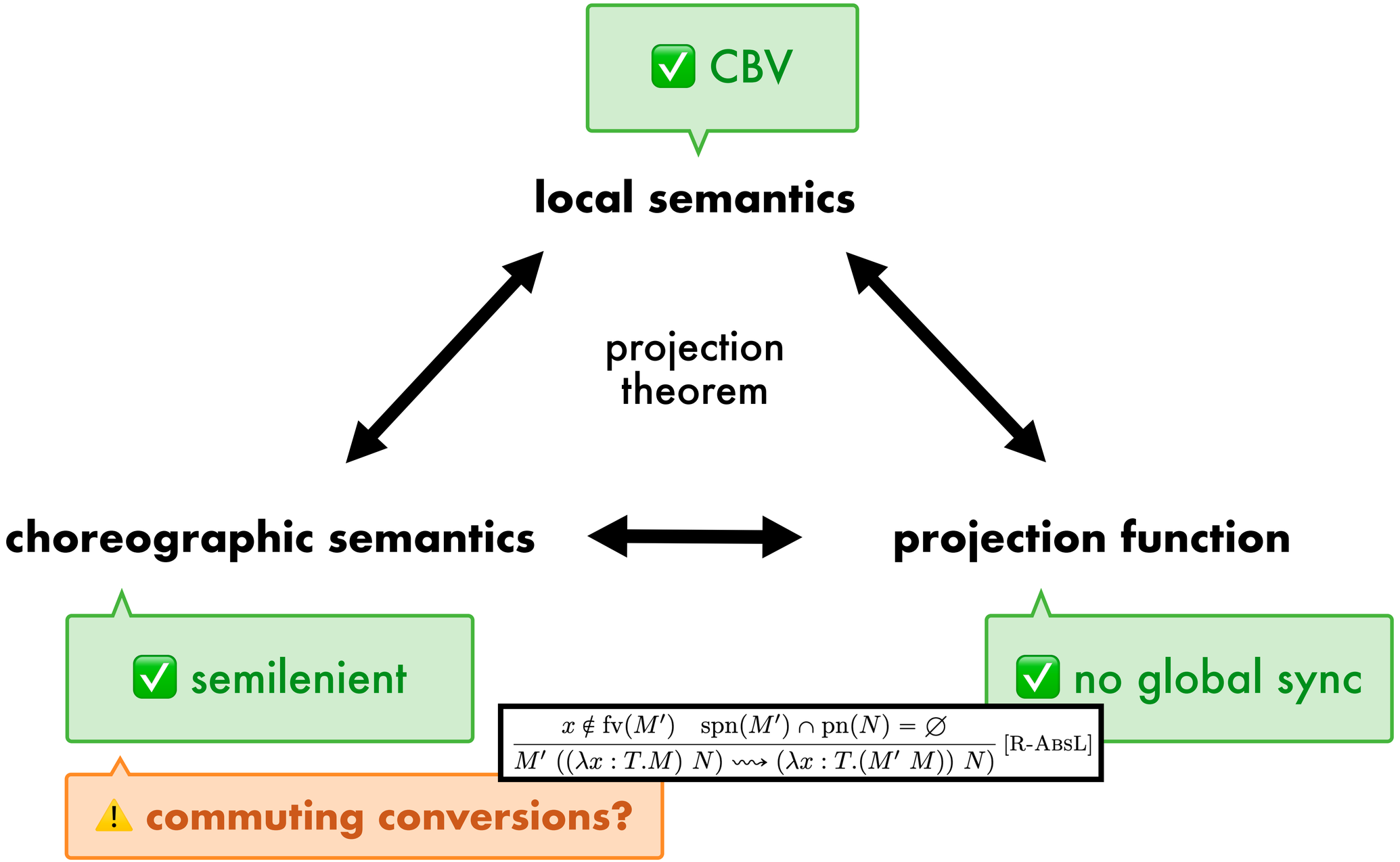
1. rewrites are **nondeterministic**
2. rewrites can **evaluate under "let"**
3. rewrites are **deterministic per process**

$E_P ::= \bullet \mid E_P\, M \mid V\, E_P \mid \textbf{if } E_P \textbf{ then } M \textbf{ else } M \mid \textbf{let } x = E_P \textbf{ in } M \mid \textbf{let } x = M \textbf{ in } E_P \textit{ if } p \notin M$

explains evaluation under lambda!

$$\frac{M \xrightarrow{\ell,\mathsf{P}}_D M'}{\lambda x : T.M \xrightarrow{\lambda,\mathsf{P}}_D \lambda x : T.M'}\ [\textsc{InAbs}]$$

what does that buy us?


✅ CBV
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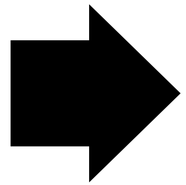
⚠ commuting conversions?
$\frac{x \notin \mathrm{fv}(M') \quad \mathrm{spn}(M') \cap \mathrm{pn}(N) = \varnothing}{M'\ ((\lambda x : T.M)\ N) \rightsquigarrow (\lambda x : T.(M'\ M))\ N)}$ [R-AbsL]

motivation:
commuting conversions

(**let** *x* = *loop*(A)
print@B) “hello!”@B

motivation:
commuting conversions

(**let** *x* = *loop*(A)
print@B) “hello!”@B

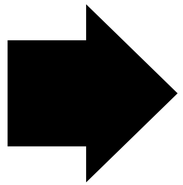


process A

loop()

motivation:
commuting conversions

(**let** *x* = *loop*(A)
print@B) “hello!”@B



process A

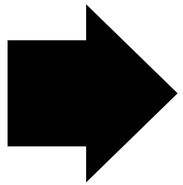
loop()

process B

print “hello”

motivation:
commuting conversions

(**let** *x* = *loop*(A)
print@B) “hello!”@B



process A

loop()

process B

print “hello”

⚠️ choreography never prints

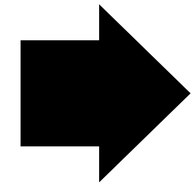
✅ local code prints “hello”

ok... add a rule:

(let x = *M* **in** *N*) *M′* ⟶ **let** x = *M* **in** *N M′*

motivation:
commuting conversions

print@B (**let** *x* = *loop*(A)
"hello!"@*B*)

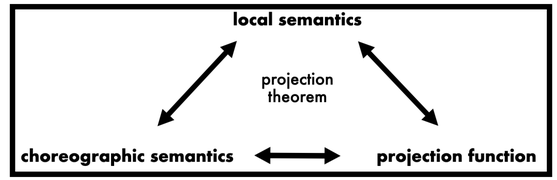


process A

loop()

process B

print "hello"



ok... add a rule:

V (**let** x = *M* **in** *N*) ⟶ **let** x = *M* **in** *V M′*

A Call-By-Need Lambda Calculus

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I-Structures: Data Structures for Parallel

Compiling without Continuations

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A Semantical and Operational Account
ll-by-Value Solvability

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SemiLenient:

Compiling without Continuations

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$$E_P ::= \bullet \mid E_P\ M \mid V\ E_P \mid \textbf{if } E_P \textbf{ then } M \textbf{ else } M \mid \textbf{let } x = E_P \textbf{ in } M \mid \textbf{let } x = M \textbf{ in } E_P \ \textit{if } p \notin M$$

SemiLenient:

Compiling without Continuations

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$$F ::= E_P\ M \mid V\ E_P \mid \textbf{if } E_P \textbf{ then } M \textbf{ else } M \mid \textbf{let } x = E_P \textbf{ in } M$$

$$A ::= \textbf{let } x = M \textbf{ in } E_P \quad \textit{if } p \notin M$$

$$E_P ::= \bullet \mid F[E_P] \mid A[E_P]$$

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$F ::= \bullet\ M \mid V\ \bullet \mid \textbf{if}\ \bullet\ \textbf{then}\ M\ \textbf{else}\ M \mid \textbf{let}\ x = \bullet\ \textbf{in}\ M$

frames consume values

$A ::= \textbf{let}\ x = M\ \textbf{in}\ \bullet \quad \textit{if}\ p \notin M$

answering contexts produce values

$E_P ::= \bullet \mid F[E_P] \mid A[E_P]$

$$F[\,A[\,M\,]\,] \longrightarrow A[\,F[\,M\,]\,]$$

$$\begin{array}{rcll}
\text{if } (\text{let } x = M_1 \text{ in } M_2) \text{ then } M_3 \text{ else } M_4 & \mapsto & \text{let } x = M_1 \text{ in } (\text{if } M_2 \text{ then } M_3 \text{ else } M_4) & \textit{(if-let)} \\
\text{let } y = (\text{let } x = M_1 \text{ in } M_2) \text{ in } M_3 & \mapsto & \text{let } x = M_1 \text{ in } (\text{let } y = M_2 \text{ in } M_3) & \textit{(let-let)} \\
V\ (\text{let } x = M_1 \text{ in } M_2) & \mapsto & \text{let } x = M_1 \text{ in } V\ M_2 & \textit{(app-let)} \\
(\text{let } x = M_1 \text{ in } M_2)\ M_3 & \mapsto & \text{let } x = M_1 \text{ in } M_2\ M_3 & \textit{(let-app)} \\
V\ (\text{select}_{p,q}\ l\ M) & \mapsto & \text{select}_{p,q}\ l\ (V\ M) & \textit{(app-sel)} \\
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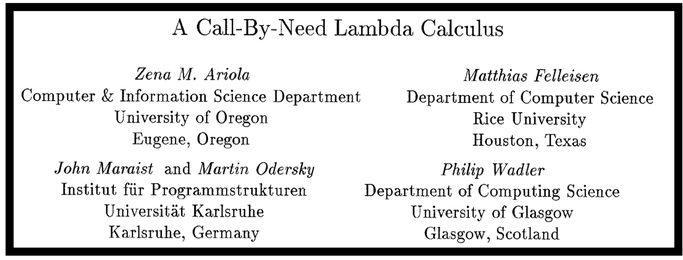
\text{if } (\text{select}_{p,q}\ l\ M_1) \text{ then } M_2 \text{ else } M_3 & \mapsto & \text{select}_{p,q}\ l\ (\text{if } M_1 \text{ then } M_2 \text{ else } M_3) & \textit{(if-sel)} \\
\text{let } x = \text{select}_{p,q}\ l\ M_1 \text{ in } M_2 & \mapsto & \text{select}_{p,q}\ l\ (\text{let } x = M_1 \text{ in } M_2) & \textit{(let-sel)}
\end{array}$$


A Call-By-Need Lambda Calculus

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Institut für Programmstrukturen
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Philip Wadler
Department of Computing Science
University of Glasgow
Glasgow, Scotland

$$
\begin{array}{rcll}
\text{if } (\text{let } x = M_1 \text{ in } M_2) \text{ then } M_3 \text{ else } M_4 & \mapsto & \text{let } x = M_1 \text{ in } (\text{if } M_2 \text{ then } M_3 \text{ else } M_4) & \textit{(if-let)} \\
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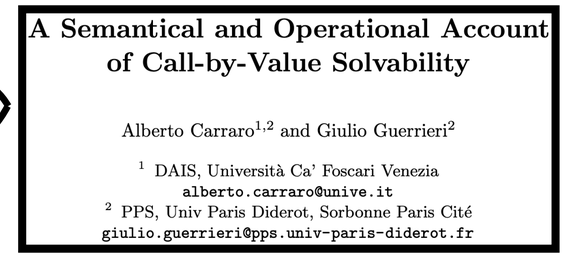

$$
\begin{aligned}
\text{if } (\text{let } x = M_1 \text{ in } M_2) \text{ then } M_3 \text{ else } M_4 &\mapsto \text{let } x = M_1 \text{ in } (\text{if } M_2 \text{ then } M_3 \text{ else } M_4) && \textit{(if-let)}\\
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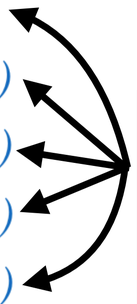
\text{if } (\text{select}_{\text{p,q}}\ l\ M_1) \text{ then } M_2 \text{ else } M_3 &\mapsto \text{select}_{\text{p,q}}\ l\ (\text{if } M_1 \text{ then } M_2 \text{ else } M_3) && \textit{(if-sel)}\\
\text{let } x = \text{select}_{\text{p,q}}\ l\ M_1 \text{ in } M_2 &\mapsto \text{select}_{\text{p,q}}\ l\ (\text{let } x = M_1 \text{ in } M_2) && \textit{(let-sel)}
\end{aligned}
$$



Modular Compilation for Higher-Order Functional Choreographies

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✅ simplified rules!

$$\text{if } (\text{let } x = M_1 \text{ in } M_2) \text{ then } M_3 \text{ else } M_4 \mapsto \text{let } x = M_1 \text{ in } (\text{if } M_2 \text{ then } M_3 \text{ else } M_4) \quad \textit{(if-let)}$$

$$\text{let } y = (\text{let } x = M_1 \text{ in } M_2) \text{ in } M_3 \mapsto \text{let } x = M_1 \text{ in } (\text{let } y = M_2 \text{ in } M_3) \quad \textit{(let-let)}$$

$$V\ (\text{let } x = M_1 \text{ in } M_2) \mapsto \text{let } x = M_1 \text{ in } V\ M_2$$

$$\frac{x \notin \mathrm{fv}(M') \quad \mathrm{spn}(M') \cap \mathrm{pn}(N) = \varnothing}{M'\ ((\lambda x : T.M)\ N) \rightsquigarrow (\lambda x : T.(M'\ M))\ N} \text{ [R-AbsL]}$$

$$(\text{let } x = M_1 \text{ in } M_2)\ M_3 \mapsto \text{let } x = M_1 \text{ in } M_2\ M_3 \quad \textit{(let-app)}$$

$$V\ (\text{select}_{p,q}\ l\ M) \mapsto \text{select}_{p,q}\ l\ (V\ M) \quad \textit{(app-sel)}$$

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✅ **simplified rules!**

✅ **found bugs in the old model!**

$$\text{if } (\text{let } x = M_1 \text{ in } M_2) \text{ then } M_3 \text{ else } M_4 \mapsto \text{let } x = M_1 \text{ in } (\text{if } M_2 \text{ then } M_3 \text{ else } M_4) \quad \textit{(if-let)}$$

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wrapping up

the semantics isn't arbitrary—it's **semilenient!**

there's a **recipe** and **laws** for making choreographic languages

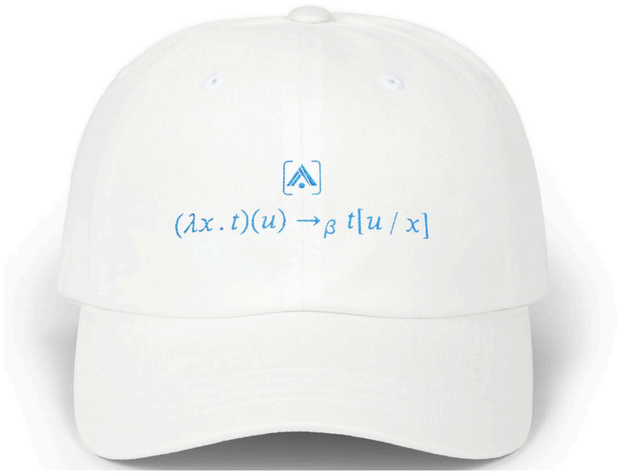
can we extract a projection function?

does it generalize?

can we automate it?

learn more:

dplyukhin.github.io



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*on the job market