Actors and Channels in Core λ-calculi

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EPSRC Centre for Doctoral Training in Pervasive Parallelism
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Actors and Channels

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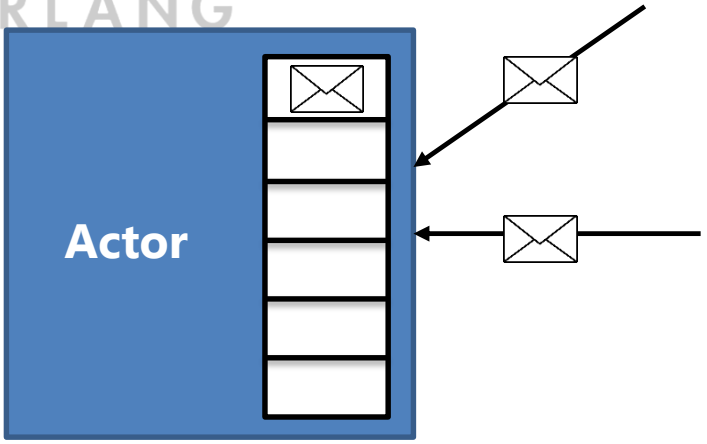
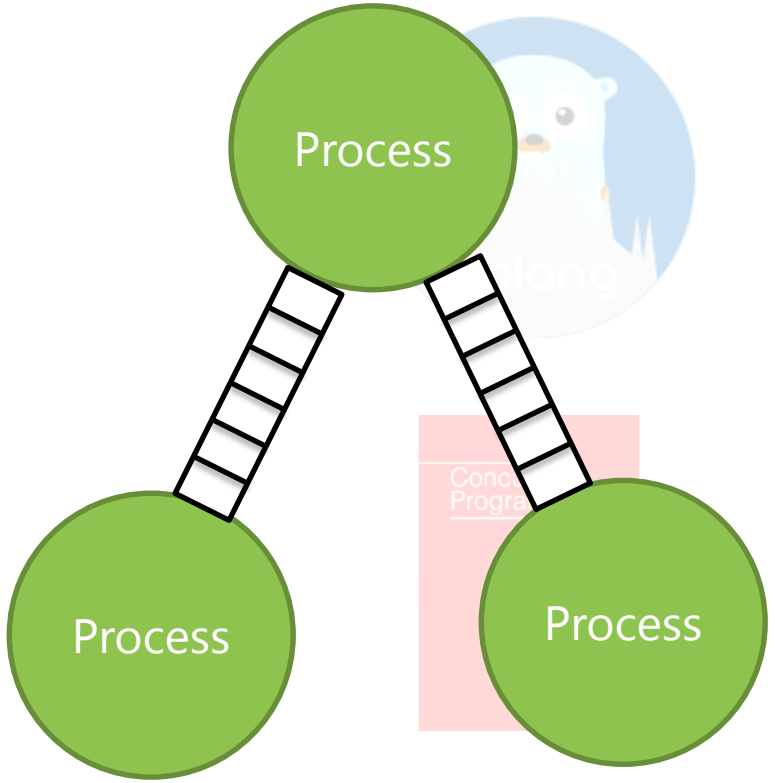
Actors and Channels





Actors and Channels

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Why?

- Concise formalisations of transformations between actors and channels
- Explore design issues with (session) type-parameterised actor calculi
- Influence design of session-typed actors for Links

$\boldsymbol{\lambda_{\mathbf{ch}}}$: A channel-based $\boldsymbol{\lambda}$-calculus

$$
\begin{array}{lll}
\text{Types} & A, B ::= & \mathbf{0} \mid \mathbf{1} \mid A \times B \mid A + B \mid A \to B \mid \mathsf{List}(A) \mid \mathsf{Chan}(A) \\
\text{Terms} & L, M, N ::= & x \mid \lambda x.M \mid M\ N \\
& \mid & (M, N) \mid \mathsf{let}\ (x, y) = M\ \mathsf{in}\ N \\
& \mid & \mathsf{rec}\ f(x : A) : B\ .\ M \\
& \mid & \mathsf{inl}\ M \mid \mathsf{inr}\ M \mid \mathsf{case}\ M\ \{\mathsf{inl}\ x \mapsto N; \mathsf{inr}\ x \mapsto N\} \\
& \mid & [\,]_A \mid [M] \mid M +\!\!+ N \mid \mathsf{case}\ L\ \{[\,]_A \mapsto N; [x] +\!\!+ y \mapsto N'\} \\
& \mid & () \mid M; N \mid \mathsf{fork}\ M \mid \mathsf{give}\ M\ N \mid \mathsf{take}\ M \mid \mathsf{newCh}_A
\end{array}
$$

$\lambda_{\mathbf{ch}}$: Channel Typing Rules

$$\textsc{Give}\ \frac{\Gamma \vdash M : A \quad \Gamma \vdash N : \mathsf{Chan}(A)}{\Gamma \vdash \mathsf{give}\ M\ N : \mathbf{1}} \qquad \textsc{Take}\ \frac{\Gamma \vdash M : \mathsf{Chan}(A)}{\Gamma \vdash \mathsf{take}\ M : A}$$

$$\textsc{NewCh}\ \frac{}{\Gamma \vdash \mathsf{newCh}_A : \mathsf{Chan}(A)} \qquad \textsc{Fork}\ \frac{\Gamma \vdash M : \mathbf{1}}{\Gamma \vdash \mathsf{fork}\ M : \mathbf{1}}$$

λ_{ch}: Communication Semantics

Configurations $\mathcal{C}, \mathcal{D} ::= \mathcal{C} \parallel \mathcal{C}' \mid (\nu x)\mathcal{C} \mid M \mid x(\overrightarrow{V})$

GIVE

$$\frac{}{E[\mathsf{give}\ W\ x] \parallel x(\overrightarrow{V}) \longrightarrow E[()] \parallel x(\overrightarrow{V}\ W)}$$

TAKE

$$\frac{}{E[\mathsf{take}\ x] \parallel x(W\ \overrightarrow{V}) \longrightarrow E[W] \parallel x(\overrightarrow{V})}$$

NEWCH

$$\frac{x \text{ is a fresh name}}{E[\mathsf{newCh}_A] \longrightarrow (\nu x)(E[x] \parallel x(\epsilon))}$$

FORK

$$\frac{}{G[\mathsf{fork}\ M] \longrightarrow G[()] \parallel M}$$

Actor-based Functional Languages

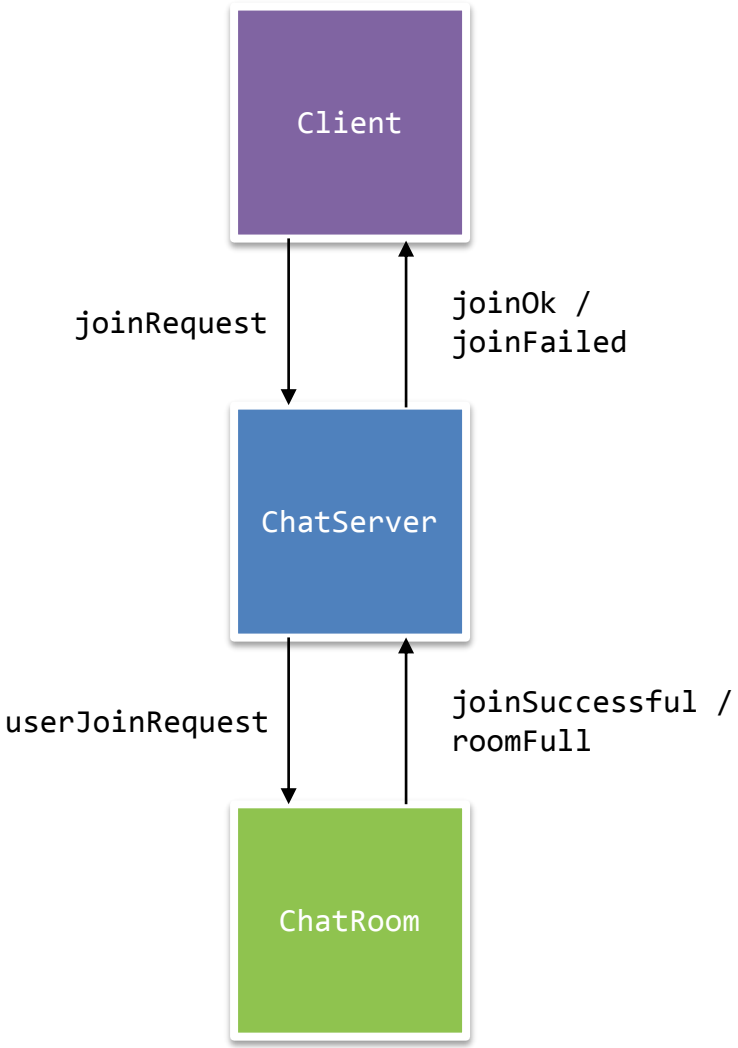
- Based on the actor model (Agha, 1985), **not the same**
  - Actors represented as **lightweight processes**, scheduled by RTS
  - No explicit notion of behaviour / become
  - Computation modelled directly

- Primitives
  - `spawn`
  - `send`
  - `receive`
  - *`(wait)`*

```
-module(stack).
-compile(export_all).
loop(State) ->
  receive
    {pop, Pid} ->
      [Hd|Tl] = State,
      Pid ! Hd,
      loop(Tl);
    {push, Item} ->
      loop([Item] ++ State)
  end.

spawn_stack() ->
  spawn(stack, loop, [[]]).
```

The Type Pollution Problem



ChatServer has type

Pid(joinRequest + joinSuccessful + roomFull)

...wherever we use it!

$\lambda_{\mathbf{act}}$: A core actor-based λ-calculus

$$
\begin{array}{lll}
\text{Types} & A, B, C ::= & \mathbf{0} \mid \mathbf{1} \mid A \times B \mid A + B \mid A \to^{C} B \mid \mathsf{List}(A) \mid \mathsf{Pid}(A, B) \\
\text{Terms} & L, M, N ::= & x \mid \lambda x.M \mid M\ N \\
& & \mid\ (M, N) \mid \mathsf{let}\ (x, y) = M\ \mathsf{in}\ N \\
& & \mid\ \mathsf{rec}\ f(x : A) : B\ .\ M \\
& & \mid\ \mathsf{inl}\ M \mid \mathsf{inr}\ M \mid \mathsf{case}\ M\ \{\mathsf{inl}\ x \mapsto N; \mathsf{inr}\ x \mapsto N\} \\
& & \mid\ [\,]_A \mid [M] \mid M +\!\!+ N \mid \mathsf{case}\ L\ \{[\,]_A \mapsto N; [x] +\!\!+ y \mapsto N'\} \\
& & \mid\ \mathsf{spawn}\ M \mid \mathsf{send}\ M\ N \mid \mathsf{receive} \mid \mathsf{wait}\ M
\end{array}
$$

$\lambda_{\mathbf{act}}$: Selected Typing Rules

$$\boxed{\Gamma; C \vdash M : A}$$

$$\textsc{Send}\ \frac{\Gamma; C \vdash M : A \quad \Gamma; C \vdash N : \mathsf{Pid}(A, B)}{\Gamma; C \vdash \mathsf{send}\ M\ N : \mathbf{1}}$$

$$\textsc{Recv}\ \frac{}{\Gamma; C \vdash \mathsf{receive} : C}$$

$$\textsc{Wait}\ \frac{\Gamma; C \vdash M : \mathsf{Pid}(A, B)}{\Gamma; C \vdash \mathsf{wait}\ M : B}$$

$$\textsc{Spawn}\ \frac{\Gamma; A \vdash M : \mathsf{Pid}(A, B) \to^{A} B}{\Gamma; C \vdash \mathsf{spawn}\ M : \mathsf{Pid}(A, B)}$$

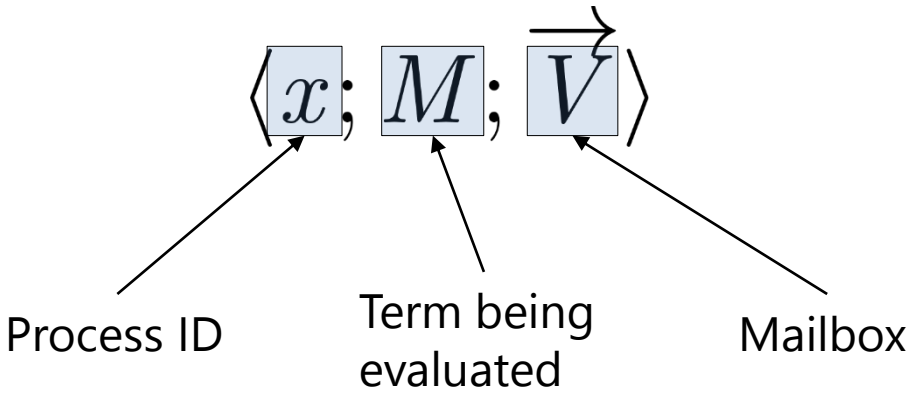
(An alternative formulation of wait)

spawnWait construct: combination of spawn and wait

$$\textsc{SpawnWait}\ \frac{\Gamma; A \vdash M : \mathsf{Pid}(A) \to^{A} B}{\Gamma; C \vdash \mathsf{spawnWait}\ M : B}$$

$\lambda_{\mathbf{act}}$: Configurations

Actors are a three-tuple:



$$\text{Configurations} \quad \mathcal{C}, \mathcal{D} ::= \mathcal{C} \parallel \mathcal{C}' \mid (\nu x)\mathcal{C} \mid \langle x; M; \overrightarrow{V} \rangle$$

$\lambda_{\mathbf{act}}$: Communication Semantics

SPAWN

$$\frac{y \text{ is a fresh name}}{\langle x; E[\mathsf{spawn}\ M]; \overrightarrow{V}\rangle \longrightarrow (\nu y)(\langle x; E[y]; \overrightarrow{V}\rangle \parallel \langle y; M\ y; \epsilon\rangle)}$$

SEND

$$\frac{}{\langle x; E[\mathsf{send}\ V'\ y]; \overrightarrow{V}\rangle \parallel \langle y; E'[M]; \overrightarrow{W}\rangle \longrightarrow \langle x; E[()]; \overrightarrow{V}\rangle \parallel \langle y; E'[M]; \overrightarrow{W}\ V'\rangle}$$

RECEIVE

$$\frac{}{\langle x; E[\mathsf{receive}]; W\ \overrightarrow{V}\rangle \longrightarrow \langle x; E[W]; \overrightarrow{V}\rangle}$$

WAIT

$$\frac{}{\langle x; E[\mathsf{wait}\ y]; \overrightarrow{W}\rangle \parallel \langle y; V; \overrightarrow{W'}\rangle \longrightarrow \langle x; E[V]; \overrightarrow{W}\rangle}$$

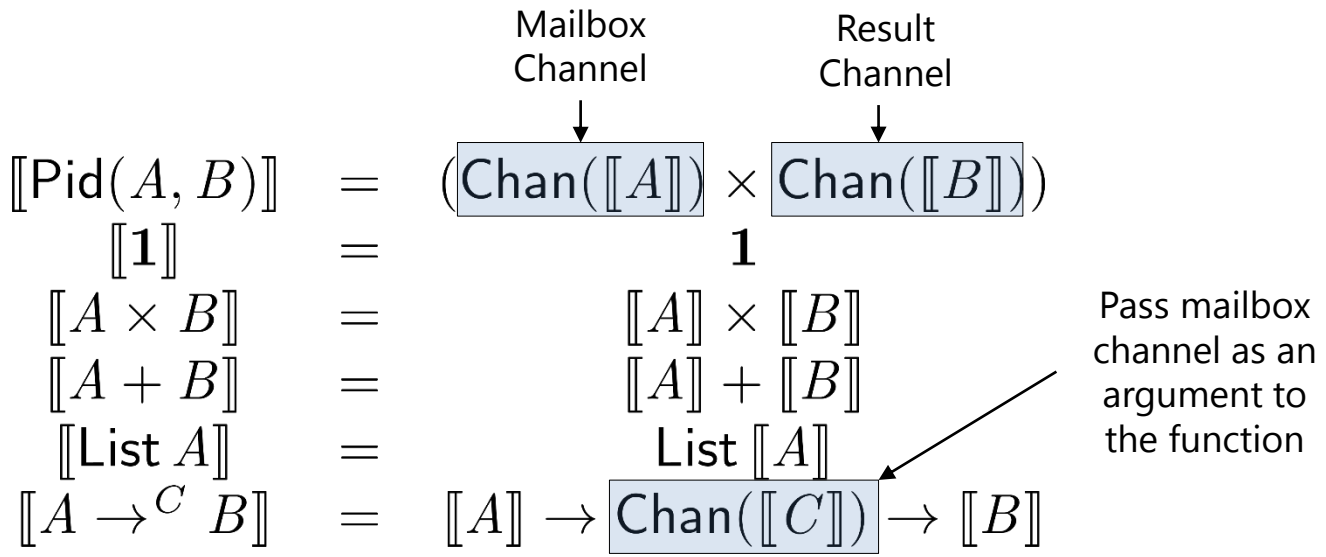
Translations: Desired Properties

- Translation function $[\![-]\!]$: Actors in terms of channels
- Type Preservation:
  - Terms:
    If $\Gamma; C \vdash_{\lambda_{\mathrm{act}}} M : A$, then $[\![\Gamma]\!], c : \mathsf{Chan}([\![C]\!]) \vdash_{\lambda_{\mathrm{ch}}} [\![M]\!]\, c : [\![A]\!]$
  - Configurations
    If $\Gamma \vdash_{\lambda_{\mathrm{act}}} \mathcal{C}$, then $[\![\Gamma]\!] \vdash_{\lambda_{\mathrm{ch}}} [\![\mathcal{C}]\!]$.

- Semantics Preservation
  - Terms
    If $M \longrightarrow_{\lambda_{\mathrm{act}}} M'$, then let $c = \mathsf{newCh}_{[\![C]\!]}$ in $[\![M]\!]\, c \longrightarrow^*_{\lambda_{\mathrm{ch}}} [\![M']\!]\, c$ for some type C.
  - Configurations
    If $\mathcal{C} \longrightarrow_{\lambda_{\mathrm{act}}} \mathcal{C}'$, then $[\![\mathcal{C}]\!] \longrightarrow^*_{\lambda_{\mathrm{ch}}} [\![\mathcal{C}']\!]$

Actors implemented using channels

Idea (based on Cooper et al., 2006): create a channel and use it as a mailbox, "threaded through" the translation



λ_{act} in λ_{ch}: Translation on Terms

Top-level term: create mailbox channel, pass as parameter to translation

$$[\![M]\!] \quad = \quad \text{let } chMb = \text{newCh}_A \text{ in } [\![M]\!]\, chMb$$

Extra parameter c' to pass mailbox channel to the function

$$[\![\lambda x.M]\!]\, c \quad = \quad \lambda x.\lambda c'.[\![M]\!]\, c'$$

$$[\![M\ N]\!]\, c \quad = \quad ([\![M]\!]\, c)\,([\![N]\!]\, c)\, c$$

c applied to translated function M

$\lambda_{\mathbf{act}}$ in $\lambda_{\mathbf{ch}}$: Translation on Terms

Create a mailbox and result channel; fork a new process; evaluate result; and give to result channel

$$[\![\text{spawn } M]\!]\ c = \text{let } chMb = \text{newCh}_A \text{ in let } chRes = \text{newCh}_B \text{ in fork}(\text{let } res = [\![M]\!]\ chMb \text{ in give } res\ chRes);\ (chMb, chRes)$$

Translate PID; `give` to mailbox channel

$$[\![\text{send } M\ N]\!]\ c = \text{let } (chMb, \_) = [\![N]\!]\ c \text{ in give } ([\![M]\!]\ c)\ chMb$$

Translate PID; `take` from result channel

$$[\![\text{receive}]\!]\ c = \text{take } c$$

$$[\![\text{wait } M]\!]\ c = \text{let } (\_, chRes) = [\![M]\!]\ c \text{ in take } chRes$$

Translations: Desired Properties

- Translation function $[\![-]\!]$: Channels in terms of actors
- Type Preservation:
  - Terms:
    $\text{If } \Gamma \vdash_{\lambda_{\text{ch}}} M : A, \text{ then } (\!|\Gamma|\!); C \vdash_{\lambda_{\text{act}}} (\!|M|\!) : (\!|A|\!) \text{ for some type } C.$
  - Configurations
    $\text{If } \Gamma \vdash_{\lambda_{\text{ch}}} \mathcal{C}, \text{ then } (\!|\Gamma|\!) \vdash_{\lambda_{\text{act}}} (\!|\mathcal{C}|\!).$

- Semantics Preservation
  - Terms
    $\text{If } M \longrightarrow_{\lambda_{\text{ch}}} M', \text{ then } (\!|M|\!) \longrightarrow^*_{\lambda_{\text{act}}} (\!|M|\!).$
  - Configurations
    $\text{If } \mathcal{C} \longrightarrow_{\lambda_{\text{ch}}} \mathcal{C}', \text{ then } (\!|\mathcal{C}|\!) \longrightarrow^*_{\lambda_{\text{act}}} (\!|\mathcal{C}'|\!).$

Channels implemented using Actors

- Idea: represent **channels** as **processes**; emulate `give` and `take` using internal state

Channels: pair of `take` and `give` functions

$$
\begin{aligned}
(\!| \mathsf{Chan}(A) |\!) &= ((\mathbf{1} \to^{(\!| A |\!)} (\!| A |\!)) \times ((\!| A |\!) \to^{(\!| A |\!)} \mathbf{1})) \\
(\!| \mathbf{1} |\!) &= \mathbf{1} \\
(\!| A \times B |\!) &= (\!| A |\!) \times (\!| A |\!) \\
(\!| A + B |\!) &= (\!| A |\!) + (\!| B |\!) \\
(\!| A \to B |\!) &= (\!| A |\!) \to^{C} (\!| B |\!) \\
(\!| \mathsf{List}\ A |\!) &= \mathsf{List}\ (\!| A |\!)
\end{aligned}
$$

C can be **any type**, as **translated** functions don't have the ability to receive from mailboxes

Translations on Terms (the easy ones)

$$
\begin{aligned}
(\!|\, \mathsf{fork}\ M \,|\!) &= \mathsf{let}\ \_ = \mathsf{spawn}\ (\!|\, M \,|\!)\ \mathsf{in}\ () \\
(\!|\, \mathsf{give}\ M\ N \,|\!) &= \mathsf{let}\ (\_, \texttt{giveFn}) = (\!|\, N \,|\!)\ \mathsf{in} \\
&\quad\ \texttt{giveFn}\ (\!|\, M \,|\!) \\
(\!|\, \mathsf{take}\ M \,|\!) &= \mathsf{let}\ (\texttt{takeFn}, \_) = (\!|\, M \,|\!)\ \mathsf{in} \\
&\quad\ \texttt{takeFn}\ () \\
(\!|\, \mathsf{newCh}_D \,|\!) &= \ldots
\end{aligned}
$$

Translation of **newCh**…

$(\!|\, \mathsf{newCh}_A \,|\!) =$

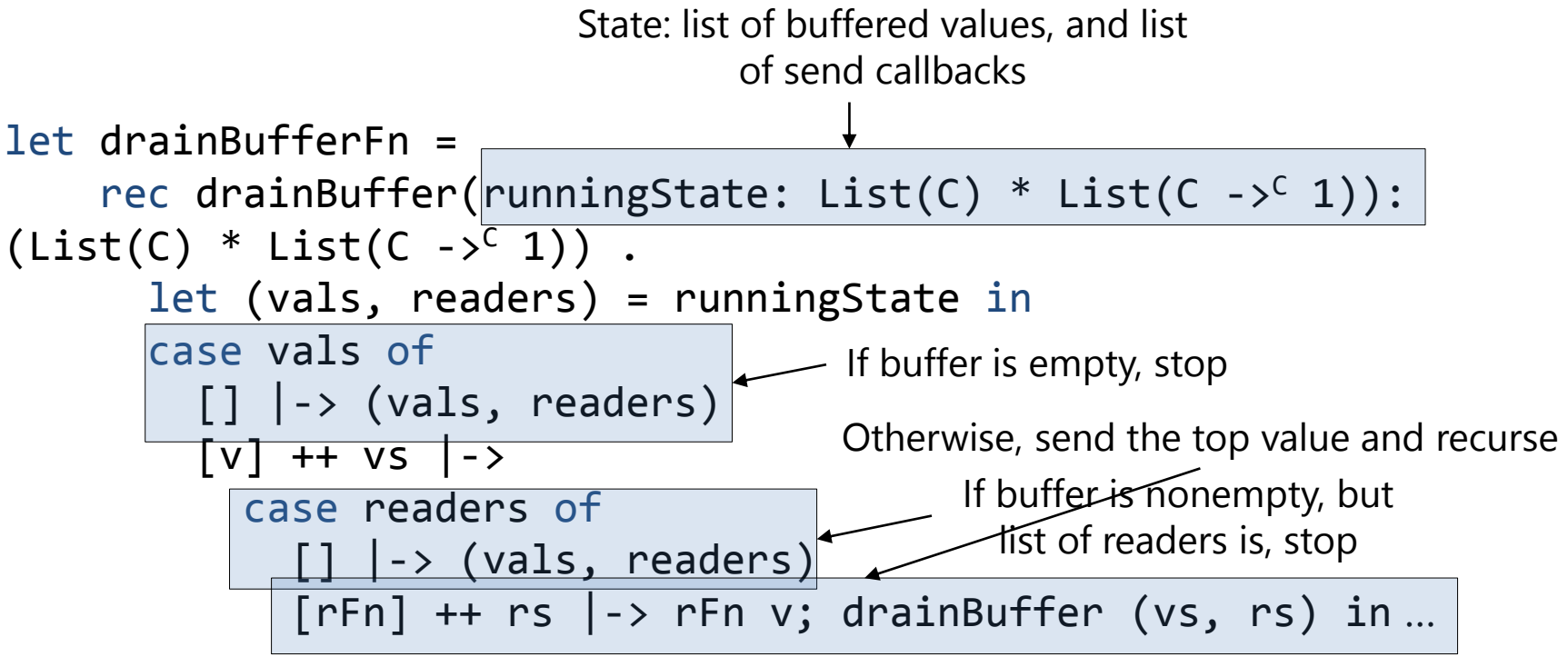
```
let drainBufferFn =
    rec drainBuffer(runningState: List(C) * List(C ->C 1)): (List(C), * List(C ->C 1)) .
      let (vals, readers) = runningState in
      case vals of
        [] |-> (vals, readers)
        [v] ++ vs |->
          case readers of
            [] |-> (vals, readers)
            [rFn] ++ rs |-> rFn v; drainBuffer (vs, rs) in

let stepFn = rec step(state: (List(C) * List(C ->C 1)): 1.
  let (vals, readers) = drainBufferFn state in
  let msg = receive in
  case msg of
      inl v |-> step (vals ++ [v], readers)
      inr sendFn |-> step (vals, readers ++ [sendFn]) in

let chanPid = spawn(stepFn([], [])) in
let giveFn = λx. send (inl x) chanPid in
let takeFn = λx.
  let newPid =
    spawn (λnewPid -> send chanPid (inr (λval -> send val newPid)); receive) in
  wait newPid in
(takeFn, giveFn)
```

Seriously though:

1. Define a function to ensure that either the buffer or list of blocked readers is empty at each step.



Seriously though:

2. Define a loop function `stepFn` which calls `drainBufferFn`, then receives a message and modifies the state

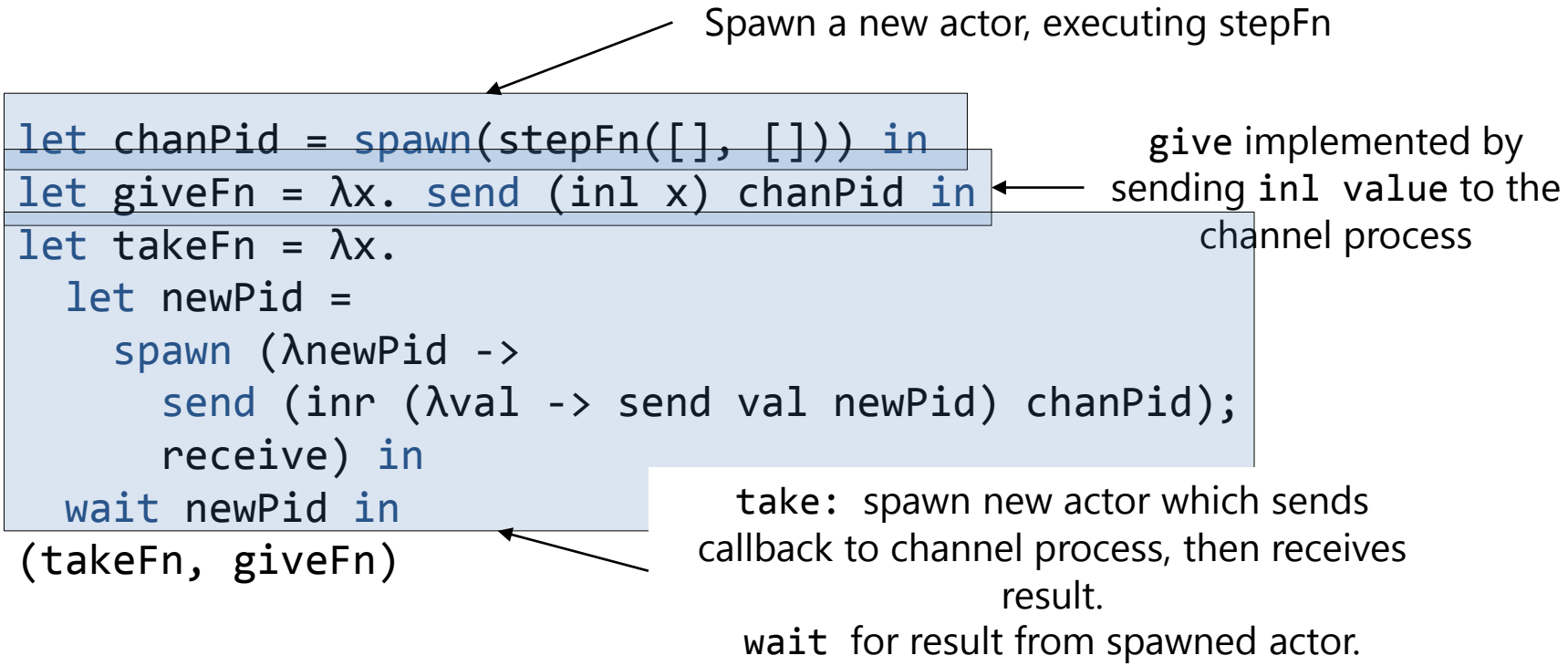
```
let stepFn = rec step(state: (List(C) * List(C ->C 1)): 1.
  let (vals, readers) = drainBu
  let msg = receive in
  case msg of
      inl v |-> step (vals ++ [v], readers)
      inr sendFn |-> step (vals, readers ++ [sendFn]) in ...
```

Message can either be inl value or

If a callback, add to callback list

Seriously though:

3. Spawn a new actor with empty state; define functions for `give` and `take`



Still to do / the future

- Goal: A minimal behaviourally typed actor calculus
  - Conjecture: there exists a minimal session-typed actor calculus
    - …which we can do analogous translations to / from asynchronous GV
    - …not needing recursion for the channel -> actor translation
    - …with simpler session types (no ! / ? required?)
  - Influence a design for session-typed actors in Links
- A better solution to type pollution
  - Subtyping?
- Lots of proving to do!

Extra slides

Actor Configuration Typing

Mailbox typing

$$\textsc{Empty}\ \frac{}{\Gamma \vdash \epsilon : \overrightarrow{A}} \qquad \textsc{Mailbox}\ \frac{\Gamma; B \vdash W : A \quad \Gamma; B \vdash \overrightarrow{V} : \overrightarrow{A}}{\Gamma; B \vdash W\,\overrightarrow{V} : \overrightarrow{A}}$$

Configuration typing

$$\textsc{Par}\ \frac{\Gamma \vdash \mathcal{C} \quad \Gamma \vdash \mathcal{C}'}{\Gamma \vdash \mathcal{C} \parallel \mathcal{C}'} \qquad \textsc{Pid}\ \frac{\Gamma, x : \mathsf{Pid}(A, B) \vdash \mathcal{C}}{\Gamma \vdash (\nu x)\mathcal{C}}$$

$$\textsc{Actor}\ \frac{\Gamma; D \vdash x : \mathsf{Pid}(A, B) \quad \Gamma; A \vdash M : B \quad \Gamma; A \vdash \overrightarrow{V} : \overrightarrow{A}}{\Gamma \vdash \langle x; M; \overrightarrow{V} \rangle}$$

Figure 1: Configuration typing

Session Actor Calculus Sketch

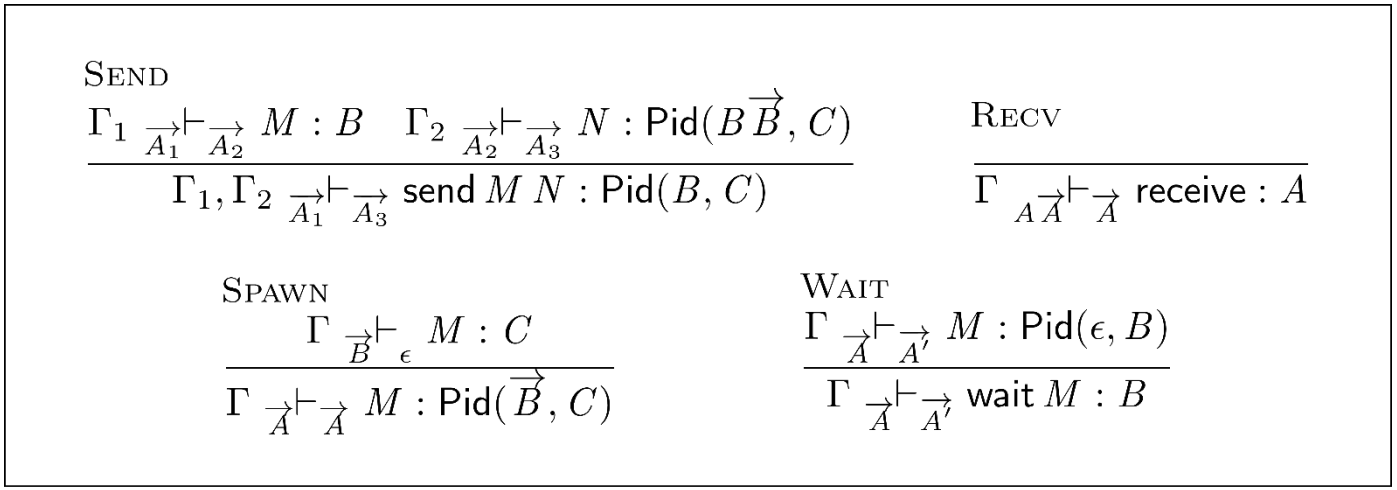
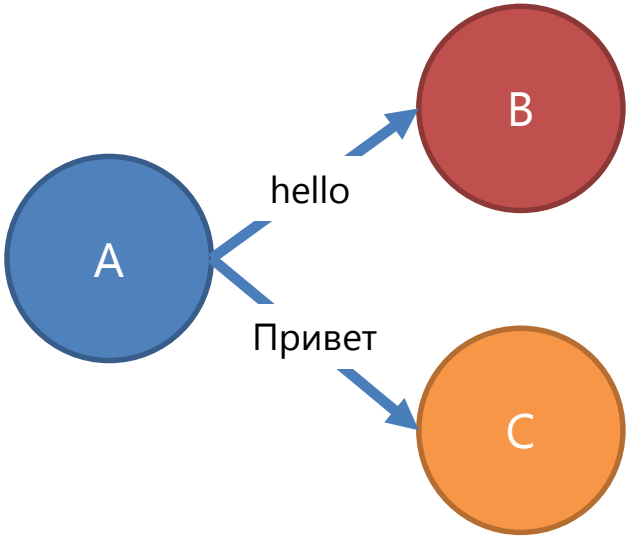


Figure 1: Possible typing rules for session actor calculus communication primitives

Actor-based Functional Languages vs. the Actor Model

- A word of caution regarding terminology!
- Actors: a minimal concurrency model
  - Unforgeable PID, message queue (mailbox)
  - Behaviour



1. Send a finite set of messages to another actor

Actor-based Functional Languages vs. the Actor Model

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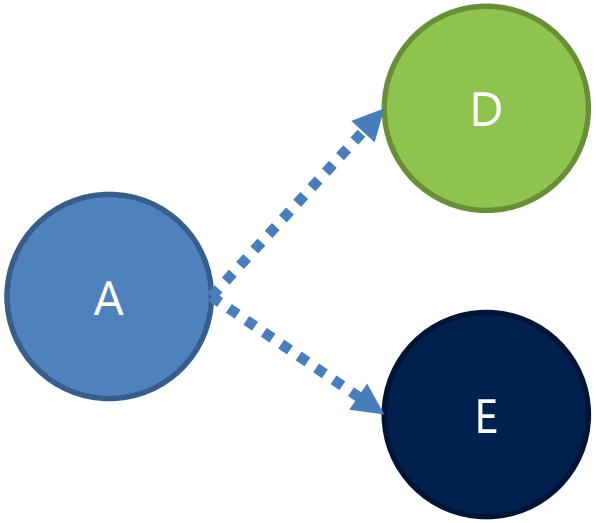
  - Behaviour



2. Spawn a finite set of new actors

Actor-based Functional Languages vs. the Actor Model

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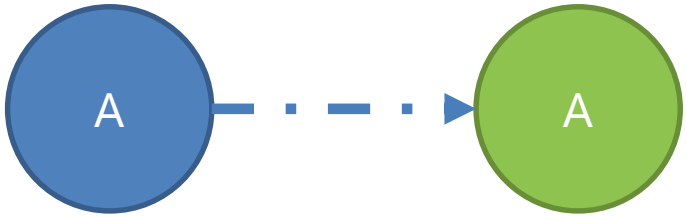
  - Behaviour



3. Change behaviour: react differently when processing next message

Actor-based Functional Languages vs. the Actor Model

- Agha (1985) introduces minimal actor languages SAL and Act, which stay very true to the core actor model: