Concurrency Theory
vs
Concurrent Languages

Silvia Crafa

Universita' di Padova

Bertinoro, OPCT 2014

Bisimulation inside

Concurrency Theory vs Concurrent Languages

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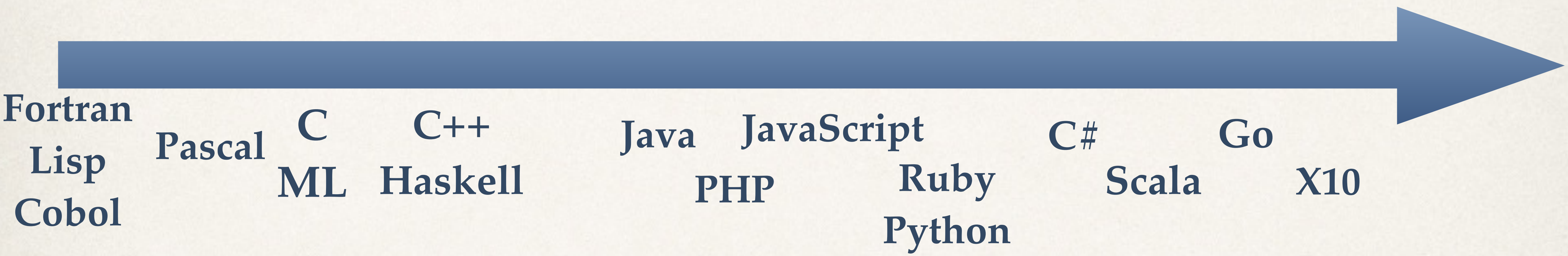
The Quest for good Abstractions



- **When** a language has been **invented** VS when became **popular**?
- **Why** has been invented VS why became popular?

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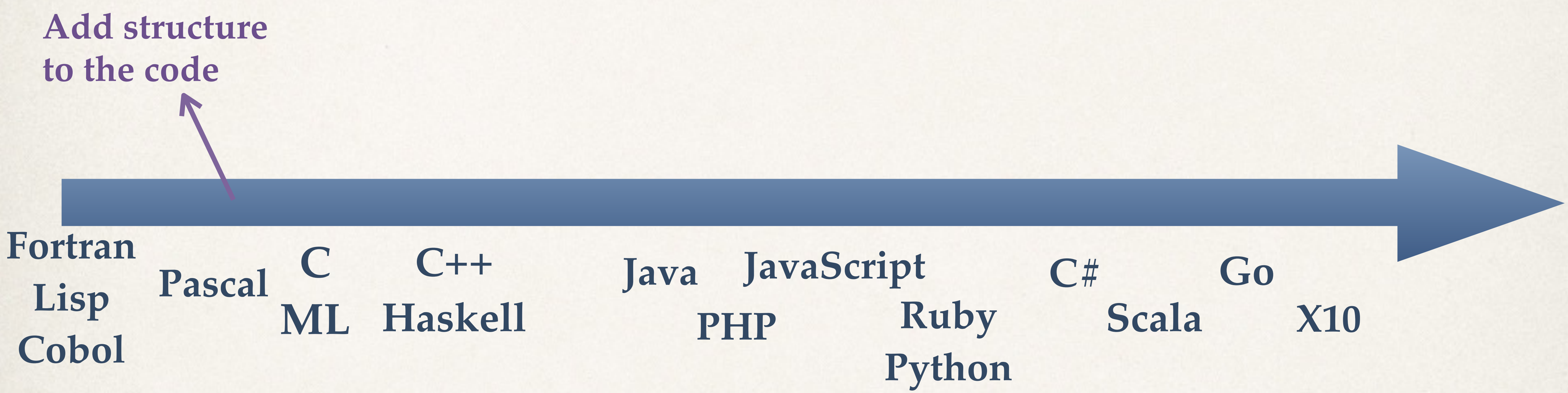

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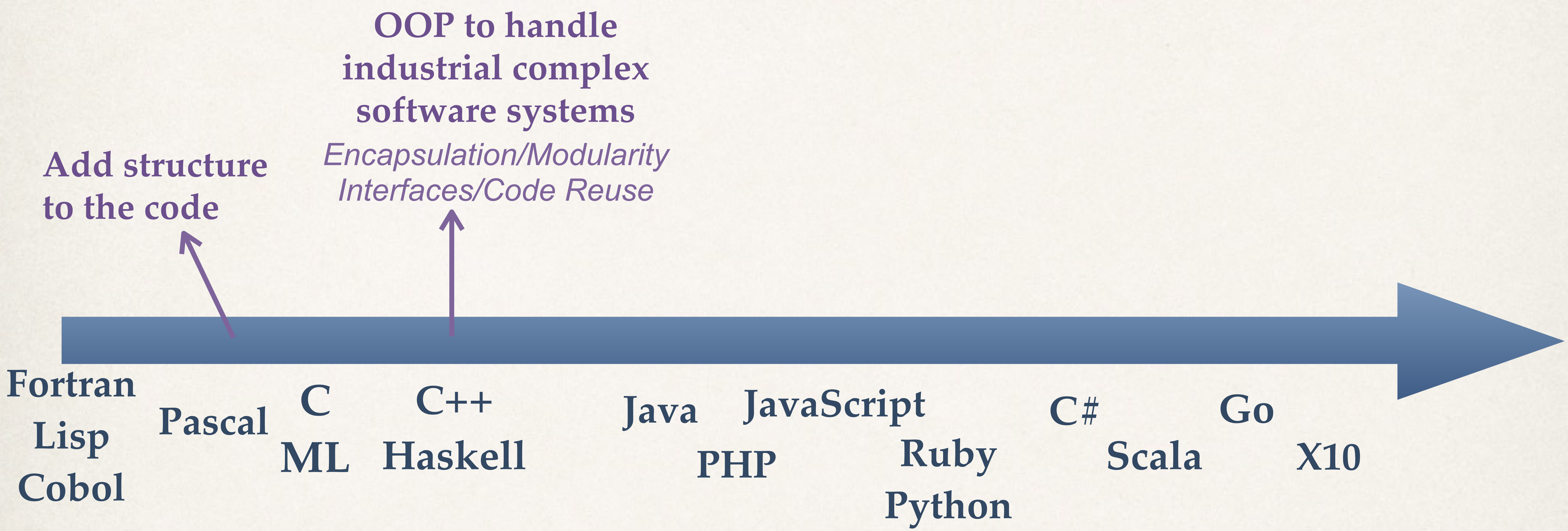

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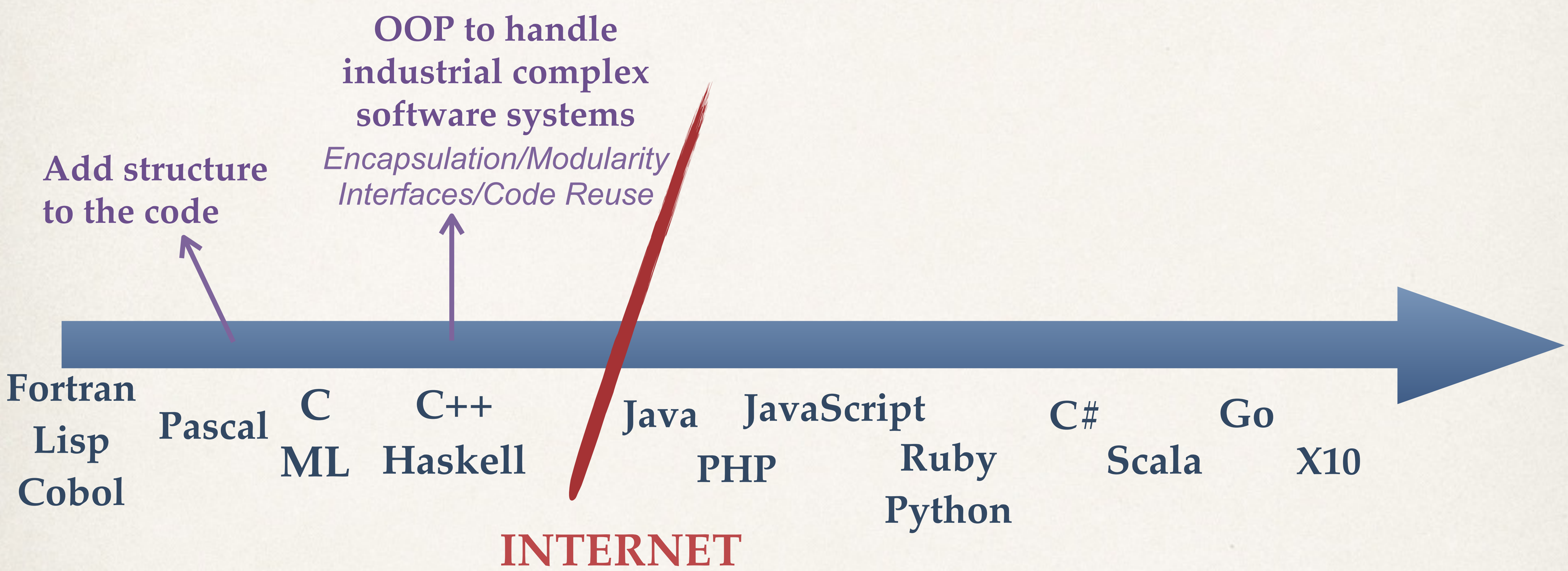

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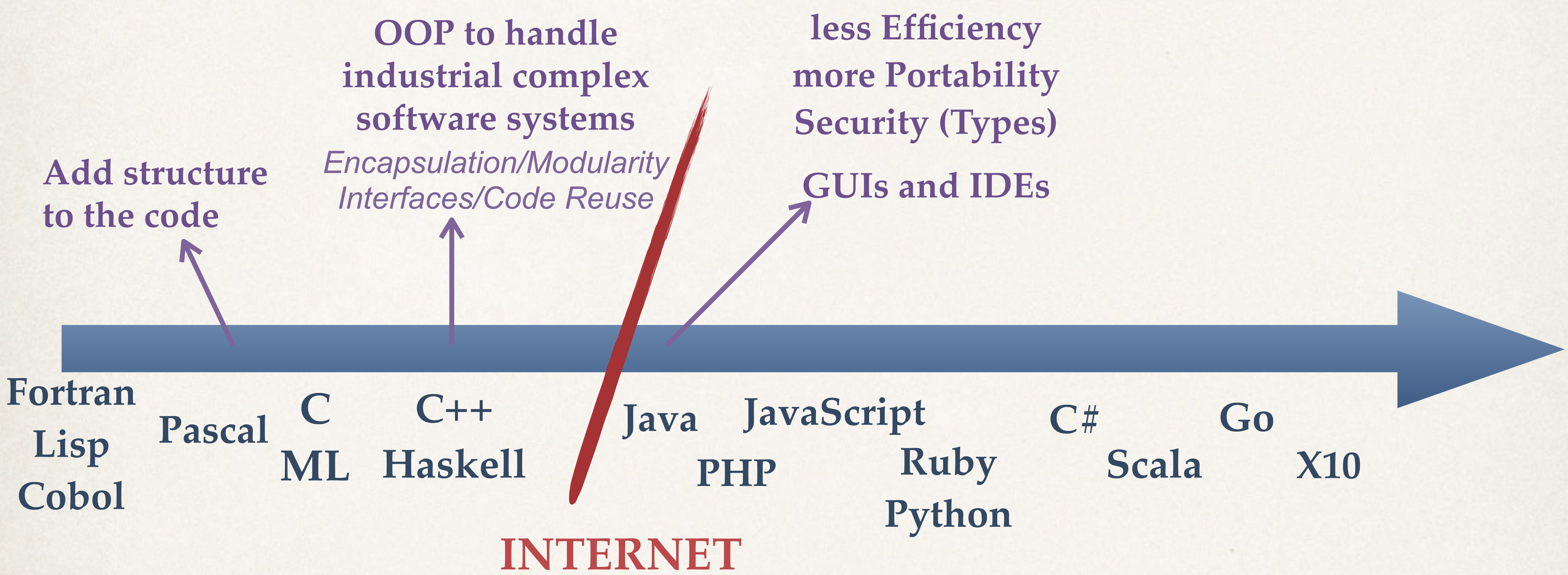

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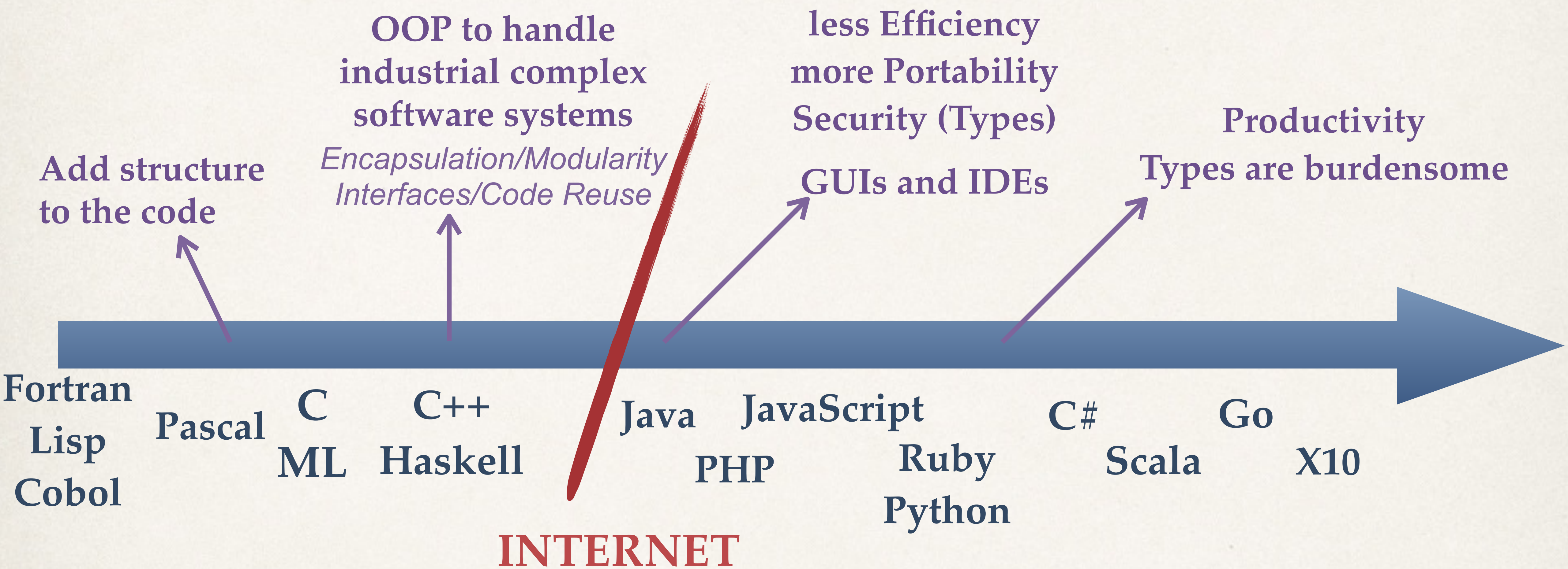

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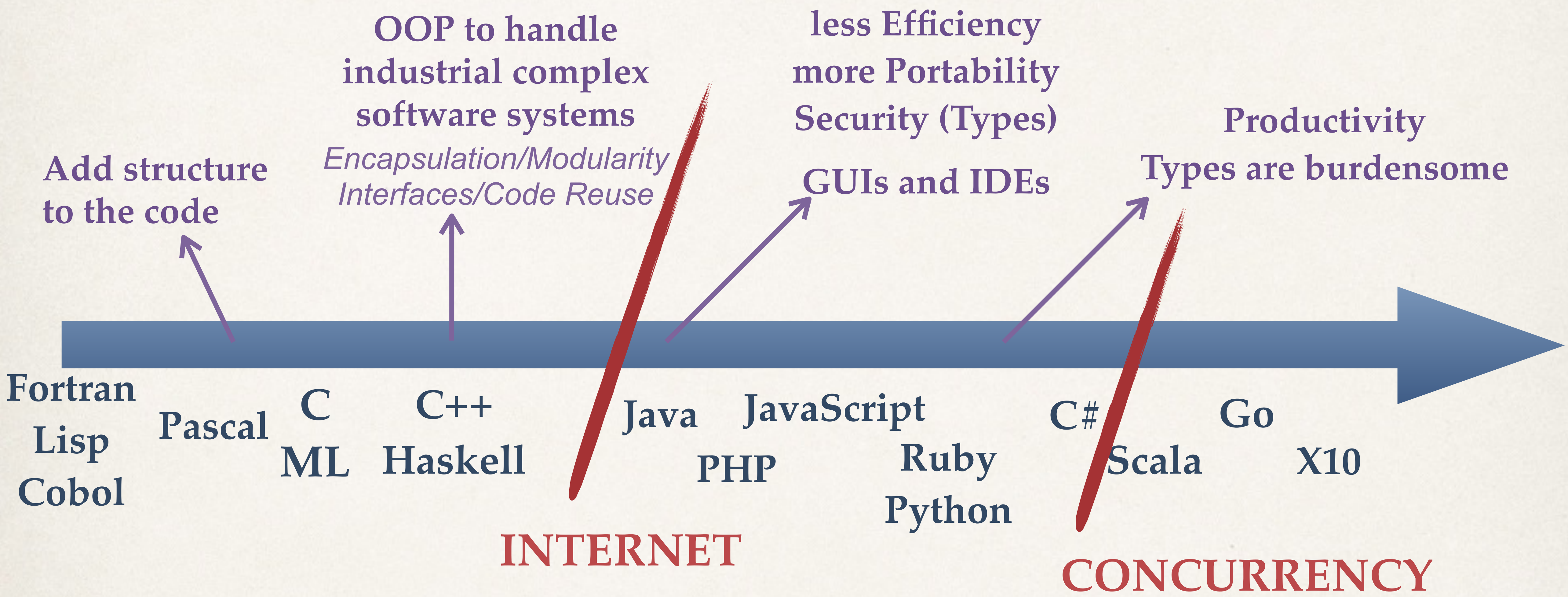

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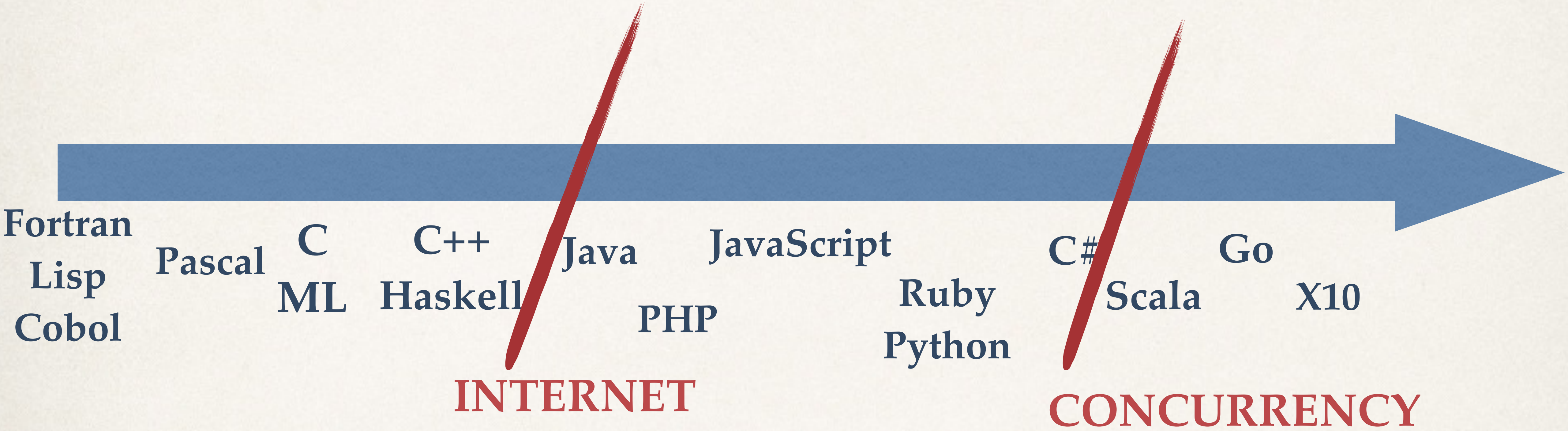
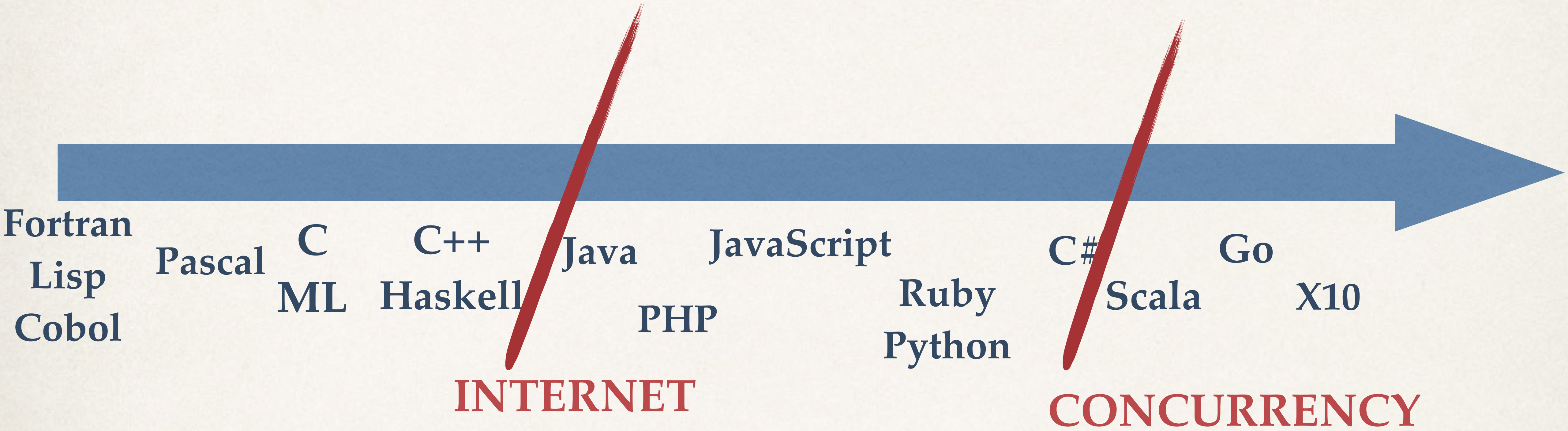


- **<u>Changes need a catalyser</u>**

The Quest for good Abstractions



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  - **new hardware can only be parallel**
  - new software must be concurrent

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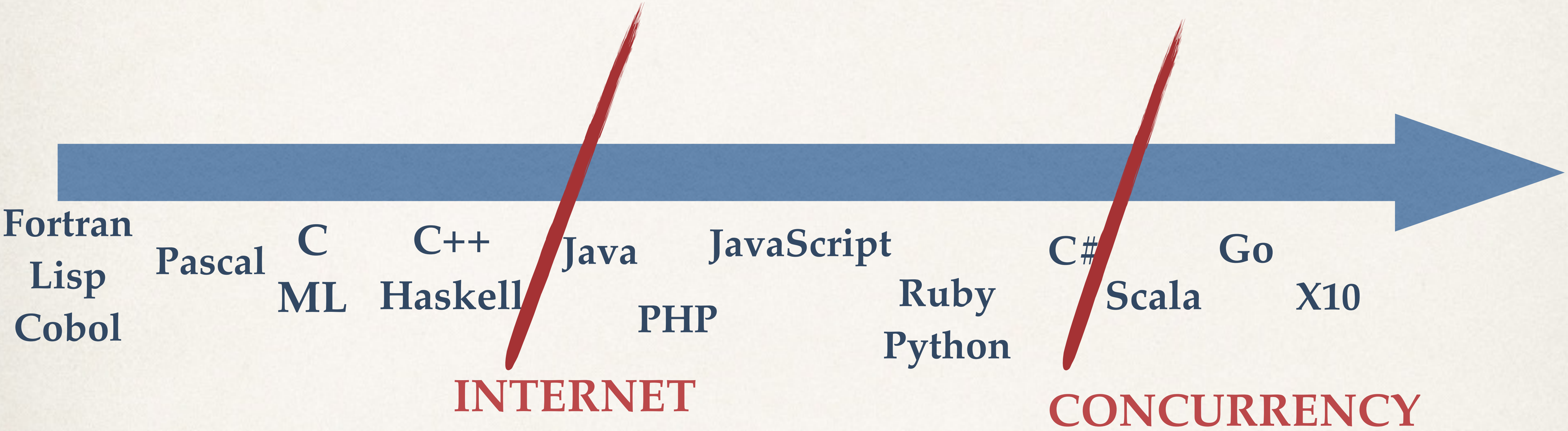

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Popular Parallel Programming Grand Challenge

How hard is Concurrent Programming?

- (correct) concurrent programming is **difficult**
- **Adding** concurrency to sequential code is even harder

Intrinsic reasons
nondeterminism

Accidental reasons
improper
programming model

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(Concurrent Algorithm)

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***Translate* into**
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DESIGN of
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High-level Concurrency Abstraction

The Quest for good Abstractions

Easy to think
Easy to reason about

↔

Expressiveness
Performance

The Quest for good Abstractions

Easy to think
Easy to reason about ⟷ **Expressiveness**
Performance

- **OOP**
  - encapsulation
  - memory management
  - multiple inheritance

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C++ —> Java —> Scala

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- **Types**
  - documentation vs verbosity

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C++ —> Java —> Ruby —>Scala

- **Functional Programming**
  - composing and passing behaviours
  - sometimes imperative style is easier to reason about

C#—> Scala C++11, Java8

The Quest for good Abstractions

Easy to think
Easy to reason about

↔

Expressiveness
Performance

- OOP

which abstractions <u>interoperate</u> productively?

- Types

- Functional Programming

The Quest for good Abstractions

Concurrency Abstractions?

Many Concurreny Models…

The Quest for good Abstractions

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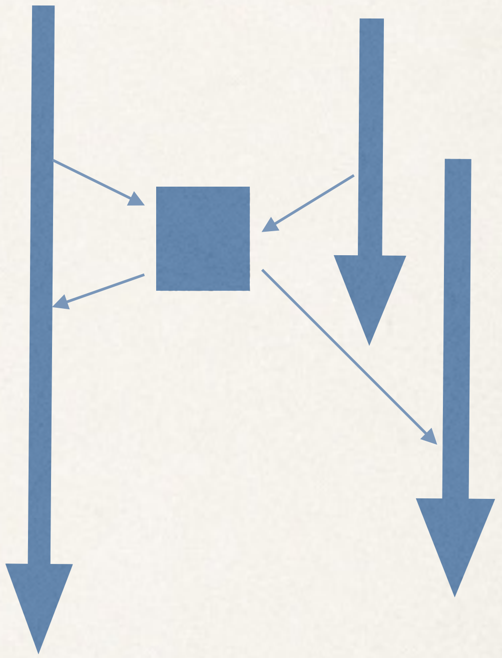


- Shared Memory Model and “Java Threads”

The Quest for good Abstractions

Concurrency Abstractions?

Many Concurreny Models…

- Shared Memory Model and "Java Threads"

Java

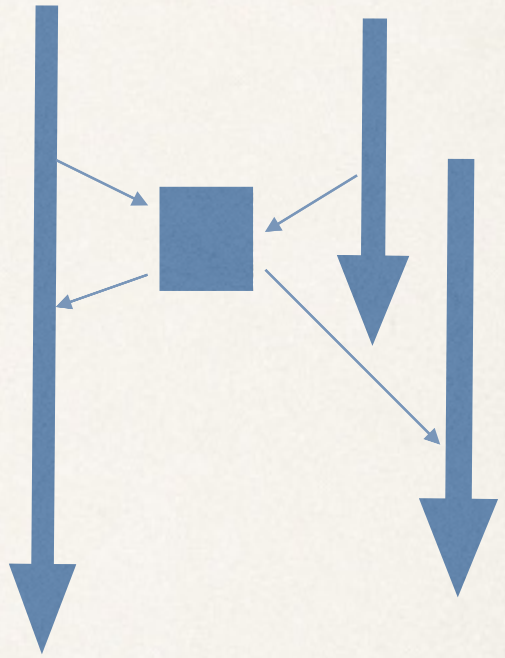
```
synchronized(lock)
lock.wait()
lock.notify()
```

STM

```
atomic {…}
when(cond){…}
```

X10

```
async{}
finish{}
```



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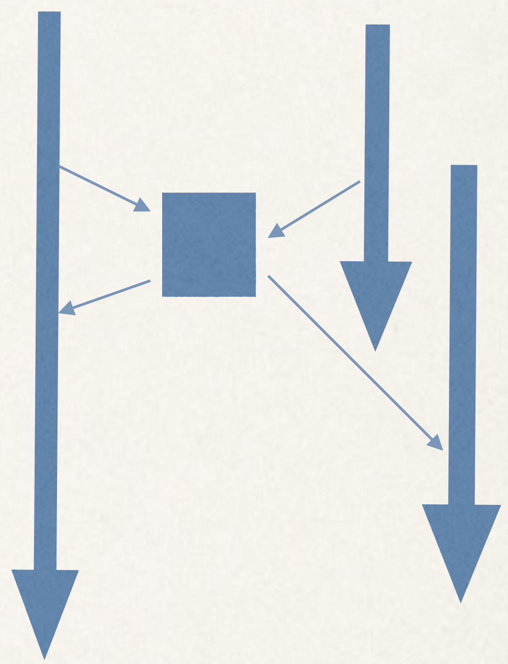

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- **logical threads** distinguished from **executors**
  (activities/tasks) (pool of thread workers)

Scalability!

The Quest for good Abstractions

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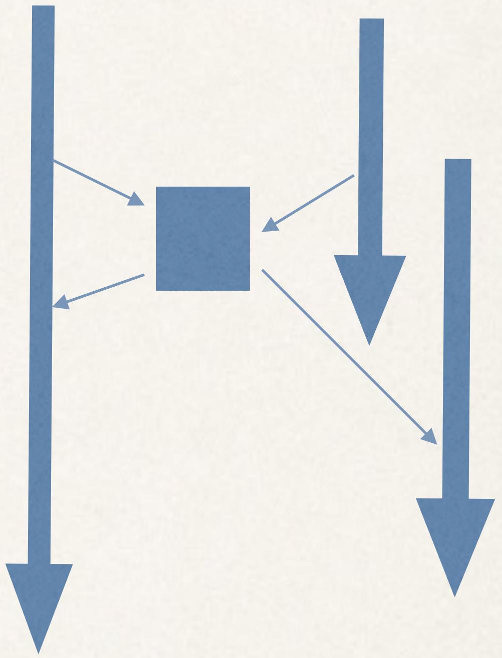

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X10

```
async{}
finish{}
```

```
new Thread().start()
```

JVM thread

Lightweight threads in the program
Pool of Executors in the runtime

Scalability!

- **logical threads** distinguished from **executors**
  (activities/tasks) (pool of thread workers)

Many Concurrency Models

- **Shared Memory**
  - is very natural for "centralised algorithms" and components operating on shared data
  - is error-prone when the sole purpose of SM is thread communication
- **Message Passing Model**
  - It is the message that carries the state!
  - **Channel based**: Google's GO
  - **Actor Model**: Erlang, Scala. It fits well both OOP and FP
  - **Sessions**
- **GPU Concurrency Model**
  - Massive data parallelism
  - integration with high-level concurrent language (X10, Nova, Scala heterogeneous compiler)

Many Concurrency Models

- Shared Memory

which abstractions <u>interoperate</u> productively?

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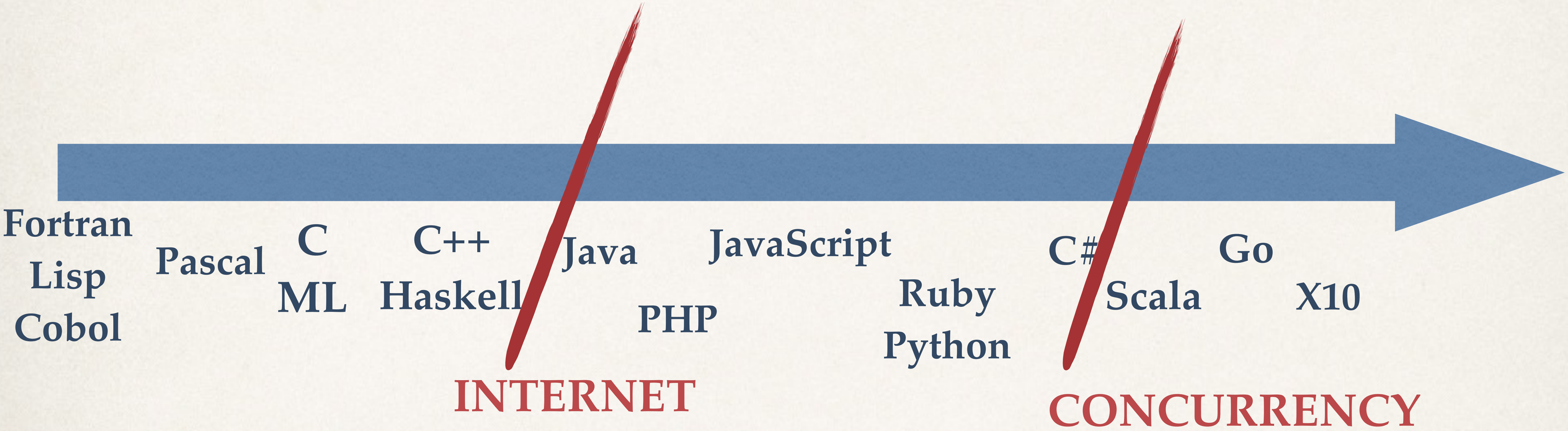
The Quest for good Abstractions



- New **catalyser**:

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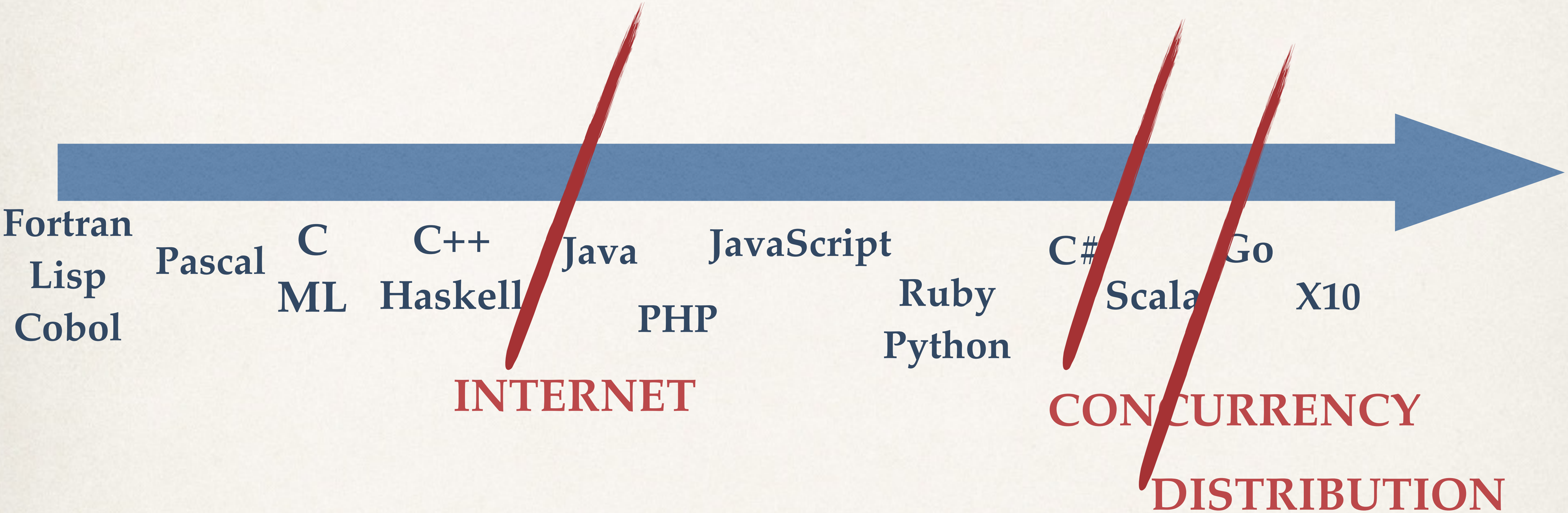

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  - **cloud computing —> distributed programming**

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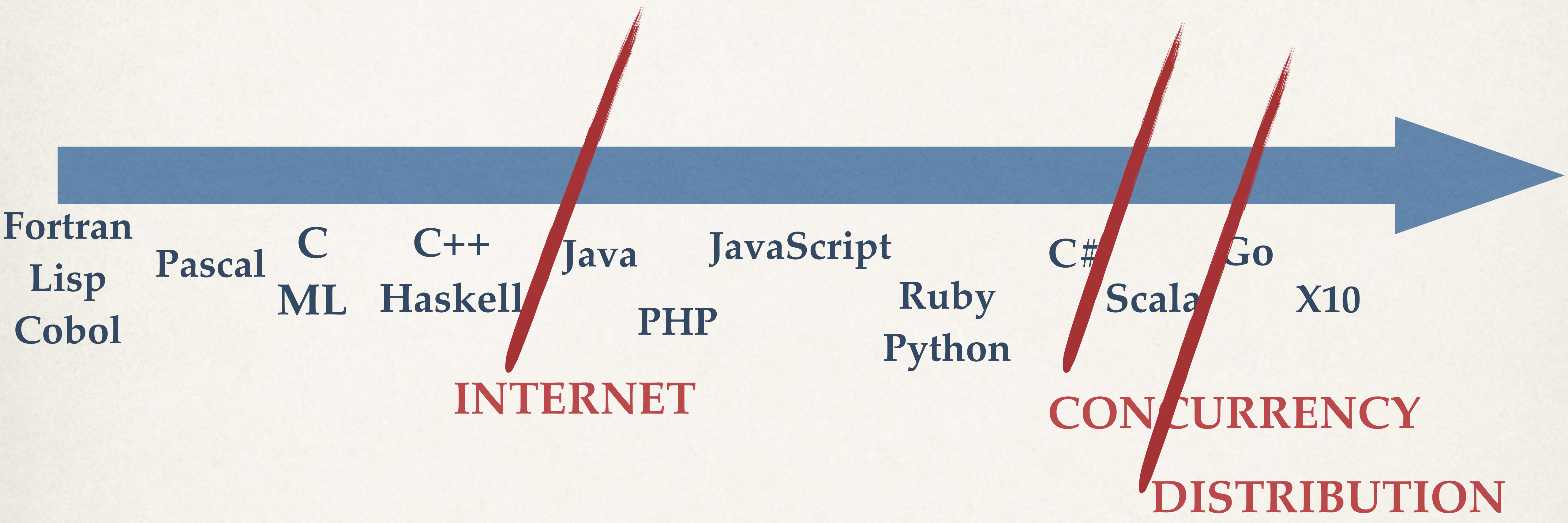

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Reactive Programming

Reactive Programming

- react to events
- react lo load
- react to failures

Reactive Programming

- react to events
  - **event - driven**
  - **asynchronous**

instead of *issuing a command that asks for a change*, *react to an event that indicates that something has changed*

- **futures**
- **push data** to consumers when available rather than polling

- react lo load

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Reactive Programming

- react to events
  - **event - driven**
  - **asynchronous**
- react lo load
  - **scalability**
    - up/down +/- CPU nodes
    - in/out +/- server
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Reactive Programming

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- react lo load
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  - **resiliency**

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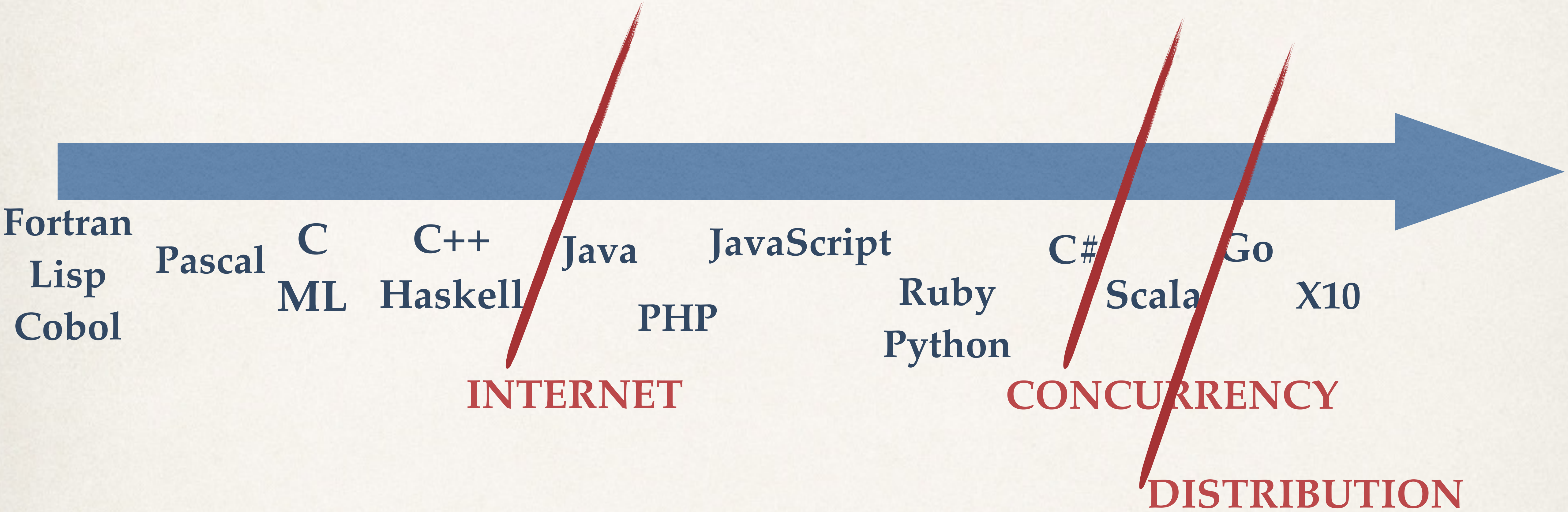

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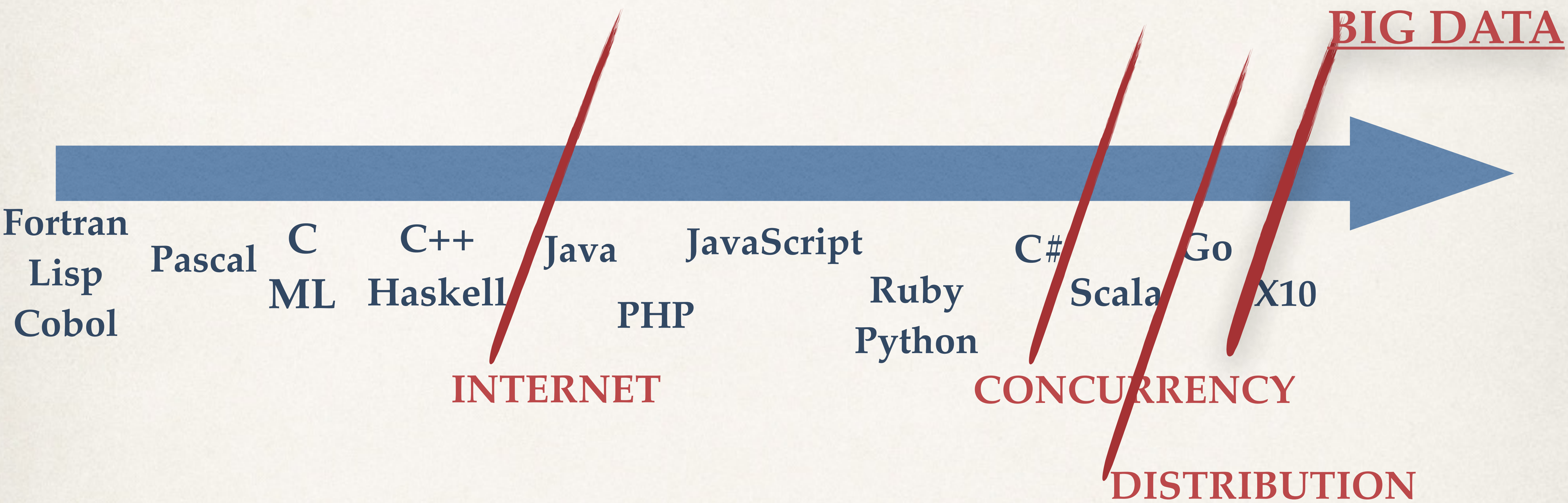

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  - multicore —> concurrent programming
  - cloud computing —> distributed programming
  - **big data application —> High Performance Computing**

High Performance Computing

- scale-out on massively parallel hardware
  - high-performance computing on supercomputers
  - analytic computations on big data
- a single program
  - runs on a collection of places on a cluster of computers
  - can create global data-structures spanning multiple places
  - can spawn tasks at remote places, detecting termination of arbitrary trees of spawned tasks

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  - **Map - Reduce Model**
  - **Bulk Synchronous Parallel Model**

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"Concurrent Patterns"
with their
distinctive abstractions

What about Theory ?

The X10 experience

IBM Research

The X10 programming language

- open-source language for HPC programming

- key design features:
  - **scaling**: code running on 100 - 10.000 multicore nodes (up to 50millions core)
  - **productivity**: high level abstractions (Java-like, Scala-like) + typing (constrained dependent types as contracts).
  - **performance on heterogeneous hardware**: it compiles to Java, to C++, to CUDA. Resilient extension
  - **concurrent abstractions**: *place-centric, asynchronous computing*

The X10 programming language

```
// double in parallel all the array elements
val a:Array[Int]= …
      for(i in 0..(a.size-1))
            async { a(i)*=2 }
println ("The End")
```

Spawns an asynchronous lightweight activity running in parallel

The X10 programming language

```
 // double in parallel all the array elements
 val a:Array[Int]= …
finish for(i in 0..(a.size-1))
          async { a(i)*=2 }
 println ("The End")
```

waits for the termination
of all the spawned activities

Spawns an asynchronous
lightweight activity
running in parallel

The X10 programming language

```
// double in parallel all the array elements
val a:Array[Int]= …
var b=0
finish for(i in 0..(a.size-1))
    async { a(i)*=2
            atomic { b=b+a(i) }
          }
println (“The End”)
```

STM `when(cond) s`

clocks

The X10 programming language

```
class HelloWholeWorld {
  public static def main(args:Rail[String]) {
    finish for (p in Place.places())
       async at(p)
          Console.OUT.println("Hello from place "+p)
    Console.OUT.println("Hello from everywhere")
}
```

The X10 programming language

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class HelloWholeWorld {
  public static def main(args:Rail[String]) {
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}
```

```
%X10_NPLACES=4
Hello from place 1
Hello from place 2
Hello from place 0
Hello from place 3
Hello from everywhere
```

The X10 programming language

```
class HelloWholeWorld {
  public static def main(args:Rail[String]) {
    finish for (p in Place.places())
      async at(p) @CUDA
        Console.OUT.println("Hello from place "+p)
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}
```

```
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Hello from place 1
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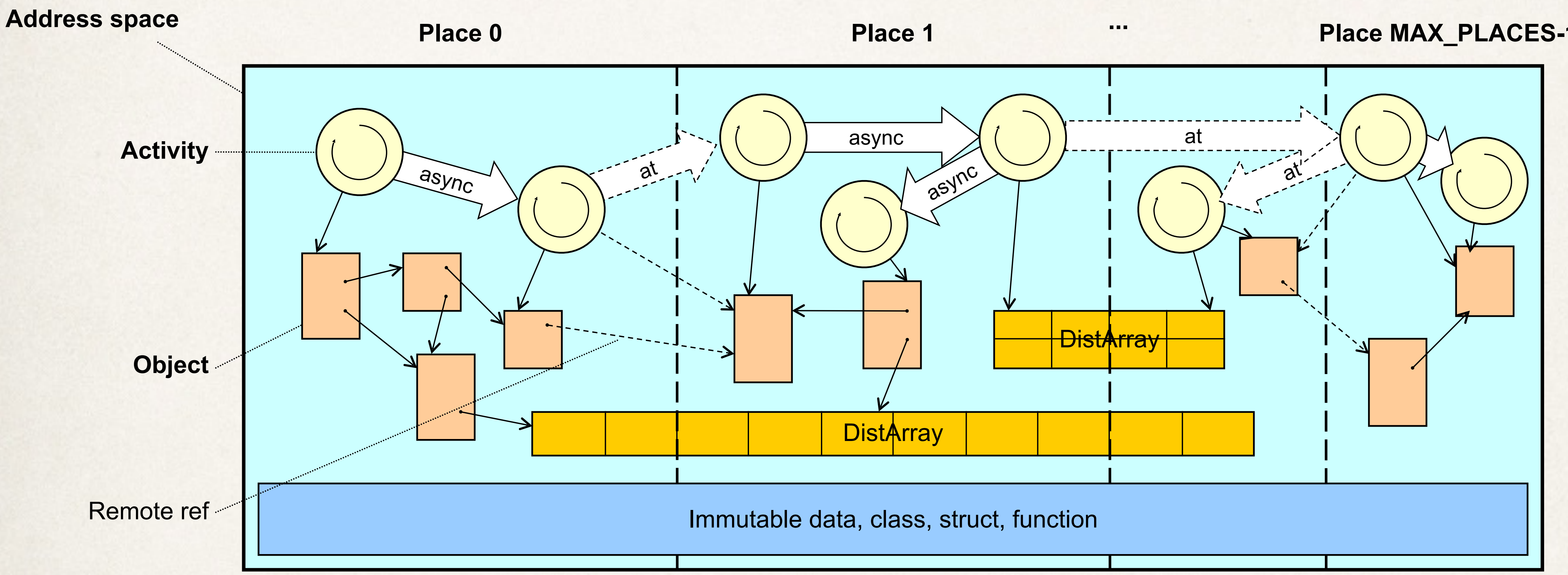
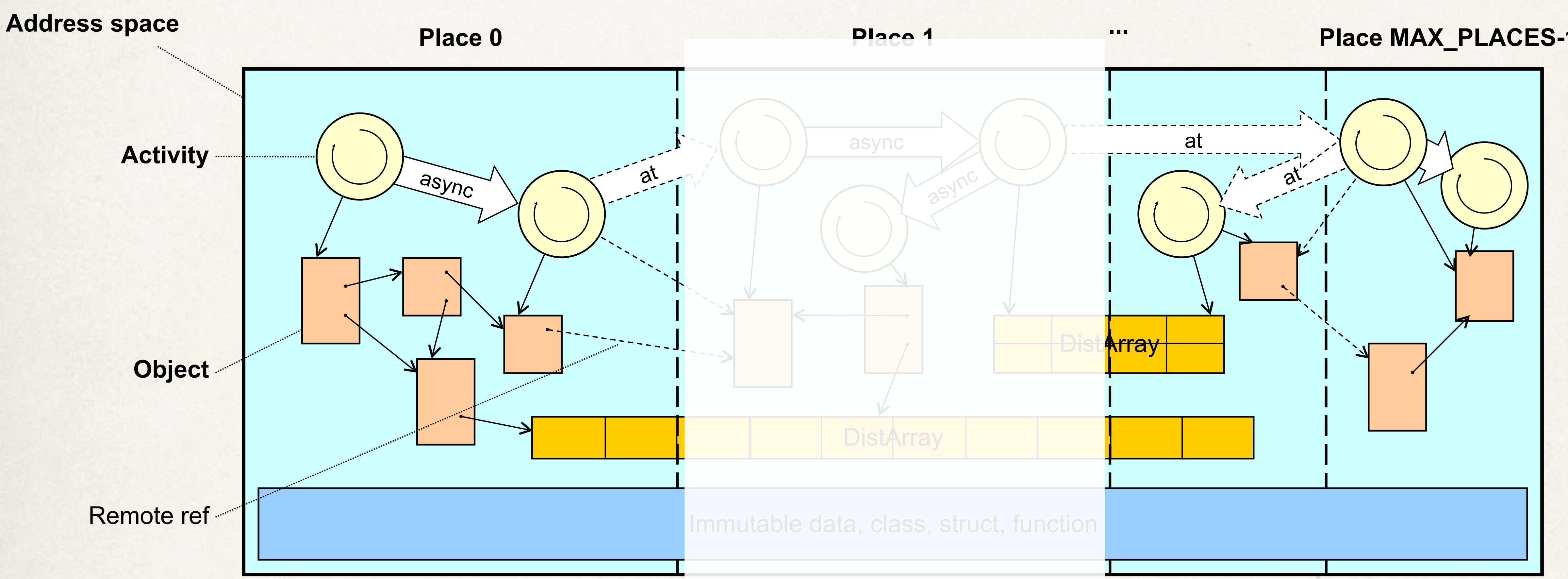
Async Partitioned Global Address Space



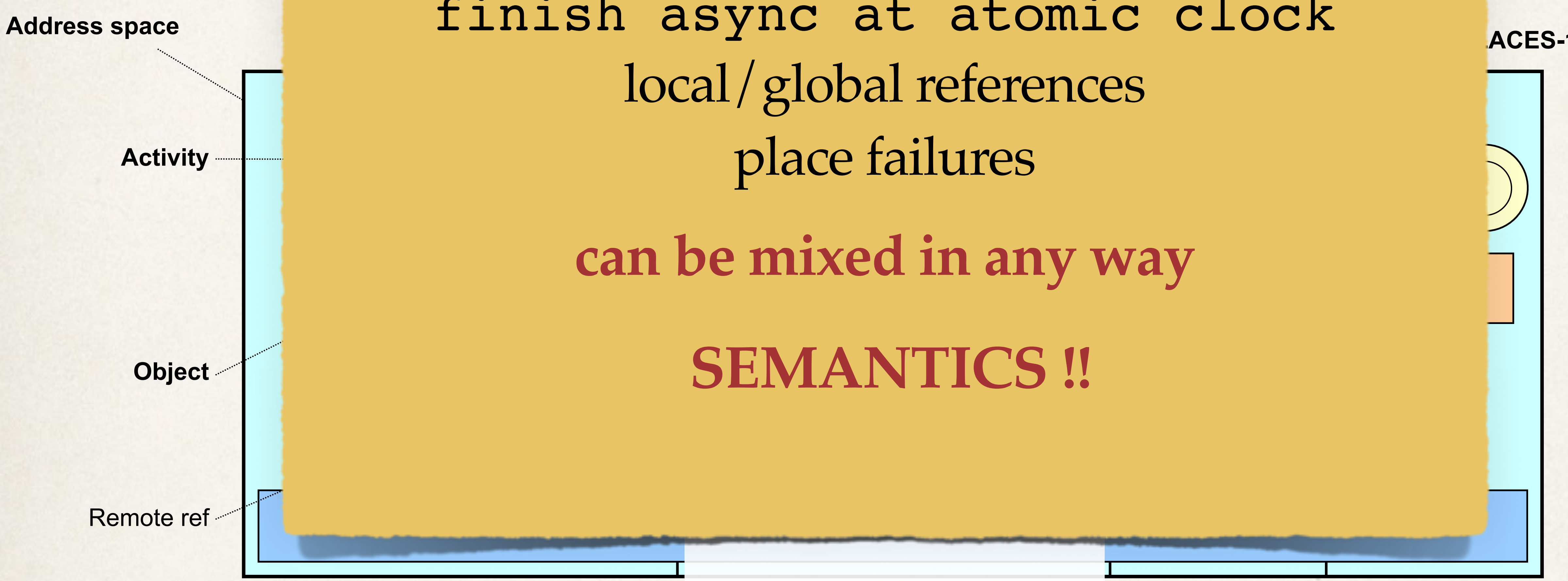
- A global address space is divided into multiple *places* (=computing nodes)
  - Each place can contain *activities* and *objects*
- An object belongs to a specific place, but can be *remotely referenced*
- **DistArray** is a data structure whose elements are scattered over multiple places

Resilient X10: if a node fails….



- it is relatively easy to **localize the impact of place death**
  - Objects in other places are still alive, but remote references become inaccessible
  - Execution continues using the remaining nodes
  - Happens Before Relation between remaining statements is preserved (HB Invariance) – no new race conditions, or sequentialization induced by failure.

Resilie



`finish async at atomic clock`

local/global references

place failures

can be mixed in any way

SEMANTICS !!

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TX10

Semantics of (Resilient) X10 [ECOOP 2014]
S.Crafa, D.Cunningham, V.Saraswat, A.Shinnar, O.Tardieu

object id → o; global object id → $o\$p$; exception → E | DPE

$$\begin{array}{llll}
\textit{Values} & v & ::= & o \mid o\$p \mid \mathsf{E} \mid \mathsf{DPE} \\
\textit{Expressions} & e & ::= & v \mid x \mid e.f \mid \{f{:}e, \ldots, f{:}e\} \mid \texttt{globalref}\ e \mid \texttt{valof}\ e \\
\textit{Statements} & s & ::= & \texttt{skip;} \mid \texttt{throw}\ v \mid \texttt{val}\ x = e\ s \mid e.f = e; \mid \{s\ \ t\} \\
 & & & \texttt{at}(p)\texttt{val}\ x = e\ \texttt{in}\ s \mid \texttt{async}\ s \mid \texttt{finish}\ s \mid \texttt{try}\ s\ \texttt{catch}\ t \\
 & & & \overline{\texttt{at}(p)\ s} \mid \overline{\texttt{async}\ s} \mid \texttt{finish}_{\mu}\ s \\
\textit{Configurations} & k & ::= & \langle s, g \rangle \mid g
\end{array}$$

error propagation and handling (→ $\texttt{try}\ s\ \texttt{catch}\ t$)

$$\textit{Global heap}\ \ g ::= \emptyset \mid g \cdot [p \mapsto h] \qquad \textit{Local heap}\ \ h ::= \emptyset \mid h \cdot [o \mapsto (\tilde{f}_i : \tilde{v}_i)]$$

Semantics of (Resilient) X10

- Small-step transition system, mechanised in Coq
- **non in ChemicalAM style** (better fits the centralised view of the distributed program)

$$\langle s, g \rangle \longrightarrow_p \langle s', g' \rangle \mid g' \qquad \langle s, g \rangle \xrightarrow{\mathsf{E}\times}_p \langle s', g' \rangle \mid g' \qquad \langle s, g \rangle \xrightarrow{\mathsf{E}\otimes}_p \langle s', g' \rangle \mid g'$$

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Async failures arise in parallel threads
and are caught by the inner `finish` waiting for their termination

```
finish {async throw E   async s2}
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Synch failures lead to the failure of any sync continuation
leaving async (remote) running code free to terminate

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Proved in Coq

Absence of stuck states

(the proof can be run, yielding an interpreter for TX10)

Semantics of Resilient X10

smoothly scales to node failure, with

- global heap is a partial map: ***dom(g)* collects non failed places**
- executing a statement at failed place results in a DPE
- place shift at failed place results in a DPE
- remote exceptions flow back at the remaining finish **masked** as DPE

contextual rules modified accordingly

(Place Failure)

$$\frac{p \in dom(g)}{\langle s, g\rangle \longrightarrow_p \langle s, g \setminus \{(p, g(p)\}\rangle}$$

$$\frac{p \notin dom(g)}{\begin{array}{r}\langle \mathtt{skip}, g\rangle \xrightarrow{\mathsf{DPE}\otimes}_p g \\ \langle \mathtt{async}\, s, g\rangle \xrightarrow{\mathsf{DPE}\otimes}_p g \\ \langle \mathtt{at}(p)\, s, g\rangle \xrightarrow{\mathsf{DPE}\otimes}_q g\end{array}}$$

Semantics of Resilient X10

- **Happens Before Invariance**
  - failure of place q does not alter the happens before relationship between statement instances at places other than q

$\overline{\texttt{at}}(0)\,\{\,\overline{\texttt{at}}(p)\ \texttt{finish}\ \overline{\texttt{at}}(q)\ \overline{\texttt{async}}\,s_1\quad s_2\}$

s2 runs at 0 <u>after</u> s1

$\overline{\texttt{at}}(0)\,\texttt{finish}\,\{\,\overline{\texttt{at}}(p)\{\overline{\texttt{at}}(q)\ \overline{\texttt{async}}\,s_1\}\quad s_2\}$

s2 runs at 0 in <u>parallel</u> with s1

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s2 runs at 0 <u>after</u> s1

p fails while s1 is running at q

$\overline{\texttt{at}}(0)\,\texttt{finish}\,\{\,\overline{\texttt{at}}(p)\{\overline{\texttt{at}}(q)\ \overline{\texttt{async}}\,s_1\}\quad s_2\}$

s2 runs at 0 in <u>parallel</u> with s1

Semantics of Resilient X10

- **Happens Before Invariance**
  - failure of place q does not alter the happens before relationship between statement instances at places other than q

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same behaviour!

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$\mathsf{DPE}\otimes$ ***flows at place 0 discarding s1***

$$\overline{\texttt{at}}(0)\,\{\,\overline{\texttt{at}}(p)\ \texttt{finish}\ \overline{\texttt{at}}(q)\ \overline{\texttt{async}}\,s_1\quad s_2\}$$

throws v

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$v\times$ ***flows at place 0 while s2 is running***

Equational theory for (Resilient) X10

$\langle s, g \rangle \;\cong\; \langle t, g \rangle$ **equivalent configurations** when

- transition steps are weakly bi-simulated
- ***under any modification of the shared heap by current activities***
  (object field update, object creation, place failure)

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$\langle s, g \rangle \; \mathcal{R} \; \langle t, g \rangle \;\; \textit{whenever}$

1. $\vdash \mathsf{isSync}\, s \;\; \textit{iff} \;\; \vdash \mathsf{isSync}\, t$
2. $\forall p, \forall \Phi \;\; \textit{environment move}$

$$\textit{if} \;\; \langle s, \Phi(g) \rangle \xrightarrow{\lambda}_p \langle s', g' \rangle \;\; \textit{then} \;\; \exists t'.\; \langle t, \Phi(g) \rangle \stackrel{\lambda}{\Longrightarrow}_p \langle t', g' \rangle$$

$$\textit{with} \;\; \langle s', g' \rangle \; \mathcal{R} \; \langle t', g' \rangle \;\; \textit{and} \;\; \textit{viceversa}$$

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models the update of g:

$$dom(\Phi(g)) = dom(g) \textit{ and}$$
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Bisimulation whose Bisimilarity is a congruence

Equational theory for (Resilient) X10

$$\{\{s \quad t\} \quad u\} \cong \{s \quad \{t \quad u\}\}$$

$$\vdash \textsf{isAsync}\ s \qquad \texttt{try}\,\{s\ t\}\,\texttt{catch}\,u \cong \{\texttt{try}\,s\,\texttt{catch}\,u \quad \texttt{try}\,t\,\texttt{catch}\,u\}$$

$$\texttt{at}(p)\{s\ t\} \not\cong_{\mathrm{R}} \{\texttt{at}(p)s \quad \texttt{at}(p)t\}$$

$$\texttt{at}(p)\texttt{at}(q)s \not\cong_{\mathrm{R}} \texttt{at}(q)s$$

$$\texttt{async at}(p)s \not\cong_{\mathrm{R}} \texttt{at}(p)\,\texttt{async}\,s$$

if s throws a sync exc. and home is failed, then l.h.s. throws a masked DPEx while r.h.s. re-throws vx since synch exc are not masked by DPE

$$\texttt{finish}\,\{s \quad t\} \cong \texttt{finish}\,s \quad \texttt{finish}\,t$$

$$\texttt{finish}\,\{s \quad \texttt{async}\,t\} \cong \texttt{finish}\,\{s \quad t\}$$

$$\texttt{finish at}(p)\,s \not\cong_{\mathrm{R}} \texttt{at}(p)\,\texttt{finish}\,s$$

Conclusions

- **Concurrecy is critical for Programming Languages**
  - heterogeneous concurrency models (Distribution)

- **What is the right level of abstraction?**
  - What are good abstractions? Expressive, flexible, easy to reason about, easy to implement in a scalable/resilient way

- **Formal method to experiment!**
  - test new primitive, *new mix* of primitives
  - tool to reason about programs

(Par Left)

$$\frac{\langle s, g\rangle \xrightarrow{\lambda}_p \langle s', g'\rangle \mid g'}{\begin{array}{ll} \lambda{=}\epsilon, v\times & \langle\{s\ \ t\}, g\rangle \xrightarrow{\lambda}_p \langle\{s'\ \ t\}, g'\rangle \mid \langle t, g'\rangle \\ \lambda = v\otimes & \langle\{s\ \ t\}, g\rangle \xrightarrow{\lambda}_p \langle s', g'\rangle \mid g' \end{array}}$$

(Par Right)

$$\frac{\vdash \mathsf{isAsync}\, t \qquad \langle s, g\rangle \xrightarrow{\lambda}_p \langle s', g'\rangle \mid g'}{\langle\{t\ \ s\}, g\rangle \xrightarrow{\lambda}_p \langle\{t\ \ s'\}, g'\rangle \mid \langle t, g'\rangle}$$

(Place Shift)

$$\frac{(v', g') = \mathsf{copy}(v, q, g)}{\langle \mathtt{at}(q)\mathtt{val}\, x = v\, \mathtt{in}\, s,\ g\rangle \longrightarrow_p \langle \overline{\mathtt{at}}(q)\{s[^{v'}/_x]\ \mathtt{skip}\}, g'\rangle}$$

(At)

$$\frac{\langle s, g\rangle \xrightarrow{\lambda}_q \langle s', g'\rangle \mid g'}{\langle \overline{\mathtt{at}}(q)\, s, g\rangle \xrightarrow{\lambda}_p \langle \overline{\mathtt{at}}(q)\, s', g'\rangle \mid g'}$$

(Spawn)

$$\frac{}{\langle \texttt{async}\, s, g\rangle \longrightarrow_p \langle \overline{\texttt{async}}\, s, g\rangle}$$

(Async)

$$\frac{\langle s, g\rangle \xrightarrow{\lambda}_p \langle s', g'\rangle \mid g'}{\begin{array}{ll} \lambda = \epsilon & \langle \overline{\texttt{async}}\, s, g\rangle \xrightarrow{\lambda}_p \langle \overline{\texttt{async}}\, s', g'\rangle \mid g' \\ \lambda{=}v\times, v\otimes & \langle \overline{\texttt{async}}\, s, g\rangle \xrightarrow{v\times}_p \langle \overline{\texttt{async}}\, s', g'\rangle \mid g' \end{array}}$$

(Finish)

$$\frac{\langle s, g\rangle \xrightarrow{\lambda}_p \langle s', g'\rangle}{\langle \texttt{finish}_\mu\, s, g\rangle \longrightarrow_p \langle \texttt{finish}_{\mu\cup\lambda}\, s', g'\rangle}$$

(End Finish)

$$\frac{\langle s, g\rangle \xrightarrow{\lambda}_p g' \quad \lambda' = \mathsf{E}\otimes \;\; \mathit{if}\, \lambda\cup\mu\neq\emptyset \;\mathit{else}\; \epsilon}{\langle \texttt{finish}_\mu\, s, g\rangle \xrightarrow{\lambda'}_p g'}$$

(Exception)

$$\frac{}{\langle \texttt{throw}\, v, g\rangle \xrightarrow{v\otimes}_p g}$$

(Try)

$$\frac{\langle s, g\rangle \xrightarrow{\lambda}_p \langle s', g'\rangle \mid g'}{\begin{array}{ll} \lambda{=}\epsilon, v\times & \langle \texttt{try}\, s\, \texttt{catch}\, t, g\rangle \xrightarrow{\lambda}_p \langle \texttt{try}\, s'\, \texttt{catch}\, t, g'\rangle \mid g' \\ \lambda{=}v\otimes & \langle \texttt{try}\, s\, \texttt{catch}\, t, g\rangle \longrightarrow_p \langle \{s' \quad t\}, g'\rangle \mid \langle t, g'\rangle \end{array}}$$

(Skip)

$$\frac{}{\langle \texttt{skip}, g\rangle \longrightarrow_p g}$$

Plus rules for expression evaluation