Programming Safe Agents in Blueprint

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Programmers are craftsmen, and, as such, they are only as productive as theirs tools allow them to be

Introduction

Agent Oriented Programming

- has been around for 20+ years
- was intended as a higher level alternative to OOP
- many regarded it as “a revolution in software”

Agent Oriented Programming

- has failed to gain wide traction
- is regarded as an experimentation tool for AI
- the community lacks focus

Blueprint

Premise: There is still place for a solution that is both high-level, yet practical

Design goals: an agent oriented programming language, focusing on concurrency, static safety, ease of use and extensibility

Defining terms

agents: computational entities that (i) have their own thread of control and can decide autonomously if and when to perform a given action; and (ii) communicate with other agents by asynchronous message passing

Defining terms

concurrency: the composition of independently executing entities

Defining terms

consistency: data consistency*, rather than logical consistency

*The ‘A’ in A.C.I.D.

Defining terms

scalability: (i) the ability of the runtime to gracefully handle a growing number of agents executing concurrently; and (ii) the ability of the language to gracefully handle growing code bases

Background and Motivation

Why another language?

Blueprint's development was motivated by my experience:

- developing the prototype of a dynamic negotiation mechanism in Jason
- teaching agent technologies to undergraduate students using JADE

Jason’s advantages

- high level
- domain oriented
- most popular AOPL

Jason’s advantages

- active community
- regularly updated
- good documentation

Jason’s disadvantages

- limited in scope
- latently typed
- exotic syntax

Jason’s disadvantages

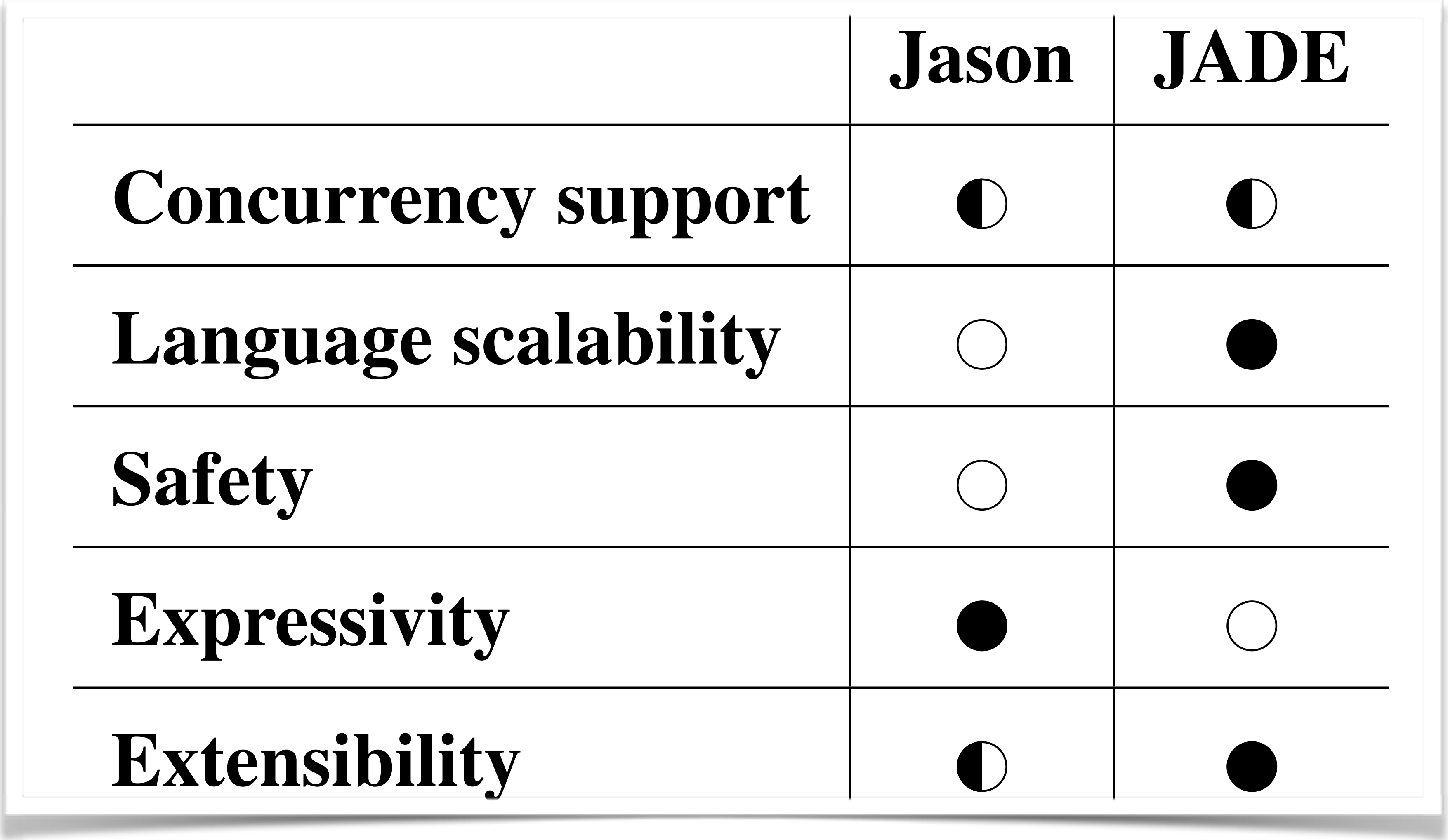
- slow interpreter
- not scalable

JADE's advantages

- manifestly typed
- scalable
- most popular agent framework

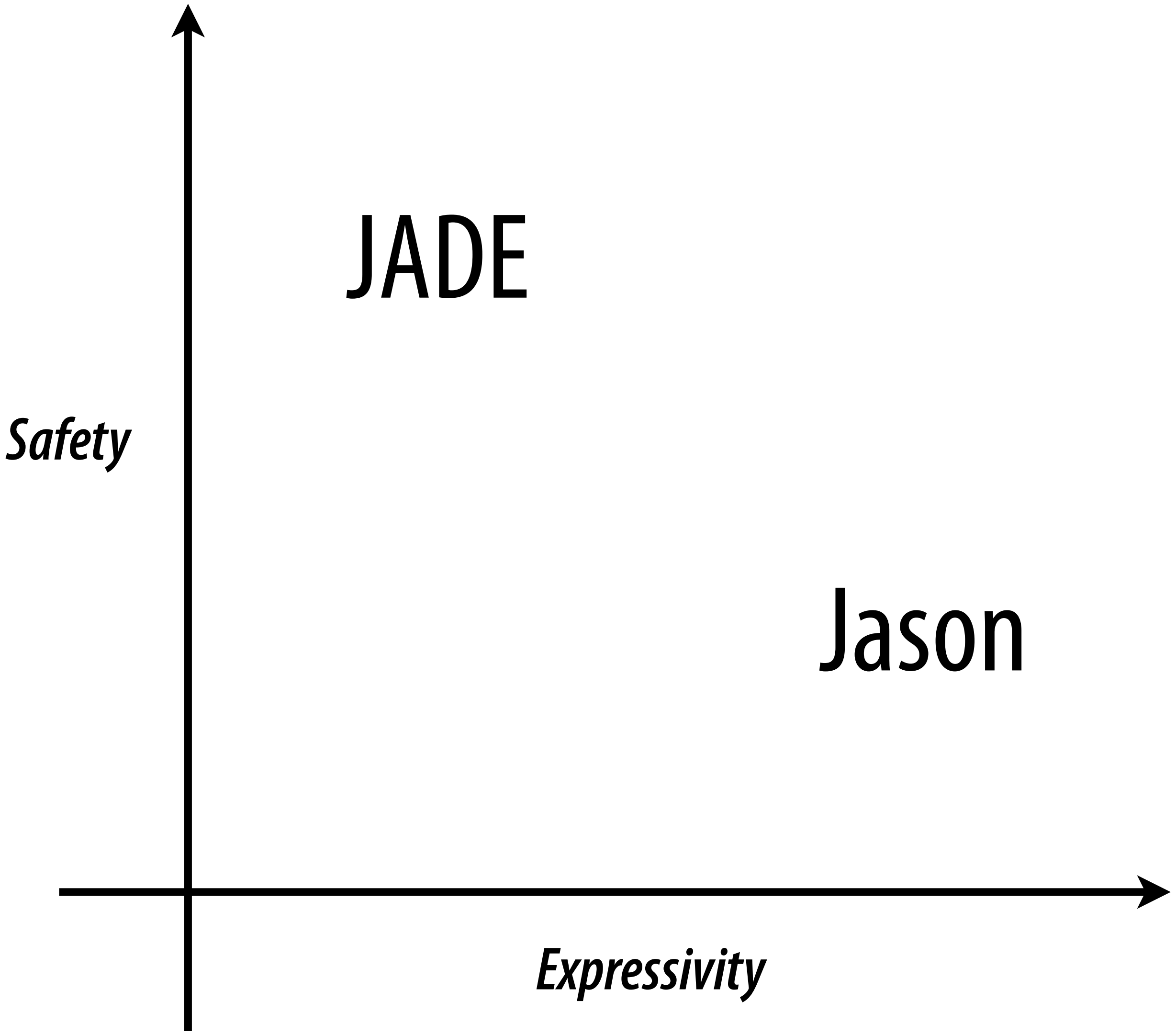
JADE's disadvantages

- lacks expressivity
- syntactic noise



	Jason	JADE
Concurrency support	◐	◐
Language scalability	○	●
Safety	○	●
Expressivity	●	○
Extensibility	◐	●

Comparing Jason and JADE

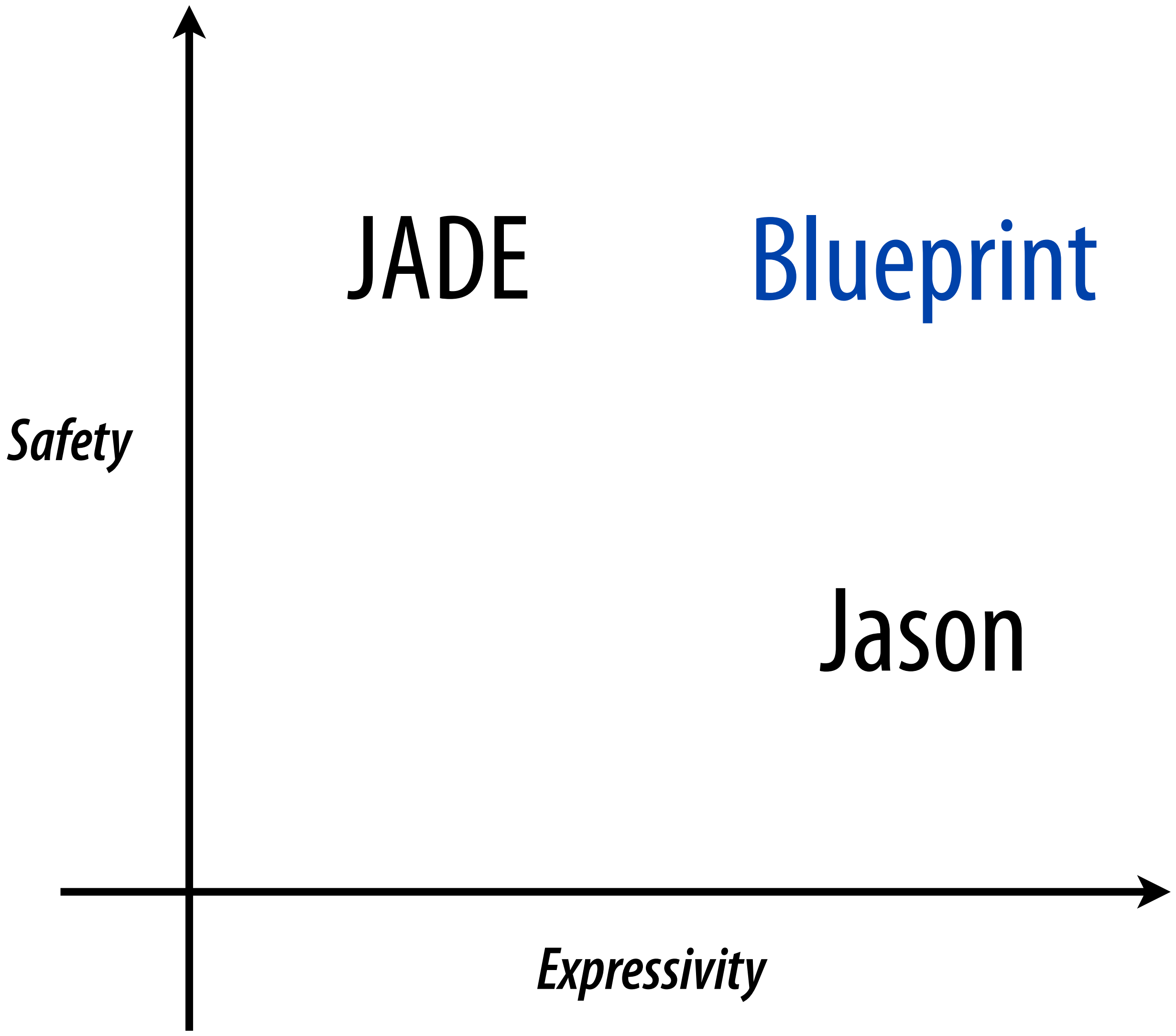


JADE

Safety

Jason

Expressivity



JADE

Blueprint

Safety

Jason

Expressivity

Monadic Foundations for Concurrent Agents

Monads

- originated in category theory
- structures that represent computation
- usually composed of a *type constructor* and *two operations*

Why monads?

- F#'s computation expressions are syntactic sugar for monads
- they are an elegant way of expressing the composition of concurrent computations
- they have been thoroughly studied

A closer look at concurrent computations

- they start *now* and they will finish sometime *in the future*
- we need to react when a concurrent computation ends
- we need to combine concurrently running computations

A closer look at concurrent computations

- the reaction to the completion of a concurrent computation is its *continuation*
- look at plans as being split in two: the *actions ran thus far* and the *actions that are still to be executed*
- a *promise* that a set of actions will get executed at some point
- this hints at a way of composing plans

The *Promise* monad

A promise for a value of type α is a function which receives a handler that can be called with the value of the promise, and it produces a value of type β. The *type constructor* for the Promise monad, $M_{promise}$, is defined as:

$$M_{promise} = (\alpha \to \beta) \to \beta$$

The *Promise* monad

The *unit operation* takes a value and returns a promise that will pass the value as an argument to the promise's handler:

$$unit_{promise} = \lambda x.\ \lambda k.\ k\ x$$

The *Promise* monad

The *bind operation* takes a promise and a continuation of the promise, and returns a promise that will invoke the continuation in a context where the result of the promise is available:

$$bind_{promise} = \lambda m.\, \lambda k.\, \lambda c.\, \boldsymbol{run}\; m\; (\lambda x.\, \boldsymbol{run}\; (k\; x)\; c)$$

where **run** is a function that executes a promise with the given callback

Conclusions

- the *Promise* monad is actually the well known *CPS* monad
- we can use monads to structure concurrent plans
- we can employ the same strategy as F#: use monads internally and perform code rewrite

The Blueprint Language

Blueprint is meant to be

- high level (e.g. agents, plans)
- safe (e.g. static types, channel protocols)
- easy to learn (e.g. C-like syntax)
- easy to use for concurrent applications

From revolution to evolution

- take a step back and look at agents as an evolution of the OOP and the Actors model
- *concurrently* executing agents with *reactive* behaviours
- respects Shoham's definition of AOP as a specialisation of OOP in the sense of the Actor model

The road to Blueprint

- agents are reactive and autonomous entities
- send messages asynchronously to mitigate deadlocks
- react to incoming events serially in order to avoid race conditions
- use monads to structure compose computations

Communication channels

- agents use *bidirectional* and *asymmetric* channels to exchange messages
- messages sends are asynchronous (i.e. non-blocking), while receives are synchronous (i.e. blocking)
- preserve message ordering
- they belong to exactly one agent
- they are introduced by the **chan** keyword

Channel endpoints

- an *exporting* endpoint, and an *importing* endpoint
- the exporting endpoint is used by the owner of the channel, while the importing endpoint can be handed off to other agents
- each endpoint has an *ordered*, *unbounded* message queue
- channel endpoints are first order entities (i.e. they can be passed as arguments and returned as values)

```
agent Account(init: int, impChan: BankAccount.Imp) {
    chan c = BankAccount.make()
    bel balance = init

    plan Start() {
        val msg = <-c.Exp.operation;
        match msg {
            case deposit(amount):
                val currentBalance = balance.take()
                balance.put(currentBalance + amount)
            case withdraw(amount):
                val currentBalance = balance.take()
                balance.put(currentBalance - amount)
            case transferTo(acc, amount):
                acc <- deposit(amount);
                val currentBalance = balance.take()
                balance.put(currentBalance - amount)
        }
    }
}
```

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                acc <- deposit(amount);
                val currentBalance = balance.take()
                balance.put(currentBalance - amount)
        }
    }
}
```

Channel protocols

- declarative mechanisms of enforcing proper message exchange between agents
- specify the flow of the data between the communicating entities (i.e. the order, and direction in which messages are sent)
- introduced by the **`proto`** keyword

```
proto ThreadProto {
    start: in nextChan(next: ThreadProto.Imp@loop) >> loop
    loop: in token(value: Token) >> loop or end
}
```

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Channel protocols

- protocols are designed from the perspective of the agent initiating the interaction (i.e. the exporting endpoint)
- there is no need to specify the dual protocol since it can be automatically derived by swapping direction specifiers

Concurrency and beliefs

- channels and protocols are a good way to control inter-agent concurrency
- we need a way to control intra-agent concurrency as well
- use *synchronised mutable variables* (mvars)

mvars

- *one-place buffers* which can be in one of the two states: *empty* or *full*
- two basic operations: *take*, and *put*
- calling take on a full mvar immediately returns the value and marks the mvar as empty
- If a take call is issued on an empty mvar, the calling thread of execution is blocked until the mvar becomes full
- the semantics of the put operations are similar

mvars

- the locks are not directly manipulated by the programmer, instead this is the job of the underlying implementation
- given the relatively low level, blocking nature of mvars (when compared to message passing), the risk of deadlock is still present

Beliefs as mvars

- Blueprint implements all beliefs as mvars
- beliefs are introduced by the **`bel`** keyword
- beliefs have two methods: take() and put()

Formal model sketch

- the semantics is defined via a CPS transform to a core language
- the core language is a small functional language

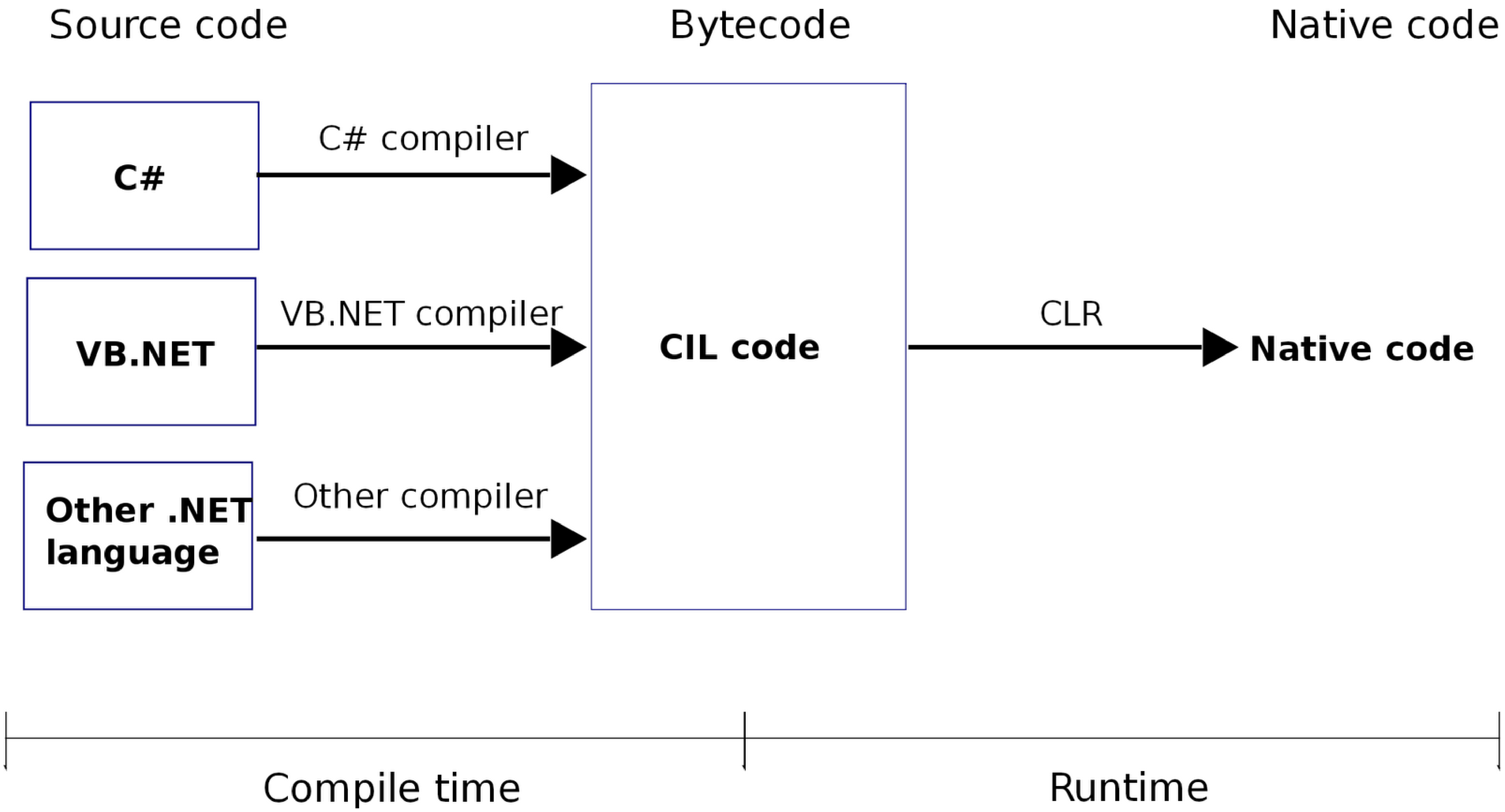
Proto π	::=	$\texttt{proto}\, id\ \{\sigma_0 \ldots \sigma_n\}$	Protocol definition
State σ	::=	$id : \overline{\mu} \gg \overline{id}$	Protocol state
MsgFlowExp $\overline{\mu}$	::=	$\mu_0 \rightarrow \ldots \rightarrow \mu_n$	Message flow expression
MsgExp μ	::=	$\texttt{in}\, id(id_0 \ldots id_n)$	Message receive expression
TargetStates $\overline{\sigma}$	::=	$id_0\ \texttt{or}\ \ldots\ \texttt{or}\ id_n$	Target states
	::=	$\texttt{out}\, id(id_0 \ldots id_n)$	Message send expression
Plan p	::=	$\texttt{plan}\, id(p_0 \ldots p_n)\ \{e\}$	Plan definition
Meth m	::=	$\texttt{def}\, id(p_0 \ldots p_n)\ \{e\}$	Method definition
Stmt s	::=	$\texttt{val}\, id = e$	Value binding
	::=	$\texttt{var}\, id = e$	Variable binding
	::=	$e_0; \ldots ; e_n$	Sequence
Exp e	::=	n	Numeral
		$true$	Boolean literal
		$false$	Boolean literal
		$''s''$	Literal
		id	Reference
		$e.id$	Field reference
		$e[i]$	Array element reference
		$e_1\ op\ e_2$	Binary operator
		$e(e_0 \ldots e_n)$	Function call
		$\leftarrow e$	Channel receive
		$e_1 \leftarrow e_2$	Channel send
		$e_1 := e_2$	Assignment
		ϵ	Empty expression

$$
\begin{aligned}
\llbracket \texttt{plan}\, id\, (p_0 \ldots p_n)\ \texttt{\{}\ e\ \texttt{\}} \rrbracket &\equiv \texttt{let}\, id = \lambda\, (p_0 \ldots p_n)\ .\ \lambda\, \kappa\ .\ \llbracket e \rrbracket \\
\llbracket e_{plan}() \rrbracket &\equiv \lambda\, \kappa\ .\ \texttt{\textbf{asyncstart}}\ (e); \kappa() \\
\llbracket e_1; e_2 \rrbracket &\equiv \lambda\, \kappa\ .\ \llbracket e_1 \rrbracket (\lambda\, ()\ .\ \llbracket e_2 \rrbracket\ \kappa) \\
\llbracket a \rrbracket &\equiv \lambda\, \kappa\ .\ a; \kappa() \\
\llbracket id := take(e) \rrbracket &\equiv \lambda\, \kappa\ .\ \texttt{\textbf{suspend}}\ (e, \lambda\, ()\ .\ set(id, take(e)); \kappa()) \\
\llbracket put(id, e) \rrbracket &\equiv \lambda\, \kappa\ .\ put(id, e); \texttt{\textbf{signal}}\ (id); \kappa() \\
\llbracket id := recv(e) \rrbracket &\equiv \lambda\, \kappa\ .\ \texttt{\textbf{suspend}}\ (id, \lambda\, ()\ .\ set(id, take(id)); \kappa())
\end{aligned}
$$

$$
\begin{array}{lrcll}
\textsc{Step}: & (\{e\} \cup A, Q, P) & \rightsquigarrow & (\{e'\} \cup A, Q, P) & , \ if \ e \mapsto e' \\
\textsc{Suspend}: & (\{ \ \texttt{\textbf{suspend}} \ (id, e)\} \cup A, Q, P) & \rightsquigarrow & (A, Q, P \cup \{id \rightarrow e\}) & \\
\textsc{Schedule}: & (A, \{e\} \cup Q, P) & \rightsquigarrow & (A \cup \{e\}, Q, P) & \\
\textsc{Signal}: & (\{ \ \texttt{\textbf{signal}} \ (id)\} \cup A, Q, P \cup \{id \rightarrow e\}) & \rightsquigarrow & (A, Q \cup \{e\}, P) & \\
\textsc{Async-Start}: & (\{ \ \texttt{\textbf{asyncstart}} \ (e)\} \cup A, Q, P) & \rightsquigarrow & (A, Q \cup \{e\}, P) &
\end{array}
$$

Implementation considerations

- Blueprint is built on top of the CLR framework
- The CLR contains a performant *Virtual Machine* with a *Just In-time Compiler* and a *Garbage Collector*
- we use the thread-pool pattern for scheduling agent reactions to incoming messages



Source code

Bytecode

Native code

C#

C# compiler

VB.NET

VB.NET compiler

Other .NET language

Other compiler

CIL code

CLR

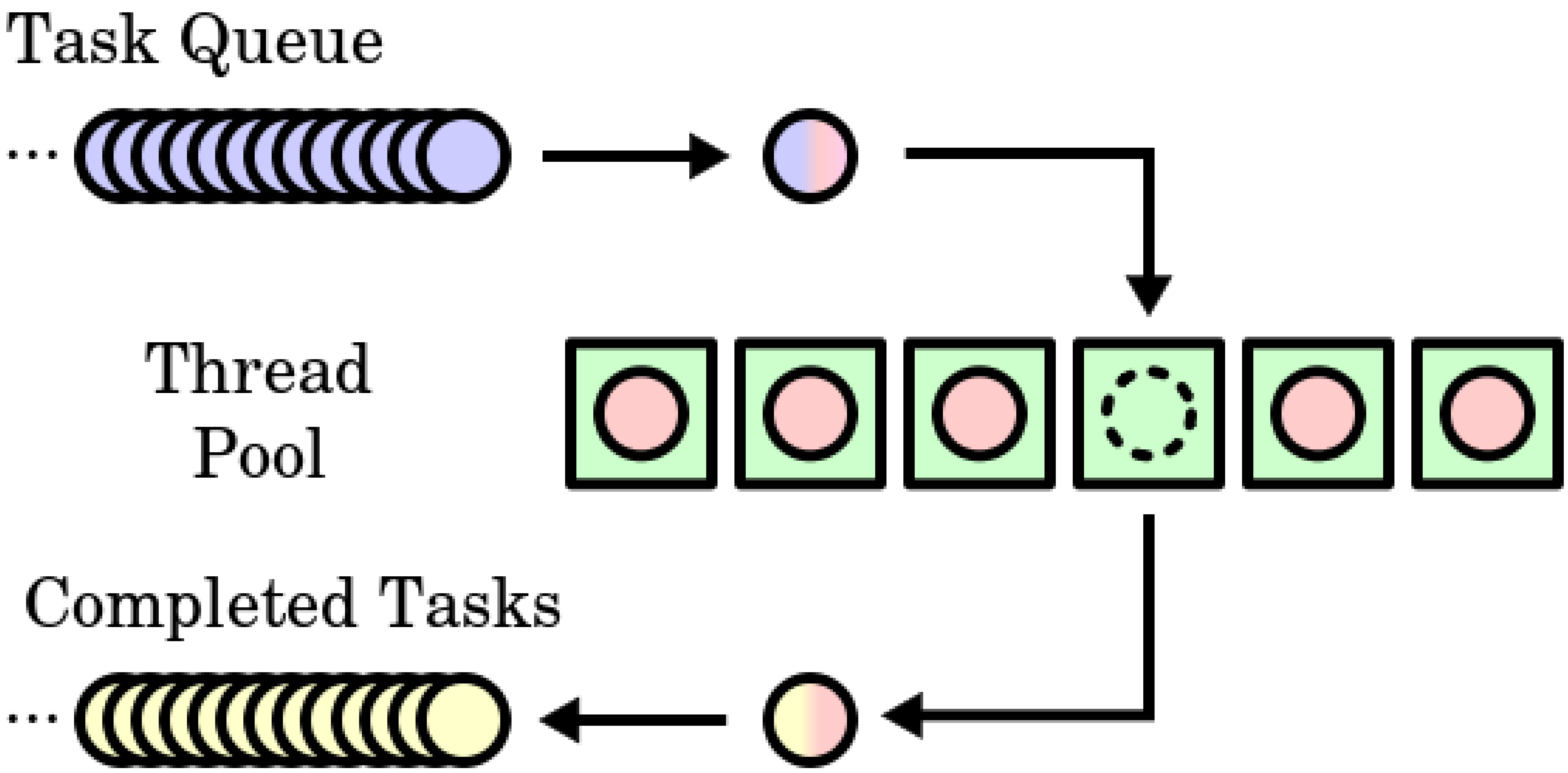
Native code

Compile time

Runtime

The thread-pool pattern

- a model where a (possibly fixed) number of threads—called worker threads—is created in order to execute waiting tasks—usually stored in a queue
- a worker thread requests the next pending task, and if one is available it runs it to completion
- the thread may sleep or it may request another task once the current task has finished


Task Queue
...
Thread
Pool
Completed Tasks
...

The thread-pool pattern

- it scales well for I/O-bound tasks
- the performance degrades when it has a lot of CPU-bound tasks

Future Directions

- investigate *code reuse* (most probably via some form of inheritance of prototypic delegation)
- investigate an extension of the concurrency model, based on the *Join calculus*
- give a full formal account of the language

- define a mechanism similar to channel protocols to characterise agent *environments*
- further investigate the object capability model in the context of security in AOP
- develop a JVM backend for Blueprint
- develop tooling for the language (i.e. plugins for popular IDEs)

Thank you. Questions?