Choreographic Programming of Adaptive Applications

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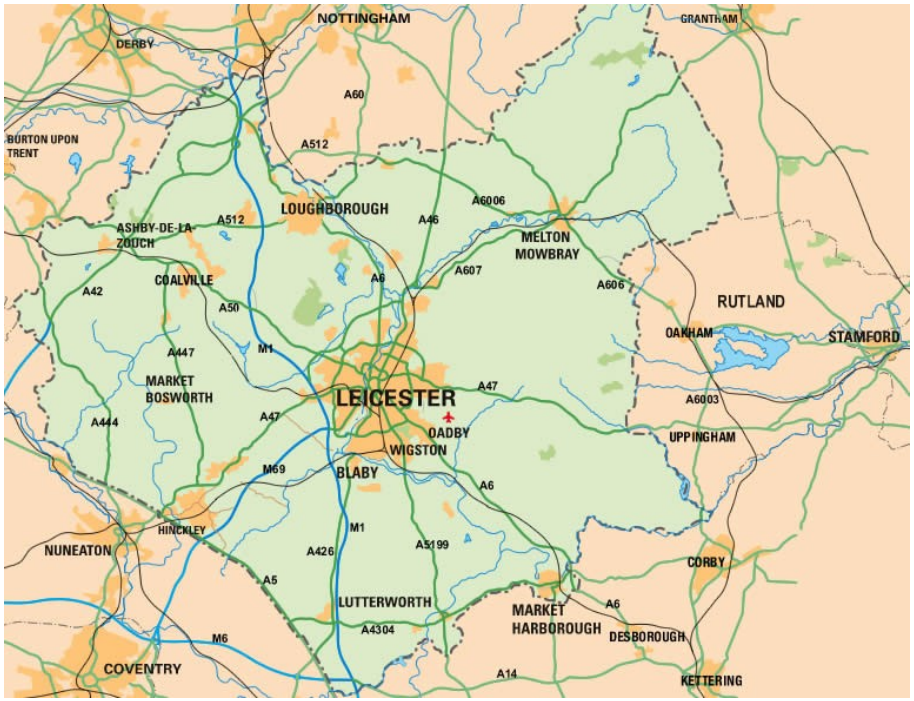
BEHAPI
Behavioural Application Program Interfaces

Map of the course

- Choreographic programming
- Choreographic programming in the real world
- Dynamic updates
- Dynamic updates in the real world
- Conclusion



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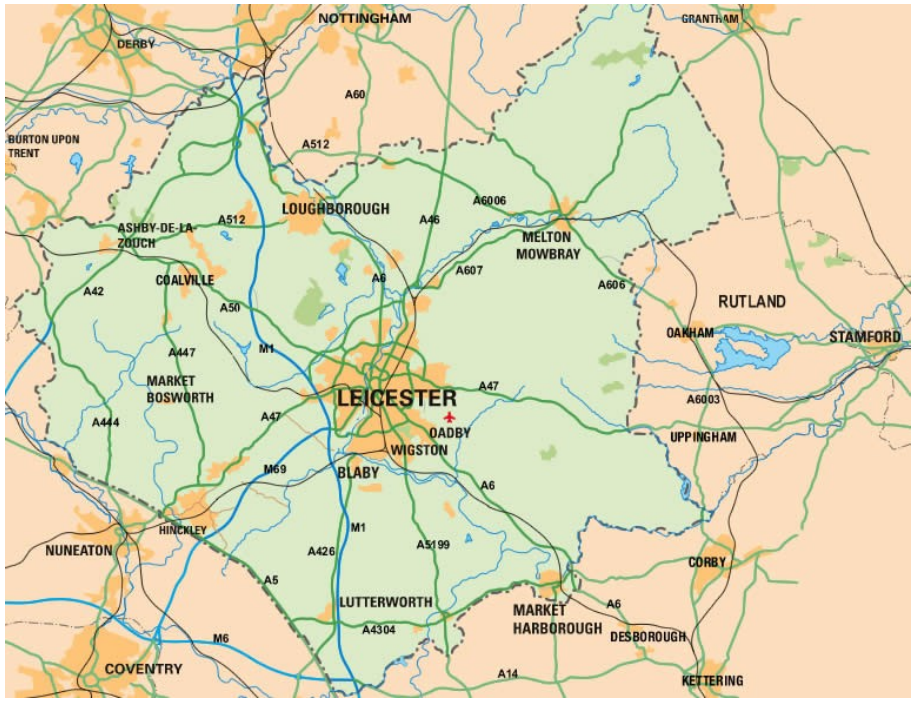

Programming distributed applications

- Distributed applications are composed by many nodes
- Each node executes a program, possibly different from the ones executing on the other nodes
- The nodes interact by exchanging messages
  - Main primitives: send and receive of a message
- The same in message-based concurrent applications
- Distributed applications are everywhere
  - Facebook, google, expedia, …
  - Banking applications, online shops, ...

Distributed programming: pitfalls

- Programming distributed applications is difficult and error-prone
- One has to reason about multiple threads of computation, and on their possible interleavings and interactions
- There can be specific errors due to concurrency
- Deadlocks: a process waits for a message that will never arrive
- Orphan messages: a message is sent to a target not expecting it
- Races: two messages are expected in a given order, but may arrive in a different one

Choreographic programming: aim

- Choreographic programming aims at avoiding these pitfalls
- Pitfalls due to a mismatch between send and receive
- Solution: send and receive cannot be written in isolation, but only composed inside an interaction
- An interaction is a communication between two participants:

$$\text{op: alice}(z+5) \rightarrow \text{bob}(x)$$

Choreographic programming: what it is?

- A programming paradigm for message-based concurrent/distributed applications
- Describing the whole distributed application as a unique program
- The term choreographic programming appeared first in: Fabrizio Montesi: Kickstarting Choreographic Programming. WS-FM 2015: 3-10
- A few approaches existed also before, e.g.: Ivan Lanese, Claudio Guidi, Fabrizio Montesi, Gianluigi Zavattaro: Bridging the Gap between Interaction- and Process-Oriented Choreographies. SEFM 2008: 323-332

Choreographic programming: basics

- A single interaction needs to be executed by two participants
  - Not just one as for standard programming language constructs
- This forces a single choreographic program to describe multiple participants
- A choreographic program is built by composing interactions using standard constructs: sequences, conditionals, loops,...
- Each construct may describe the behavior of one, two, or more participants

Relation with multiparty session types

- Choreographic programming and multiparty session types have commonalities and differences
  - Similar aim: avoid communication errors in message-passing programs
  - Similar idea: use interactions as building block
  - Different level: programming language vs type system
  - Similar technicalities
    - choreographic programs ≈ global types + data + conditions

Relation with multiparty session types (2)

- Choreographic programming and multiparty session types have different advantages and disadvantages

Choreographic programming	Multiparty session types
Used to write programs	Used to check programs
Requires a dedicated language	Can be applied to existing languages and programs
You only need to think about programs	You need to think about both programs and types

- Choreographic programming also allows for some more flexibility

Choreographic syntax

- C ::= o: s(e) → r(x) — interaction
  - | x@r = e — assignment
  - | skip — do nothing
  - | C ; C’ — sequence
  - | C | C’ — parallel
  - | if b@r {C} else {C’} — conditional
  - | while b@r {C} — loop

- Notation: o for operations, s,r for roles, e for expressions, b for Boolean expressions, x for variables
- The @ symbol specifies which role takes some action
- Key feature: a single construct may involve multiple roles

Execution model

- Each participant corresponds to an executable program
- Participants can be deployed in the same or in different machines
  - In our examples they are deployed in the same machine for simplicity
- Each participant has its own state (no global state)
- Interactions occur only by exchanging messages
- Communication is synchronous
  - Asynchronous communication is doable, but requires some more work

A sample choreographic program

product_name@client = getInput("Insert product name");

quote: client(product_name) → seller(sel_product);

price@seller = getInput("Quote " + sel_product)

Choreographic programming advantages

- Unique description of the whole distributed system ⇒
  Clear view of the global behavior
- The global description is a program ⇒
  Automatic compilation into a distributed application
- Sends and receives are paired into interactions ⇒
  No deadlocks, orphan messages nor races by construction

How to execute choreographic programs?

- A choreographic program describes the behavior of many participants
- We want to compile the choreographic program generating multiple executable programs, one for each participant
- When executed, the derived local programs should interact as specified in the choreographic program
  - Correctness of the compilation
  - No deadlocks, orphan messages nor races
- Compilation is quite tricky
- We give an high-level description of compilation as a projection function
  - cfr. endpoint projection in multiparty session types

The target language

- P ::= o: send e to r — message send
  - | o: receive x from r — message receive
  - | x = e — assignment
  - | skip — do nothing
  - | P ; P’ — sequence
  - | P | P’ — parallel
  - | if b {P} else {P’} — conditional
  - | while b {P} — loop

- A distributed program is composed by multiple named participants r_i each executing its own program P_i

Projection: basic idea

- Projection takes a choreographic program and a role r and produces the local program of r
- An interaction o: s(e) → r(x) is projected as
  - o: send e to r on s
  - o: receive x from s on r
  - skip on all the other participants
- Assignments x@r = e are executed by the role r
- Other constructs are projected homomorphically

- Very simple…
- …but it does not work

Projection problems: sequentiality

- Actions of different participants are independent

  $o_1: s_1(5) \rightarrow r_1(x)$; $o_2: s_2(7) \rightarrow r_2(y)$

- Interaction on o_2 should happen after interaction on o_1
  - No participant can force this
  - (Some approaches treat this as hidden parallel)
- No such problem in

  $o_1: s_1(5) \rightarrow r_1(x)$; $o_2: r_1(7) \rightarrow r_2(y)$

  $o_1: s_1(5) \rightarrow r_1(x)$; $o_2: s_1(7) \rightarrow r_2(y)$

  $o_1: s_1(5) \rightarrow r_1(x)$; $o_3: r_1(\text{“go”}) \rightarrow s_2(\text{aux})$; $o_2: s_2(7) \rightarrow r_2(y)$

Projection problems: choices (and loops)

- The behavior of a participant may depend on the decision of another participant
  if $b@s_1$ $\{o: s_2(5) \rightarrow r(x)\}$ else $\{o: s_2(7) \rightarrow r(x)\}$
- Participant s_2 should send 5 or 7 according to a local decision of s_1
- Similar problem in
  while $b@s_1$ $\{o: s_2(5) \rightarrow r(x)\}$
- s_2 and r do not know whether to loop or to exit, s_1 does not know when to re-evaluate the condition

Projection: 2 possible solutions

- Restriction approach: restrict to those cases where the projection works
  - In a sequence C;C’ the last participant in C should be the first participant in C’
  - In a conditional if b@r {C} else {C’} participant r should be the first participant in C and C’
- Smart projection approach: introduce auxiliary communications to force the desired behaviour
  - In a sequence C;C’, the participants in C notify the participants in C’ when C is finished and C’ can start
  - In if b@r {C} else {C’} participant r notifies participants in C and C’ of the outcome of the choice

Smart projection example

- The conditional
  if b@s_1 {o: s_2(5) → r(x)} else {o: s_2(7) → r(x)}
- Will be projected as follows
- On s_1: if b {cnd*: send true to s_2 | cnd*: send true to r}
  else {cnd*: send false to s_2 | cnd*: send false to r}
  On s_2: cnd*: receive z from s_1; if z {o: send 5 to r}
  else {o: send 7 to r}
  On r: cnd*: receive z from s_1; if z {o: receive x from s_2}
  else {o: receive x from s_2}
- Operations with * (like cnd*) are auxiliary operations

Restriction vs smart projection

	Restriction	Smart projection
Usability of the language	-	+
Simplicity of compilation (and proofs)	+	-
Efficiency	+	- (could be optimized)

- Smart projection could deal with other problems too (e.g., adding security guarantees)

Semantics

- In order to prove properties (e.g., correctness of compilation) we need to give semantics to choreographies and projected systems
- Both semantics are defined as labelled transition systems (LTS)
- Generated from operational semantics

Semantics of choreographies

- Quite simple semantics (the one in the paper has a few more technical additions)
- Sample rules:

$$\frac{[\![e]\!]_{\Sigma(s)} = v}{\langle \Sigma, o : s(e) \to r(x) \rangle \overset{o : s(v) \to r(x)}{\to} \langle \Sigma, x@r = v \rangle}$$

$$\frac{[\![e]\!]_{\Sigma(r)} = v}{\langle \Sigma, x@r = e \rangle \overset{\tau}{\to} \langle \Sigma[{}^{v}\!/_{x}, r], 1 \rangle}$$

$$\langle \Sigma, 1 \rangle \overset{\surd}{\to} \langle \Sigma, 0 \rangle$$

$$\frac{\langle \Sigma, I \rangle \overset{\mu}{\to} \langle \Sigma', I' \rangle \qquad \mu \neq \surd}{\langle \Sigma, I ; J \rangle \overset{\mu}{\to} \langle \Sigma', I' ; J \rangle}$$

$$\frac{\langle \Sigma, I \rangle \overset{\surd}{\to} \langle \Sigma', I' \rangle \qquad \langle \Sigma', J \rangle \overset{\mu}{\to} \langle \Sigma'', J' \rangle}{\langle \Sigma, I ; J \rangle \overset{\mu}{\to} \langle \Sigma'', J' \rangle}$$

Semantics of projected systems

- Slightly more complex (synchronization close to pi calculus)
- Sample simplified rules:

$$\frac{[\![e]\!]_\Gamma = v}{(\Gamma, o : \text{send } e \text{ to } r)_s \xrightarrow{o\langle v\rangle \text{ from } s \text{ to } r} (\Gamma, 1)_s}$$

$$(\Gamma, x = v)_r \xrightarrow{\tau} (\Gamma[{}^{v}\!/_{x}], 1)_r$$

$$(\Gamma, o : \text{receive } x \text{ from } s)_r \xrightarrow{o : x \leftarrow v \text{ from } s \text{ to } r} (\Gamma, x = v)_r$$

$$(\Gamma, 1)_s \xrightarrow{\surd} (\Gamma, 0)_s$$

$$\frac{N \xrightarrow{o\langle v\rangle \text{ from } s \text{ to } r} N' \qquad N'' \xrightarrow{o : x \leftarrow v \text{ from } s \text{ to } r} N'''}{N \| N'' \xrightarrow{o : s(v) \to r(x)} N' \| N'''}$$

$$\frac{N \xrightarrow{\surd} N' \qquad N'' \xrightarrow{\surd} N'''}{N \| N'' \xrightarrow{\surd} N' \| N'''}$$

Results: correctness of compilation

- When the projected programs are executed in parallel, they implement the desired behaviour
- The behaviour is represented by the LTS
- The LTSs of the choreographic program and of the projected system are weak equivalent
  - Equivalent: can be trace equivalence or bisimilarity
  - Weak: we only consider non-auxiliary interactions and ✓
  - (We have some pruning on the LTS of the projected system, but this can be avoided with a smarter LTS)
- Non-auxiliary interactions and successful termination are preserved and reflected

Results: freedom from concurrency errors

- Deadlocks, orphan messages and message races are avoided by construction
  - These behaviours cannot be written in a choreographic language
  - Projection reflects behaviours, hence they cannot occur in the projected system either

An example: deadlock

- A system has a deadlock when some roles have not finished their computation, yet no transition is possible
- If all roles have successfully terminated, the operational semantics produces a ✓
- There are no other ways of producing a ✓
- Hence, we have a deadlock if there is a finite trace which does not end with ✓
- All finite traces of choreographic programs end with ✓
- Since weak traces are reflected by projection, the projected system never deadlocks

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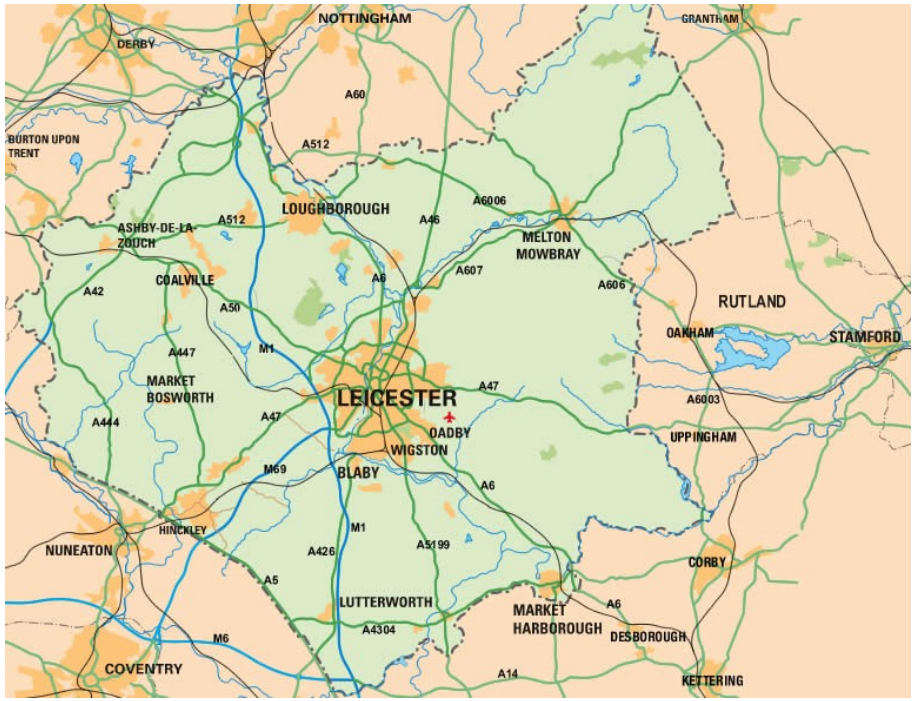

From abstract theory to the real world

- We implemented AIOCJ as an instance of this theory
- AIOCJ is composed by
  - An Eclipse plugin allowing one to write and compile choreographic programs
  - A middleware to enable adaptation (we will see it in the next days)
- Projection generates microservices in the Jolie language
- Choreographic programs could be projected to any language but…
- ...the choice of the Jolie language has some advantages
- The microservices can be executed, obtaining the desired behaviour

A note on microservices

- Services are independent entities communicating via message passing over well-defined APIs
  - Enables communication among heterogeneous entities
  - Thanks to standards such as XML, HTTP and SOAP
- Microservices is an architectural style for service-oriented systems that takes to an extreme the emphasis on modularity and scalability
- Suited to be deployed in Docker containers, frequently on the Cloud
  - We do not yet support this possibility in AIOCJ
- The choreographic approach combines well with modularity

A note on the Jolie language

- The Jolie programming language
  - is a language to program services, and microservices in particular
  - provides suitable abstractions (e.g., communication ports with well-defined APIs)
  - natively supports multiple standards from the area (SOAP, HTTP, RMI, JSON, …)
  - developped at University of Bologna
  - currently supported and exploited by company ItalianaSoftware
  - see https://www.jolie-lang.org/
- AIOCJ inherits some of its features

A note on projection

- AIOCJ projection uses a mixed approach
- Restriction for sequence
  - The Eclipse plugin checks this
- Smart projection for conditionals and loops
  - Auxiliary communications are introduced during compilation

Integration with Legacy Software

- In the real world applications are not built from scratch
- One uses external libraries, services (e.g., google maps), existing applications…
- We want to integrate them into our framework
- We want AIOCJ distributed applications to be able to interact with existing software
  - While preserving the correctness guarantees
- External software invocations are seen as function invocations from a theoretical point of view
  - They need to have functional behaviour
  - That is, they are invoked and they give back a value
  - No synchronization (e.g., wait on a monitor)

Declaring external dependences

- External function should be declared including
  - where they are: location (URL, ...)
  - which technologies (sockets, bluetooth, ...) and protocols (SOAP, HTTP, …) need to be used
- include makePayment from "socket://localhost:8001/IBAN" with HTTP
- Leverages Jolie ability to interact using different technologies and protocols
- No assumption on the language/technology used to implement them
  - In particular, not necessarily Jolie services

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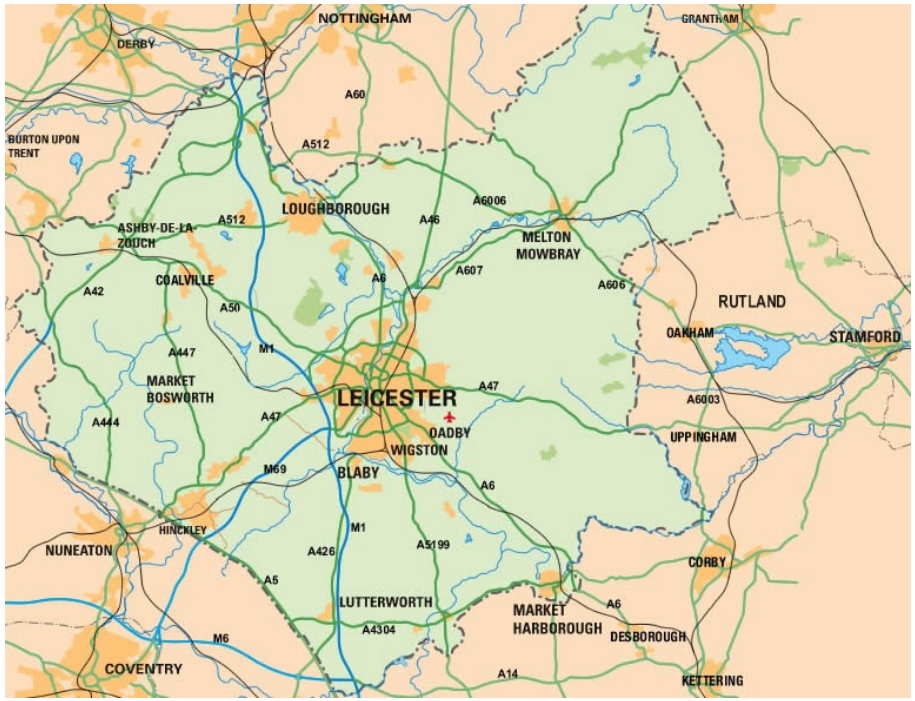


Adaptation, update, evolution

- Applications need to change during their lifetime
- This can be referred to as adaptation, update, evolution
- Slightly different flavours, but the same basic idea, and terminology is not always used in a consistent way
- We will use them as synonyms

Why to update?

- Error fixing
- Environment that evolves
  - Old services no more available
  - Partner applications that evolve
  - New services may become available, exploiting them may improve the results/non functional properties
- Completely new environments
  - Mobile or configurable applications
- New requirements
  - New functionalities
  - Improving non functional properties

Static vs dynamic updates

- Update can be performed statically or dynamically
- Static update: we update the code and then (re)start the application
- Dynamic update: we update a running application, without shutdown and with limited service disruption
- Dynamic update is more challenging
  - Need to interact with running code
  - New code should use pre-existing data
  - Need to keep attention to transient behaviour
  - In a distributed system, need to synchronize updates to different participants

Why dynamic updates?

- Many systems (should) never stop
  - Internet
  - Online services (bank, shopping, ...)
  - Industrial plants
- Mainly for economic reasons
  - Customers do not want services to be down
  - No production on shutdown times
- Yet these systems need to be updated

Our approach to (very) dynamic updates

- We want dynamic updates: we want to change the code of running applications
- An update replaces an existing piece of choreographic program with a new piece of choreographic program coming from outside
  - The external piece of code is called an update fragment
  - The update fragment is not known when the application is started
- A single update may concern more than one participant

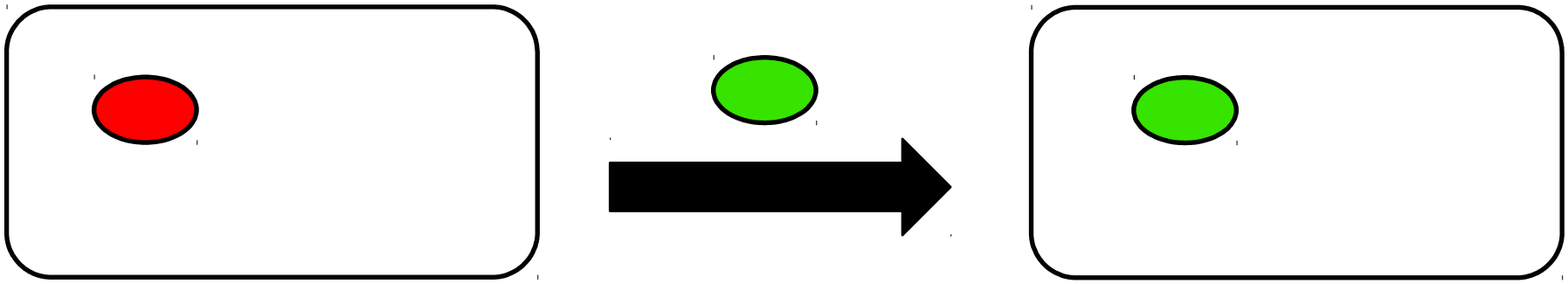
Timing of updates

- At any time there is a set of available update fragments
- New update fragments may become available at any time and without notice
- Update fragments may stop to be available at any time and without notice
- The running application performs a check for update for a given piece of choreographic program just before executing it
  - but the same piece of choreographic program could have been already executed before

Our approach, syntactically

- Pair a running application with a set of update fragments
  - Each update fragment is a choreographic program
  - The set of update fragments may change at any time
- At the choreographic level, the update fragment may replace a part of the choreographic program
  - Which part?
- Extend choreographic programs with scopes
  - scope @r {C}
  - Normally executes C, but executes an update fragment instead if a suitable one is available
  - That is, a check for update is performed before executing C
  - Participant r is in charge of managing the update procedure

Our approach, graphically



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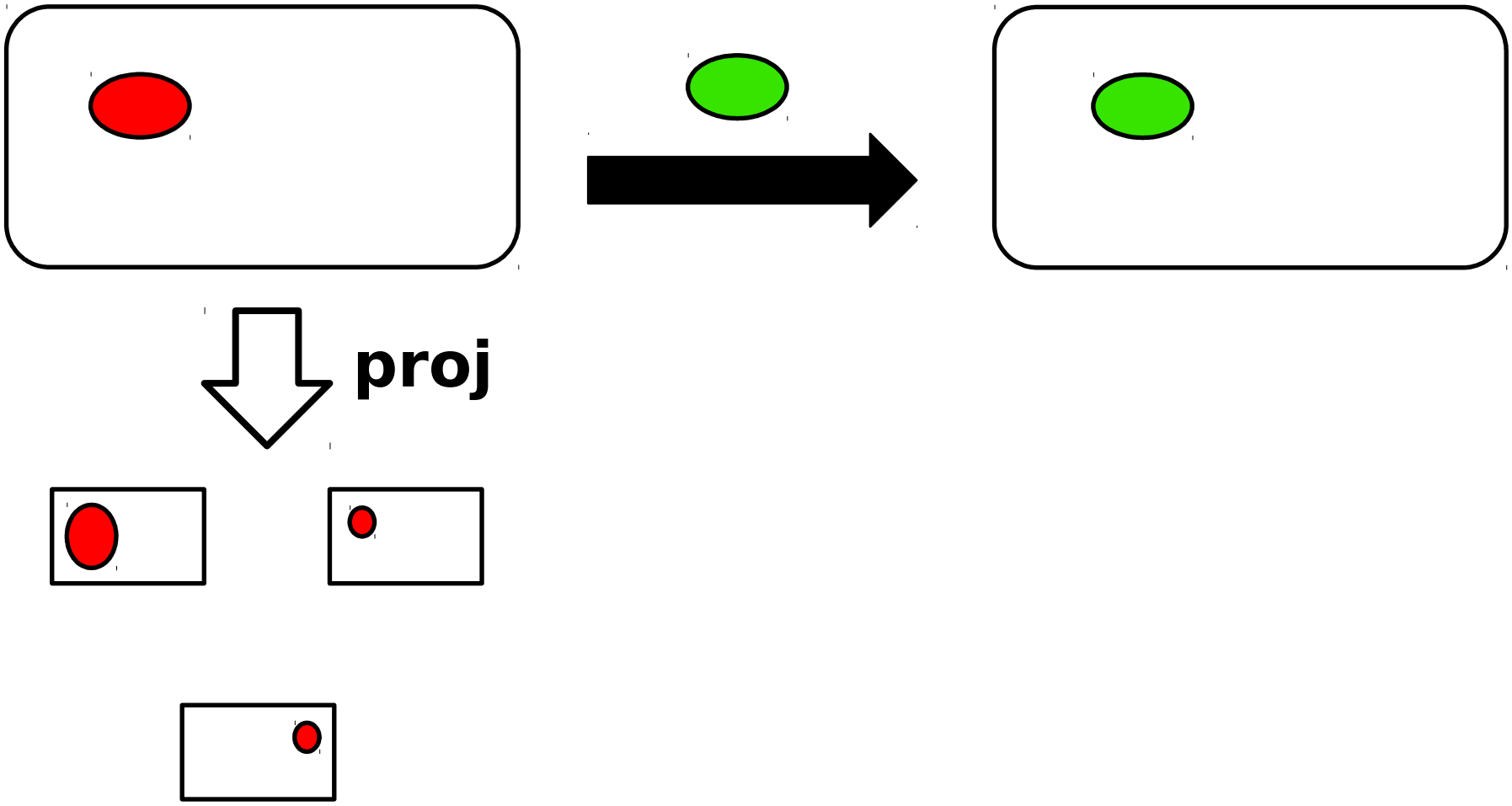

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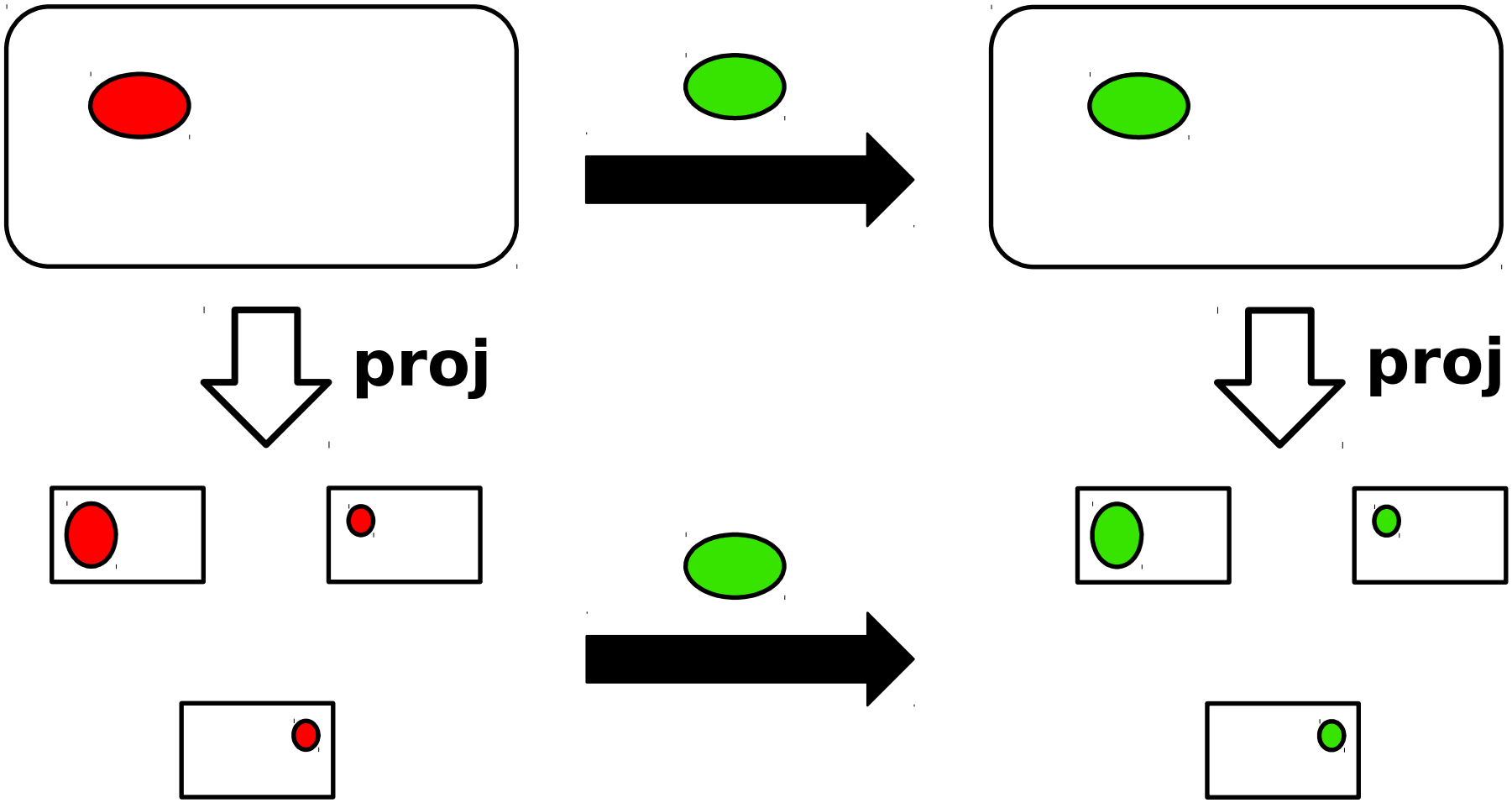

Dynamic updates: challenges

- All the participants should agree on
  - whether to update a scope or not
  - in case, which update fragment to use
- All the participants need to retrieve (their part of) the update fragment
  - Not easy, since update fragments may disappear
- No participant should start executing the code inside a scope that needs to be updated

Dynamic updates: our approach

- For each scope a single participant coordinates its execution
  - Decides whether to update it or not, and in case which update fragment to apply
  - Gets the update fragment, and sends to the other participants their part
- The other participants wait for the decision before executing the scope

How to program with scopes: difficulties

- Deciding where to put scopes in your code is tricky
- If a piece of code is not inside a scope it cannot be updated
- One need to foresee which piece of code may need adaptation
- If a scope is too small, you may want to change more than one scope in a coordinated way, what is not possible
- If a scope is too large
  - You can only update it at the very beginning
  - You need to provide the whole new code, even if you want to update a single line
- Intersecting scopes must be nested
- (And, of course, scopes cause some overhead)

How to program with scopes: guidelines

- Scopes must enclose pieces of code with a precise aim
  - Roughly, what you would put into a procedure
- You should select pieces of code that may need to be updated
  - Pieces of code depending on some regulation that may change
  - Pieces of code depending on the environment
  - Pieces of code critical for performance or security reasons
  - ...
- You do not neet to foresee when they will be updated, why or how

Dynamic updates: formalization (1)

- Updates can be formalized by extending the choreographic language and the target language with scopes
- At the choreographic level scope @r {C} has two kinds of transitions:
  - Either it reduces to its body C
  - Or it reduces to an available update fragment C’
- At the projected system level there are two kinds of scopes, coordinator scopes and non-coordinator scopes
- The construct scope @r {C} is projected to
  - A coordinator scope on r
  - A non-coordinator scope on the other roles in C
  - skip on the other roles

Dynamic updates: formalization (2)

- A coordinator scope:
  - Decides whether to update or not
  - Sends the decision and the projections of the selected update fragment, if any, to the other roles
  - Executes its own code (original or updated)
  - Waits for an end-of-scope message from the other roles
- A non-coordinator scope:
  - Waits for a message telling him whether to update or not, and containing in the first case its new code
  - Executes its own code (original or updated)
  - Sends an end-of-scope message to the coordinator

Results

- A choreographic program and its projection behave the same
  - Their LTSs are weak equivalent
  - Under all possible, dynamically changing, sets of updates
- The projected application has no deadlocks, orphan messages nor races by construction

- These results are strong given that we are considering an application which is
  - distributed
  - dynamically updatable

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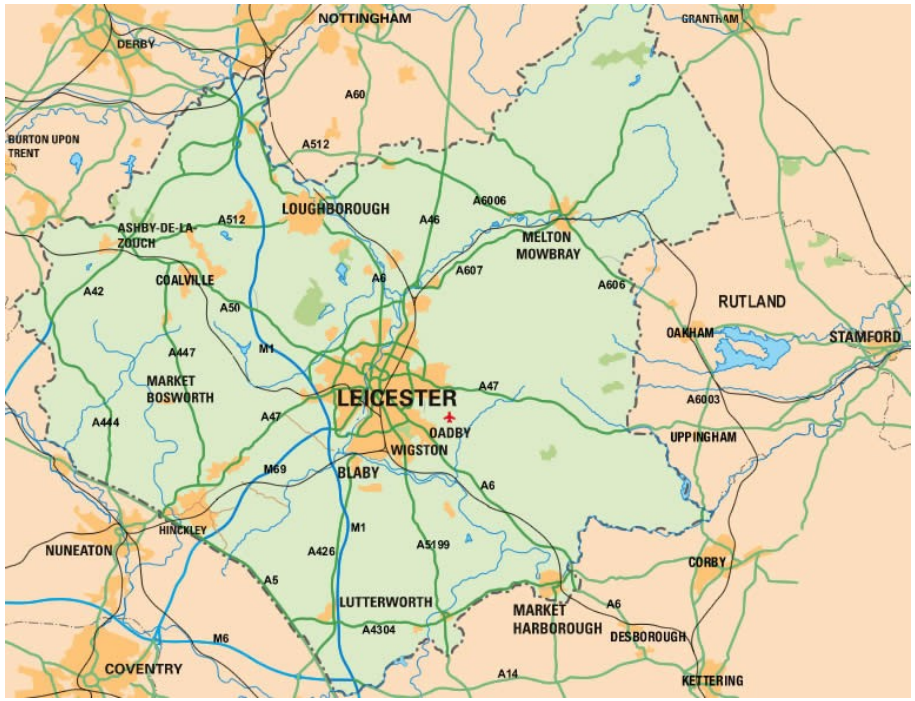


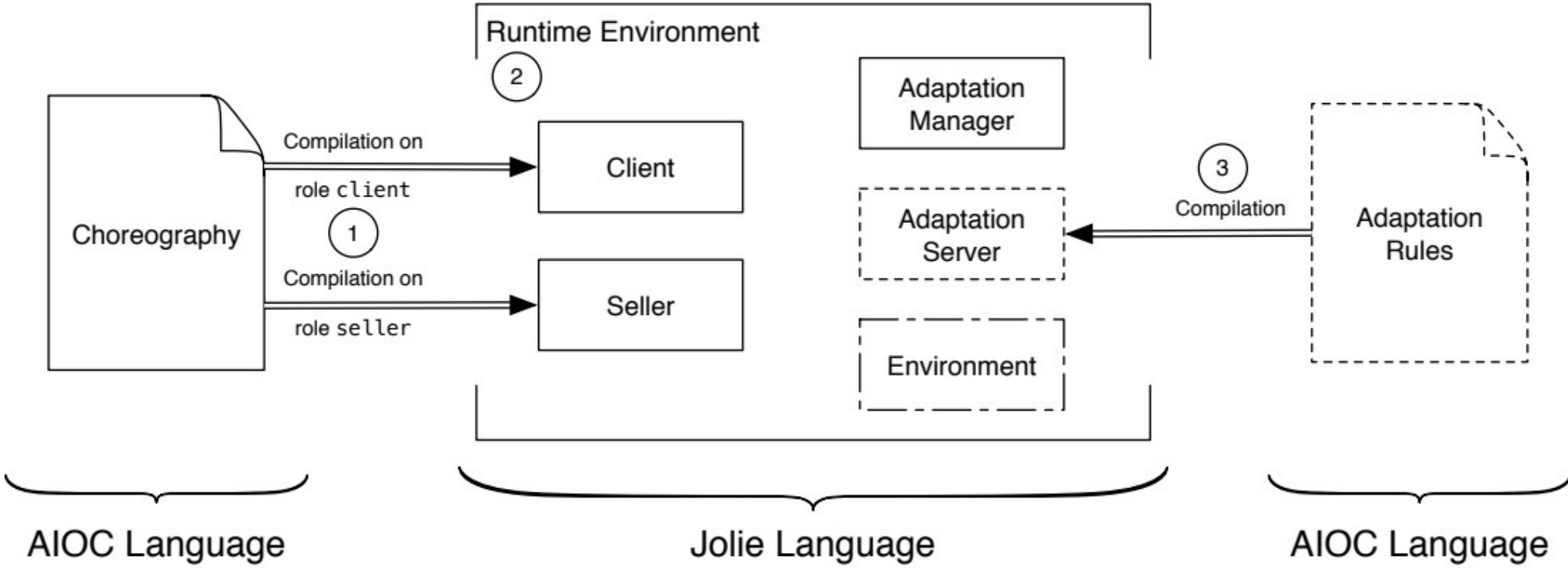
From update fragments to adaptation rules

- Non-determinstic application of updates is not practical
- We use adaptation rules composed by an update fragment and its applicability condition
  - May refer to environment variables, scope properties, and local variables of the coordinator of the update
- If at least one adaptation rule is applicable, update is performed
- This does not avoid nondeterminism, but gives some control
  - Other mechanisms could be added (e.g., priorities)

AIOCJ middleware

- Adaptation managed by a dedicated middleware composed of microservices
- Rules are managed by dedicated microservices called adaptation servers
- A microservice called adaptation manager coordinates the adaptation procedure
- A microservice stores environment information

Our approach, architecturally



Adding, removing and applying rules

- Adaptation servers can be added and removed at any time
- When added, an adaptation server registers to the adaptation manager
- In order to check for update, the role managing adaptation interacts with the adaptation manager and, as a result, with all available adaptation servers
- Each rule is checked for applicability
- The first applicable rule, if any, is applied
  - Of course, different policies would be meaningful

Implementing adaptation

- We need a mechanism for runtime code update
- Not directly supported by Jolie
  - (Erlang would support it)
- Scopes' body externalized as services
- When a scope needs to be updated, the updated body is deployed as a service, and the invocation switched to it
- All the involved services need to have access to variables
- Variables externalized in a state service

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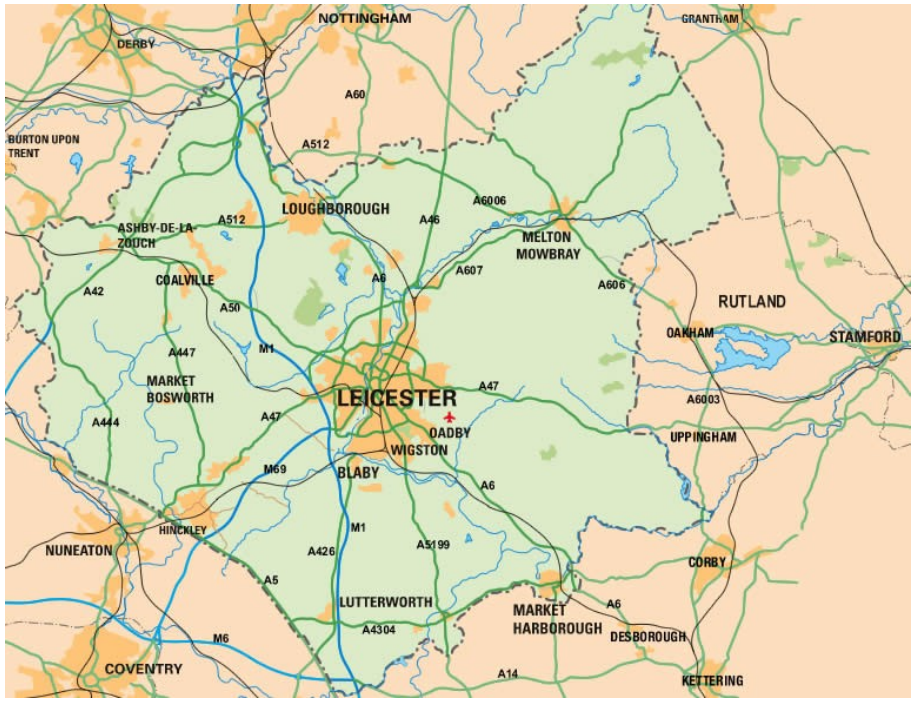

Conclusion

- A choreographic approach to program distributed applications
- The derived distributed application follows the behaviour defined by the choreographic program
- Applications have no deadlocks, orphan messages nor races
- We allow integration of external functionalities
- We allow dynamic update, preserving the correctness guarantees
- We instantiated the theoretical framework into a real programming language

Future work

- Is choreographic programming practical?
  - We need to allow asynchronous communication
  - We need to improve performance
    - Drop redundant auxiliary communications
  - We need error handling
- Only a serious case study can tell
  - Not so easy to find a suitable case study for this framework

A question for our industrial partners

- Could you imagine a use case for AIOCJ
  - You could assume that future work discussed on previous slide has been done
- If yes, which one?
- If no, why? Would something else be needed? What?
- And for the part without adaptation?

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End of talk