Reactive Method Dispatch for Context-Oriented Programming

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Ph.D. Public Defence
12th December 2012

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Software Languages Lab.
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Roadmap

Motivation

Reactive context-aware applications

Characteristics

Issues

Programming Language Approach

Language Requirements

State of the Art

The ICoDE Model

The Flute Language

Semantics and Validation

iScheme

An Executable Semantics for Flute

Validation

Motivation

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Reactive context-aware applications

Characteristics

Issues

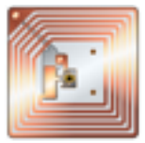
Sensor Equipment Mobile Devices

GPS

Camera

Compass

Accelerometer



RFID

Sensor Equipment Mobile Devices

Reactive
Context-aware
Applications

Reactive Context-aware Applications

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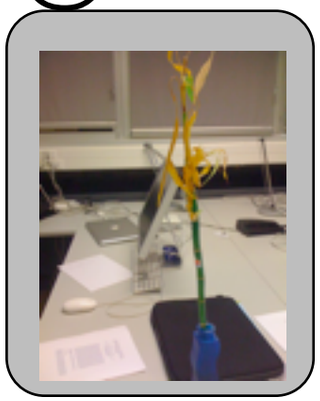

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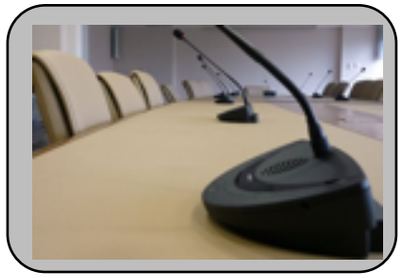

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Reactive Context-aware Applications

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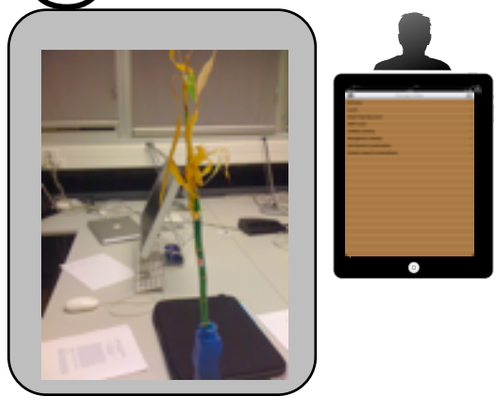

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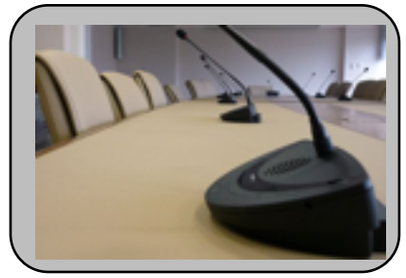

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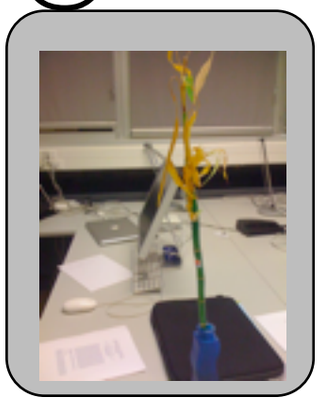

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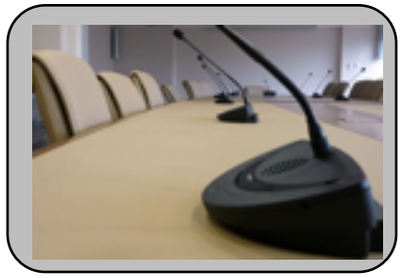

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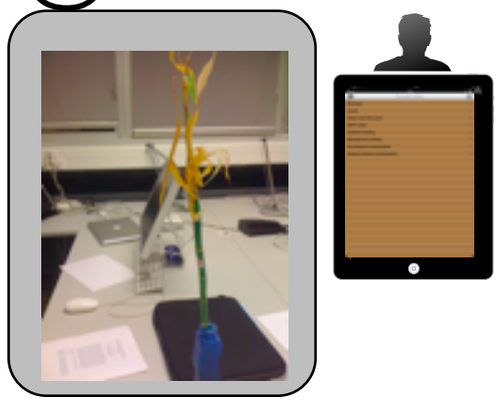

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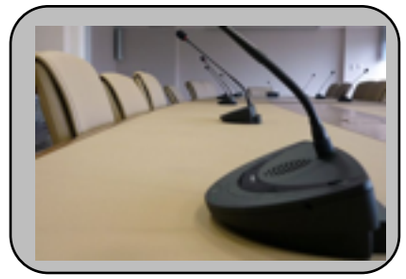

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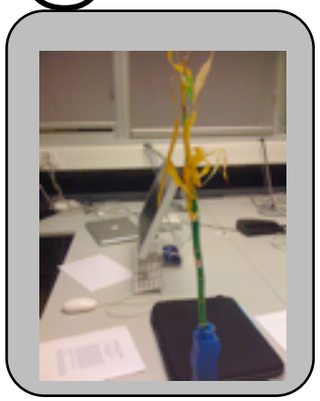

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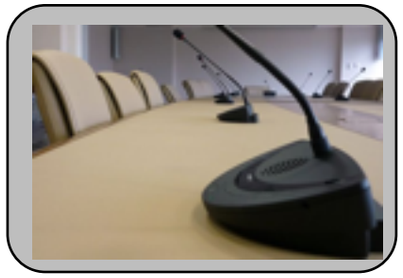

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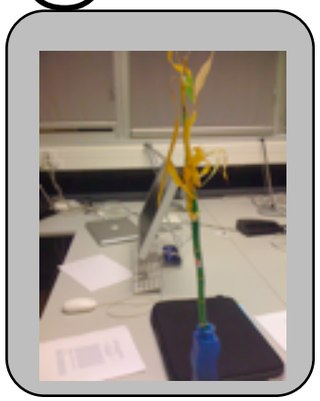

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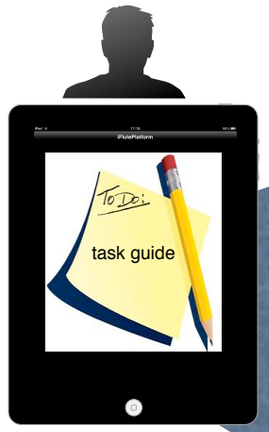


to-call

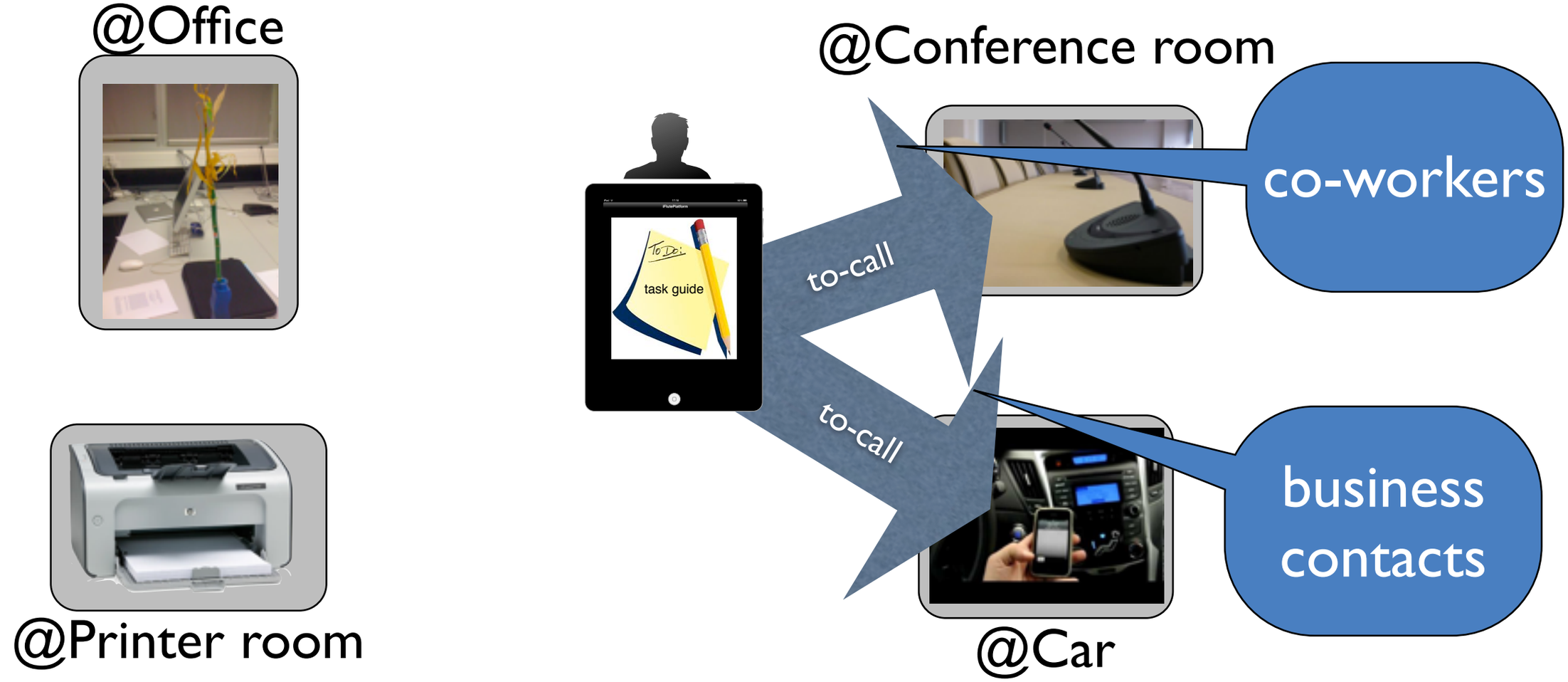
co-workers

to-call

business contacts

@Car

Reactive Context-aware Applications



Fundamental Characteristics:

1. **Context-constrained** executions.
2. **Sudden** interruptions.
3. **Prompt** adaptability.

Programming Reactive Context-aware Applications

```
1 (define call-from-car
2   (lambda (contacts-list)
3     (show "calling business contacts")
4     (if (null? contacts-list)
5       (show "business contacts list empty")
6       (let ((contact (car contacts-list)))
7         (show (contact-name contact))
8         (dial (phone-number contact))
9         (turn-on-phone-speaker)
10        (connect-to-car-speakers)
11        (if (dial-next-contact? (user-response))
12          (call-from-car (cdr contacts-list)))))))
```

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7         (show (contact-name contact))
8         (dial (phone-number contact))
9         (turn-on-phone-speaker)
10        (connect-to-car-speakers)
11        (if (dial-next-contact? (user-response))
12          (call-from-car (cdr contacts-list)))))))
```

Context-independent

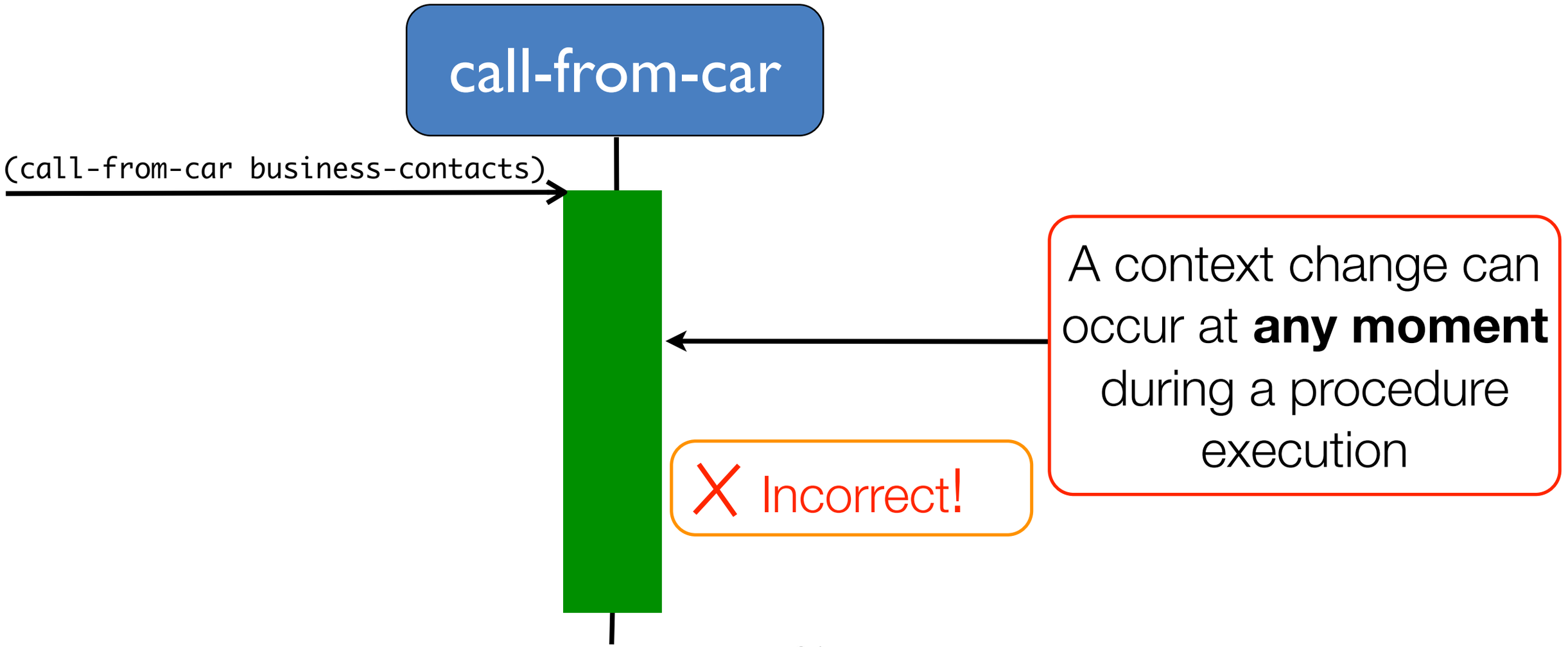
Programming Reactive Context-aware Applications

```
(if (is-in-car? location)
    (call-from-car business-contacts))
```

Programming Reactive Context-aware Applications

```
(if (is-in-car? location)
    (call-from-car business-contacts))
```

Not enough!



Programming Reactive Context-aware Applications

```
1 (define call-from-car
2   (lambda (contacts-list)
3     (show "calling business contacts")
4     (if (null? contacts-list)
5       (show "business contacts list is empty")
6       (let ((contact (car contacts-list)))
7         (show (contact-name contact))
8         (dial (phone-number contact))
9         (turn-on-phone-speaker)
10        (connect-to-car-speakers)
11        (if (dial-next-contact? (user-response))
12          (call-from-car (cdr contacts-list)))))))
```

Fundamental Research Questions:

1. How to **constrain an entire procedure execution** to the right context?

2. What to do when a **context change occurs** in the **middle of an ongoing execution**?

Manual Checks, Coroutines, Continuations, ...

```
1 (define call-from-car
2   (lambda (contacts-list)
3     (if (is-in-car? location)
4       (show "calling business contacts")
5       (save/suspend))
6     (if (null? contacts-list)
7       (show "business contacts list is empty")
8       (let ((contact (car contacts-list)))
9         (if (is-in-car? location)
10          (show (contact-name contact))
11          (save/suspend))
12        (if (is-in-car? location)
13          (dial (phone-number contact))
14          (save/suspend))
15        (if (is-in-car? location)
16          (turn-on-phone-speaker)
17          (save/suspend))
18        (if (is-in-car? location)
19          (connect-to-car-speakers)
20          (save/suspend))
21        (if (dial-next-contact? (user-response))
22          (call-from-car (cdr contacts-list))))))))
```

Repetitive
context checks

Resumptions?

Context management?

Manual Checks, Coroutines, Continuations, ...

```
1 (define call-from-car
2   (lambda (contacts-list)
3     (if (is-in-car? location)
4       (show "calling business co
5       (save/suspend))
6     (if (null? contacts-list
7       (show "business cont                pty")
8       (let ((contact (c                  )))
9         (if (is-in-c
10          (show (co                    act))
11          (save/s
12        (if (i                         ion)
13          (di                        er contact))
14
15                                     location)
16                                     one-speaker)
17                                     spend))
18                                     n-car? location)
1                                      nect-to-car-speakers)
                                       ave/suspend))
2                                  if (dial-next-contact? (user-response))
22                                 (call-from-car (cdr contacts-list))))))
```

Need for a dedicated software technology

Repetitive
context checks

Resumptions?

Context management?

Reactive Method Dispatch for Context-Oriented Programming

Programming Language Approach

Language Requirements

State of the Art

The ICoDE Model

The Flute Language

Programming Language Requirements

```
(is-in-car? location)
```

```
1 (define to-call
2   (lambda (contacts-list)
3     (show "calling business contacts")
4     (if (null? contacts-list)
5       (show "business contacts list is empty")
6       (let ((contact (car contacts-list)))
7         (show (contact-name contact))
8         (dial (phone-number contact))
9         (turn-on-phone-speaker)
10        (connect-to-car-speakers)
11        (if (dial-next-contact? (user-response))
12          (to-call (cdr contacts-list)))))))
```

```
(is-in-conference-room? location)
```

```
1 (define to-call
2   (lambda (contacts-list)
3     (show "calling co-workers contacts")
4     (if (null? contacts-list)
5       (show "co-workers contacts list is empty")
6       (let ((contact (car contacts-list)))
7         (show (contact-name contact))
8         (dial (phone-number contact))
9         (turn-on-phone-speaker)
10        (connect-to-conference-equipment)
11        (if (dial-next-contact? (user-response))
12          (to-call (cdr contacts-list)))))))
```

Language

Requirements:

R.1 Chained Context Reactions

R.2 Contextual Dispatch

R.3 Reactive Dispatch

R.4 Context-dependent Interruptions

R.5 Context-dependent Resumptions

R.6 Reactive Scope Management

A Survey of the State of the Art

	Chained Context Reactions	Context-dependent Interruptions	Context-dependent Resumptions	Contextual Dispatch	Reactive Dispatch	Reactive Scope Management
Context-Oriented Programming (COP) Languages						
ContextL and other Layer-based Languages	✗	✗	✗	✓	✗	✗
Lambic	✗	✗	✗	✓	✗	✗
Ambience	✗	✗	✗	✓	✗	✗
Contextual Values	✗	✗	✗	✓ variable	✗	✓ scoped construct
Functional Reactive Programming (FRP) Languages						
FrTime and its Siblings	✓ behaviours and events	✗	✗	✗	✓ same function re-evaluation	✗
Reactive SML	✗	✓ explicit	✓ explicit	✗	✗	✗
Advanced Control Flow Constructs						
Coroutines	✗	✓ explicit	✓ explicit	✗	✗	✗
First-class Continuations	✗	✓ explicit	✓ explicit	✗	✗	✗
Threads (Cooperative)	✗	✓ explicit	✓ explicit	✗	✗	✗
Other Programming Language Facilities						
Guards	✗	✓ blocking at the beginning	✓ from the beginning	✗	✗	✗
Assertions	✗	✓ explicit abort	✗	✗	✗	✗
Invariants	✗	✓ only at the beginning and the end	✗	✗	✗	✗

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Explicit Layer and Context Activation, …

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Bainomugisha, E. *et.al.* (2012). A Survey on Reactive Programming. *ACM Computing Surveys (to appear)*.

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No Contextual Dispatch, …

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Lambic	✗	✗	✗	✓	✗	✗
Ambience	✗	✗	✗	✓	✗	✗
Contextual Values	✗	✗	✗	✓ variable	✗	✓ scoped construct
Functional Reactive Programming (FRP) Languages						
FrTime and its Siblings	✓ behaviours and events	✗	✗	✗	✓ same function re-evaluation	✗
Reactive SML	✗	✓ explicit	✓ explicit	✗	✗	✗
Advanced Control Flow Constructs						
Coroutines	✗	✓ explicit	✓ explicit	✗	✗	✗
First-class Continuations	✗	✓ explicit	✓ explicit	✗	✗	✗
Threads (Cooperative)	✗	✓ explicit	✓ explicit	✗	✗	✗
Other Programming Language Facilities						
Guards	✗	✓ blocking at the beginning	✓ from the beginning	✗	✗	✗
Assertions	✗	✓ explicit abort	✗	✗	✗	✗
Invariants	✗	✓ only at the beginning and the end	✗	✗	✗	✗

Bainomugisha, E. *et.al.* (2012). A Survey on Reactive Programming. *ACM Computing Surveys (to appear)*.

A Survey of the State of the Art

	Chained Context Reactions	Context-dependent Interruptions	Context-dependent Resumptions	Contextual Dispatch	Reactive Dispatch	Reactive Scope Management
Context-Oriented Programming (COP) Languages						
ContextL and other Layer-based Languages	✗	✗	✗	✓	✗	✗
Lambic	✗	✗	✗	✓	✗	✗
Ambience	✗	✗	✗	✓		✗
Contextual Values	✗	✗	✗	✓ variab		✓ scoped construct
Functional Reactive Programming (FRP) Languages						
FrTime and its Siblings	✓ behaviours and events	✗	✗			✗
Reactive SML	✗	✓ explicit	✓ exp			✗
Advanced Control Flow Constructs						
Coroutines	✗	✓ explicit	✓ exp		✗	✗
First-class Continuations	✗	✓ explicit	✓ explicit		✗	✗
Threads (Cooperative)	✗	✓ explicit	✓ explicit	✗	✗	✗
Other Programming Language Facilities						
Guards	✗	✓ blocking at the beginning	✓ from the beginning	✗	✗	✗
Assertions	✗	✓ explicit abort	✗	✗	✗	✗
Invariants	✗	✓ only at the beginning and the end	✗	✗	✗	✗

Repetitive Context Checks, Manual Resumptions, …

Bainomugisha, E. *et.al.* (2012). A Survey on Reactive Programming. *ACM Computing Surveys (to appear)*.

There is a Need for a New COP Paradigm

	Chained Context Reactions	Context-dependent Interruptions	Context-dependent Resumptions	Contextual Dispatch	Reactive Dispatch	Reactive Scope Management
Context-Oriented Programming Languages						
ContextL and oth Languages						✖
Lambic						✖
Ambience						✖
Contextual Values						✔ scoped construct
Functional Re						
FrTime and its Siblings	✔ events	✖	✖	✖	✔ evaluation	✖
Reactive SML	✖	✔ explic	✔ explicit	✖	✖	✖
Advanced Control Flow Constructs						
Coroutines	✖	✔ explic	✔ explicit	✖	✖	✖
First-class Continuation						✖
Threads (Cooperative)						✖
Other Programmin						
Guards	✖	✔ beginning	✔ beginning	✖	✖	✖
Assertions	✖	✔ explicit abort	✖	✖	✖	✖
Invariants	✖	✔ only at the beginning and the end	✖	✖	✖	✖

Reactive Programming
+
Context-Oriented Programming
+
Implicit Interruptions

Reactive Method Dispatch for Context-Oriented Programming

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FrTime and its Siblings	✓ events	✗	✗	✗	✓ evaluation	✗
Reactive SML	✗	✓ explic	✓ explicit	✗	✗	✗
Advanced Control Flow Constructs						
Coroutines	✗	✓ explic	✓ explicit	✗	✗	✗
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Other Programmin						
Guards	✗	✓ beginning	✓ beginning	✗	✗	✗
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Invariants	✗	✓ only at the beginning and the end	✗	✗	✗	✗

Reactive Programming
+
Context-Oriented Programming
+
Implicit Interruptions

Reactive Method Dispatch for Context-Oriented Programming

Reactive Method Dispatch for Context-Oriented Programming

Programming Language Approach

Language Requirements

State of the Art

The ICoDE Model

The Flute Language

The ICoDE Model: Design Space

Language Property	Design Considerations
Property #1 Predicated procedures	D.C #1.1 Associating a context predicate with a procedure - As part of procedure definition - Outside the procedure definition
	D.C #1.2 Propagation of context predicates - Dynamic context predicate propagation - Lexical context predicate propagation - No propagation of context predicates
	D.C #1.3 Grouping of related predicated procedures
Property #2 Representation of context as reactive values	
Property #3 Reactive dispatching	D.C #3.1 Dealing with ambiguous context predicates
	D.C #3.2 Handling return values
Property #4 Interruptible executions	D.C #4.1 Implicit interruptions
	D.C #4.2 Explicit interruptions
Property #5 Resumable executions	D.C #5.1 Proactive resumptions
	D.C #5.2 Event-driven resumptions
Property #6 Scoped state changes	

Bainomugisha, E. *et.al*. (2012). Interruptible Context-dependent Executions: A Fresh Look at Programming Context-aware Applications. SPLASH/*OnWard! 2012*

Reactive Method Dispatch for Context-Oriented Programming

Programming Language Approach

Language Requirements

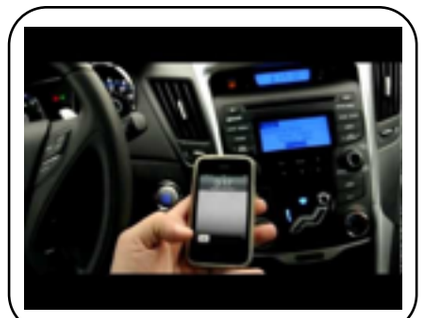
State of the Art

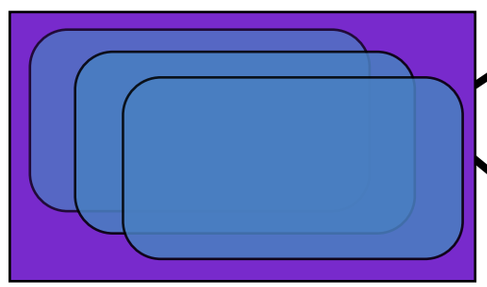
The ICoDE Model

The Flute Language

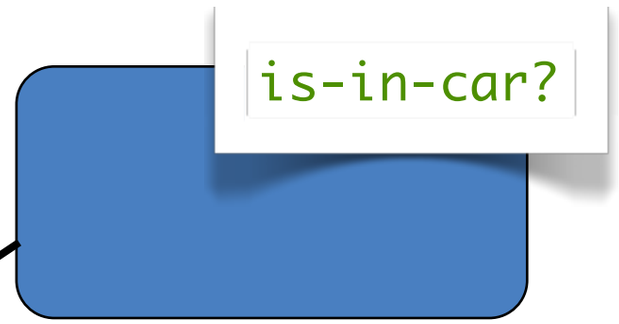
The ICoDE Model in Flute

Context sources
as reactive values





to-call **modal**



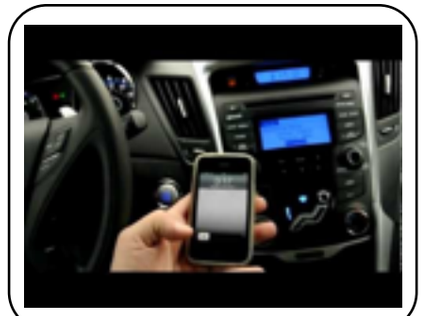
call-from-car **mode**

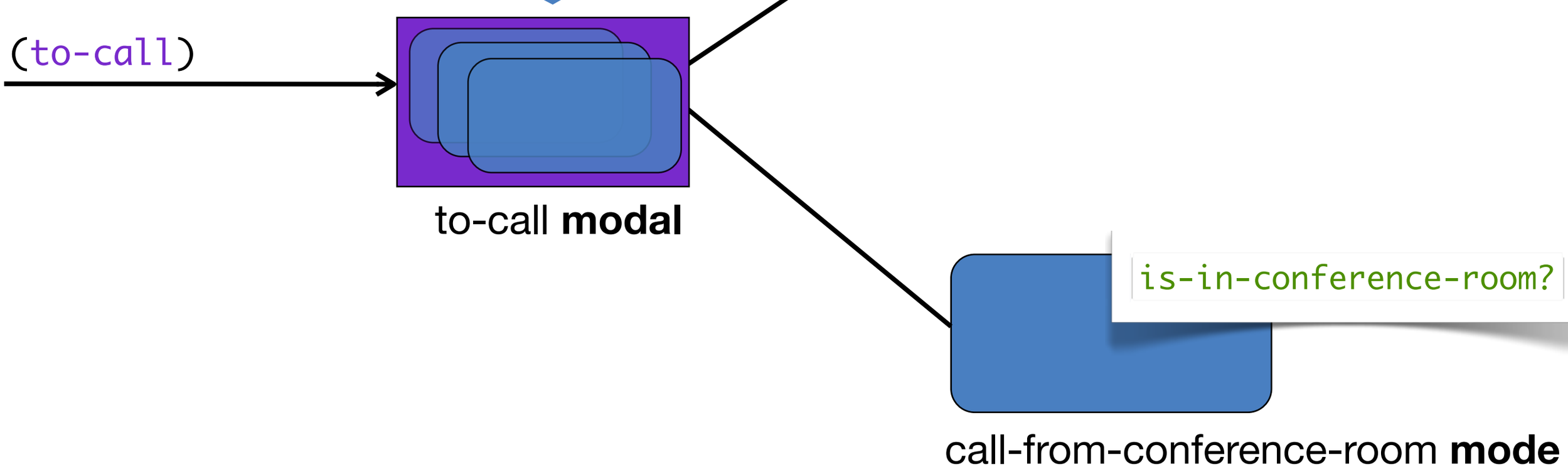
call-from-conference-room **mode**

Bainomugisha, E. *et.al*. (2012). Interruptible Context-dependent Executions: A Fresh Look at Programming Context-aware Applications. SPLASH/*OnWard! 2012*

Contextual and Reactive Dispatching

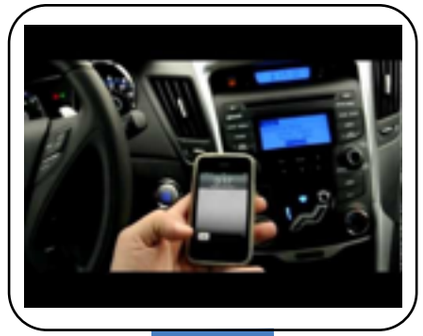
Context sources
as reactive values

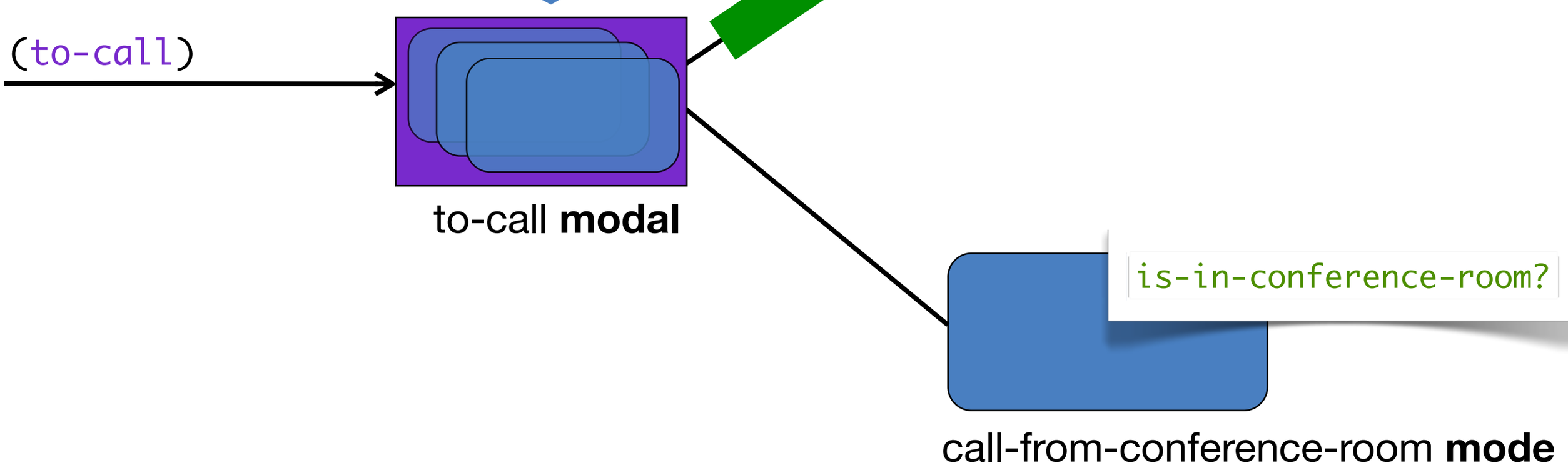




Contextual and Reactive Dispatching

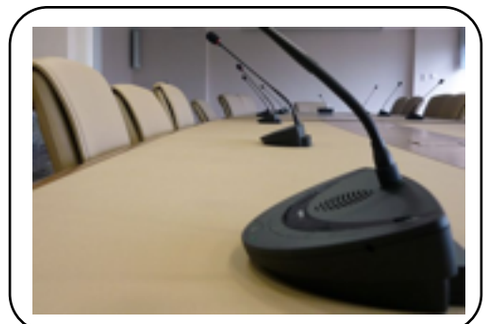
Context sources
as reactive values

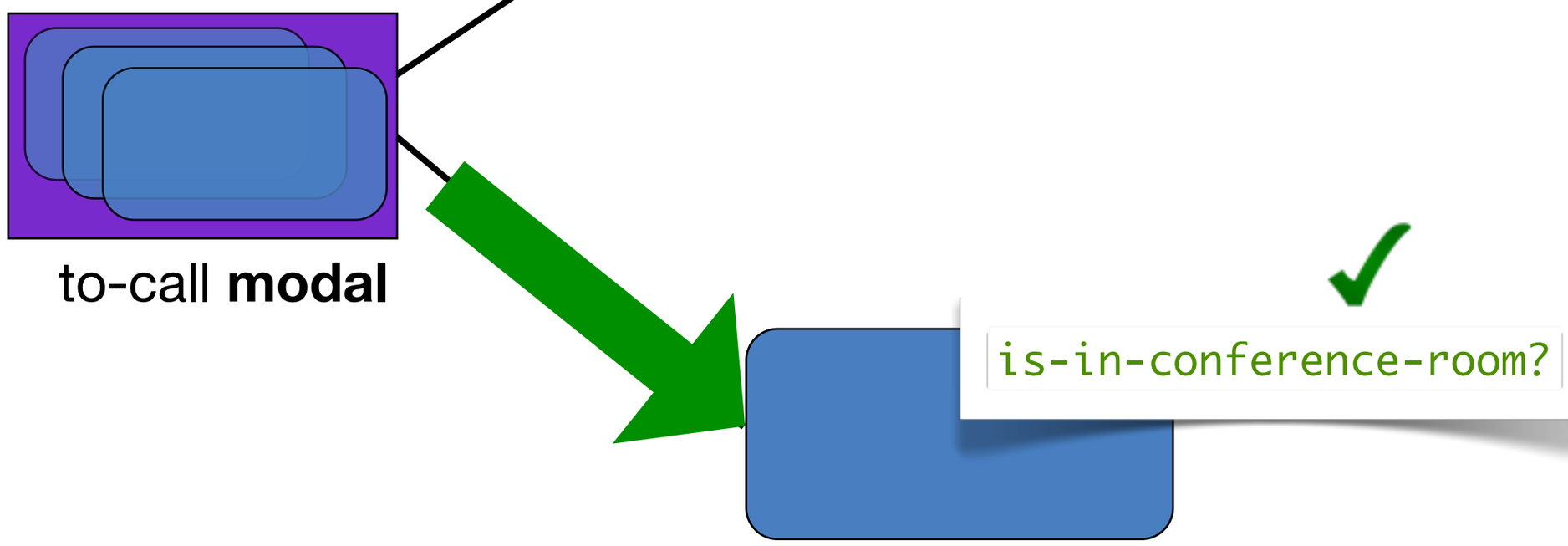




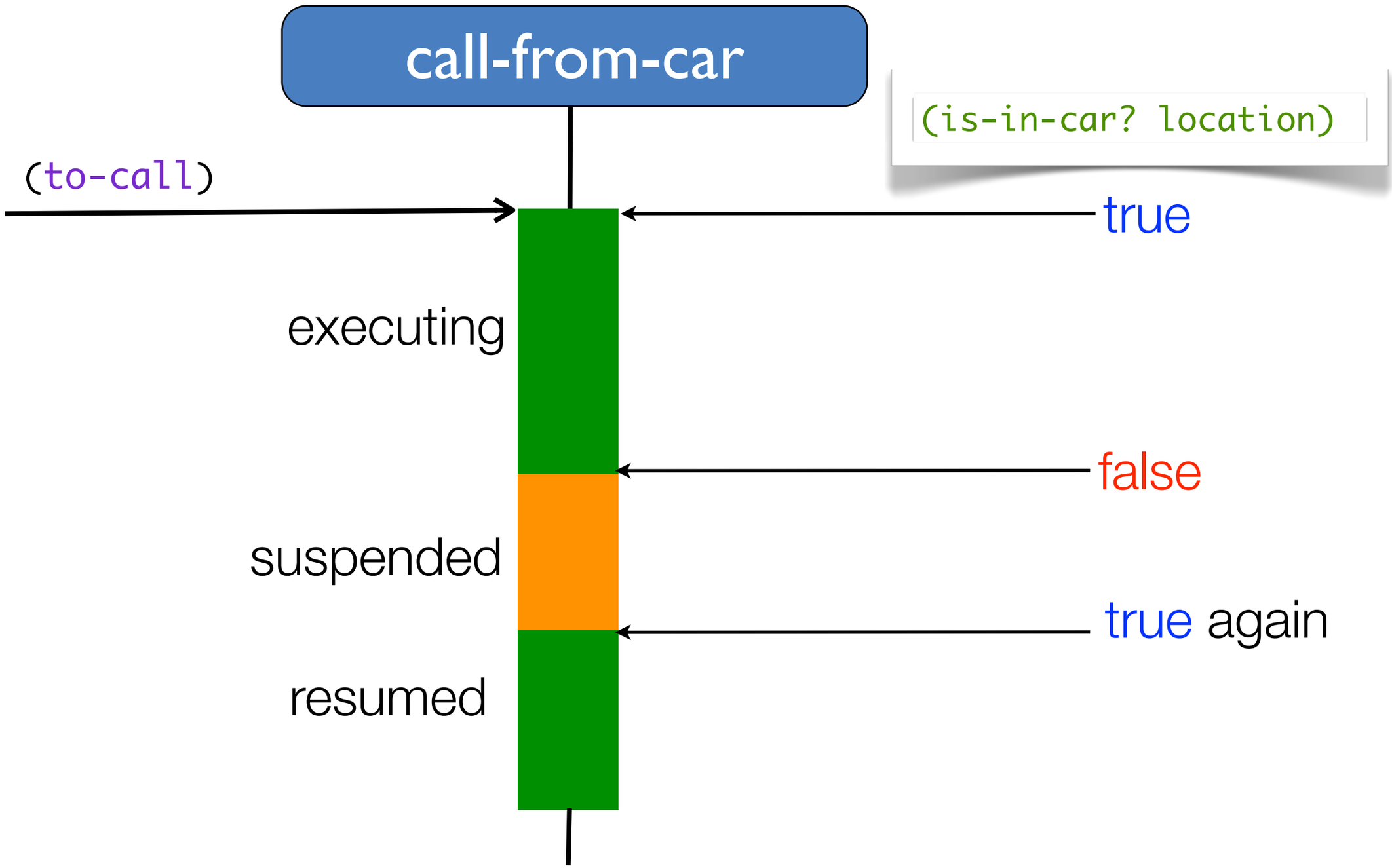
Contextual and **Reactive** Dispatching

Context sources
as reactive values





Interruptible and Resumable Executions



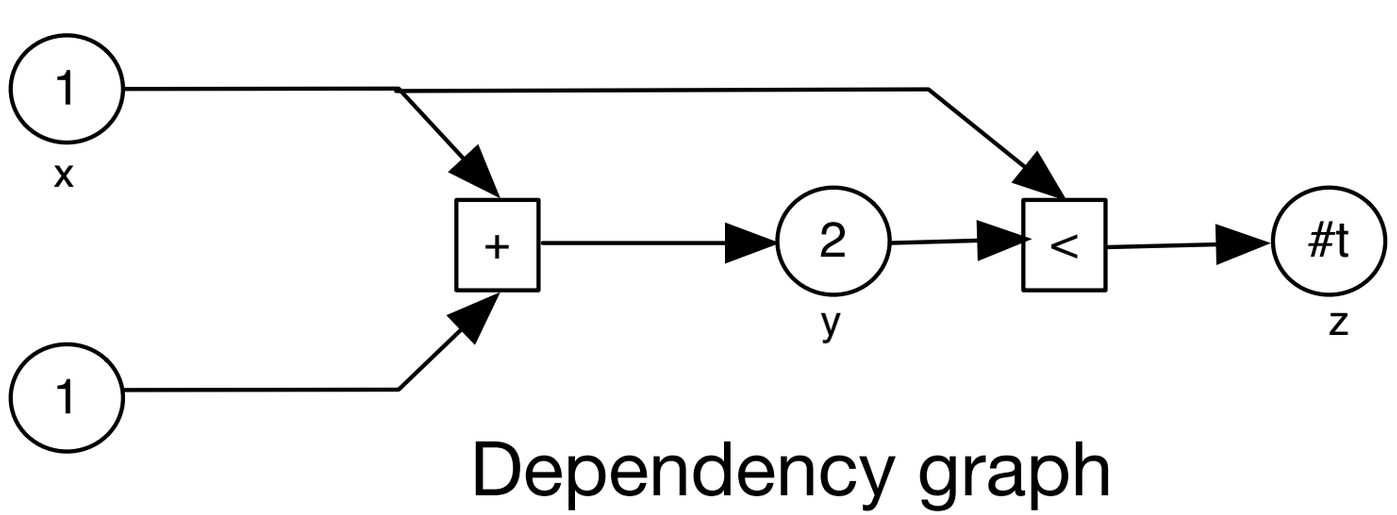
Reactive Programming in Flute

Reactive programming:

- Eliminates the use of explicit callbacks.
- Automatic propagation of changes among dependent values.

```
(define x (ctx-event 1))
(define y (+ x 1))
(define z (< x y))
```

Procedures are implicitly lifted.



Dependency graph

Bainomugisha, E. *et.al*. (2012). A Survey on Reactive Programming. *ACM Computing Surveys (to appear)*.

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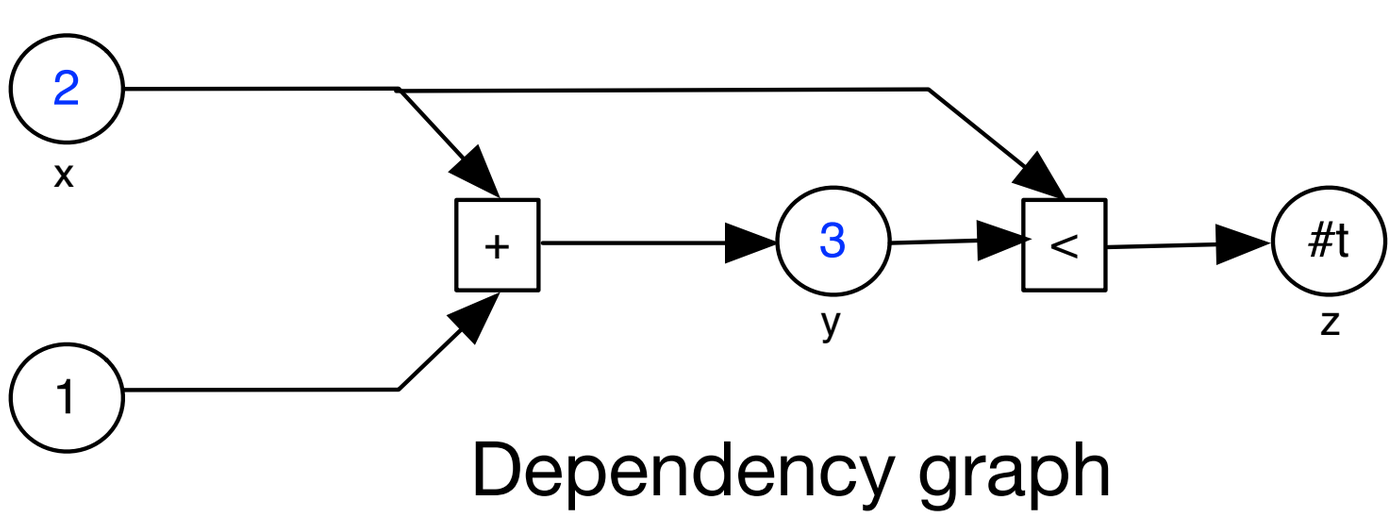


Dependency graph

Bainomugisha, E. *et.al*. (2012). A Survey on Reactive Programming. *ACM Computing Surveys (to appear)*.

Reactive Context Sources in Flute

Reactive
context sources

```
(define gps-coordinates (ctx-event))
(define location (gps->location gps-coordinates))



(CURRENT-LOCATION
 (lambda (latitude longitude)
   (update-value! gps-coordinates
                  (cons latitude longitude))))
```

Acquiring non-reactive values

from sensors.

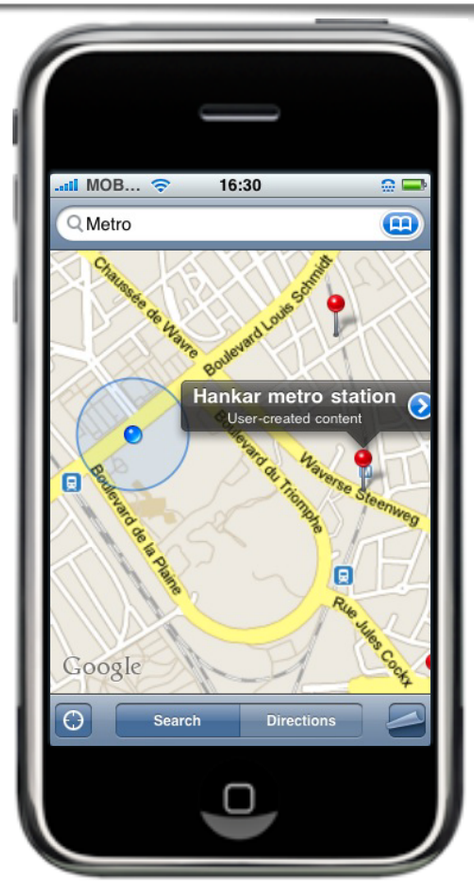
Bainomugisha, E. *et.al*. (2012). A Survey on Reactive Programming. *ACM Computing Surveys (to appear)*.

Reactive Context Sources in Flute

Reactive
context sources

```
(define gps-coordinates (ctx-event))
(define location (gps->location gps-coordinates))
(define nearby-metro-station (get-metro-station location))
```

```
(show-map nearby-metro-station)
```



Bainomugisha, E. *et.al*. (2012). A Survey on Reactive Programming. *ACM Computing Surveys (to appear)*.

Procedure Modals and Modes in Flute

Procedure Modal:

```
(define to-call (modal (location)
  (define num-of-calls 0)))
```

Reactive context source

Shared variable

Procedure Mode:

```
(define call-from-car
  (mode (to-call)
    (is-in-car? location)
    (suspend resume deferred)
    (lambda ()
      (show "calling business contacts")
      (if (null? contacts-list)
          (show "business contacts list is empty")
          (let ((contact (car contacts-list)))
            (set! contacts-list (cdr contacts-list))
            (show (contact-name contact))
            (dial (phone-number contact))
            (turn-on-phonespeaker)
            (connect-to-car-speakers)
            (if (dial-next-contact? (user-response))
                (to-call))))))))
```

Modal

Context predicate

Interruption, resumption, and scoping strategies

Procedure Modals and Modes in Flute

Procedure Modal:

```
(define to-call (modal (location)
  (define num-of-calls 0)))
```

Reactive context source

Shared variable

Procedure Mode:

```
(define call-from-car
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      (if (null? contacts-list)
          (show "business contac
          (let ((contact (car co
            (set! contacts-list
            (show (contact-name
            (dial (phone-number
            (turn-on-phonespeake
            (connect-to-car-spec
            (if (dial-next-conta
                (to-call)))))))
```

```
(define call-from-conference-room
  (mode (to-call)
    (is-in-conference-room? location)
    (suspend resume deferred)
    (lambda ()
      (show "calling co-workers contacts")
      (if (null? contacts-list)
          (show "co-workers contacts list is empty")
          (let ((contact (car contacts-list)))
            (set! contacts-list (cdr contacts-list))
            (show (contact-name contact))
            (dial (phone-number contact))
            (turn-on-phonespeaker)
            (connect-to-conference-equipment)
            (if (dial-next-contact? (user-response))
                (to-call)))))))
```

Variable Modals and Modes in Flute

Variable Modal:

```
(define contacts-list (modal (location)))
```

Variable Modes:

```
(mode (contacts-list)
  (is-in-car? location)
  (biz-contacts))
```

```
(mode (contacts-list)
  (is-in-conference-room? location)
  (co-workers-contacts))
```

Modal

Context predicate

Value

Variable Modals and Modes in Flute

```
(define call-from-car
  (mode (to-call)
    (is-in-car? location)
    (suspend resume deferred)
    (lambda ()
      (show "calling business contacts")
      (if (null? contacts-list)
          (show "business contacts list is empty")
          (let ((contact (car contacts-list)))
            (set! contacts-list (car contacts-list))
            (show (contact-name contact))
            (dial (phone-number contact))
            (turn-on-phonespeaker)
            (connect-to-car-speakers)
            (if (dial-next-contact? (user-response))
                (to-call)))))))
```

```
(define call-from-conference-room
  (mode (to-call)
    ference-room? location)
    esume deferred)

    alling co-workers contacts")
    l? contacts-list)
    w "co-workers contacts list is empty")
     ((contact (car contacts-list)))
    et! contacts-list (car contacts-list))
    how (contact-name contact))
    ial (phone-number contact))
    urn-on-phonespeaker)
    onnect-to-conference-equipment)
    o-call))))))
```

Different value depending on the current context.

Context-dependent Scoping for Modal Variables

```
(define call-from-car
  (mode (to-call)
    (is-in-car? location)
    (suspend resume deferred)
    (lambda ()
      (show "calling business contacts")
      (if (null? contacts-list)
          (show "business contacts list is empty")
          (let ((contact (car contacts-list)))
            (set! contacts-list (cdr contacts-list))
            (show (contact-name contact))
            (dial (phone-number contact))
            (turn-on-phonespeaker)
            (connect-to-car-speakers)
            (if (dial-next-contact? (user-response))
                (to-call))))))))
```

```
(define call-from-conference-room
  (mode (to-call)
    (is-in-conference-room? location)
    (suspend resume deferred)
    )
    calling co-workers contacts")
    ll? contacts-list)
    ow "co-workers contacts list is empty")
    t ((contact (car contacts-list)))
    set! contacts-list (cdr contacts-list))
    show (contact-name contact))
    dial (phone-number contact))
    turn-on-phonespeaker)
    connect-to-conference-equipment)
    f (dial-next-contact? (user-response))
        (to-call))))))))
```

Scoped assignments

Interruption and Resumption Strategies in Flute

Interruption Strategies

`abort` The execution is aborted when its context predicate is no longer satisfied.

`suspend` The execution is suspended and its execution state is saved.

Resumption Strategies

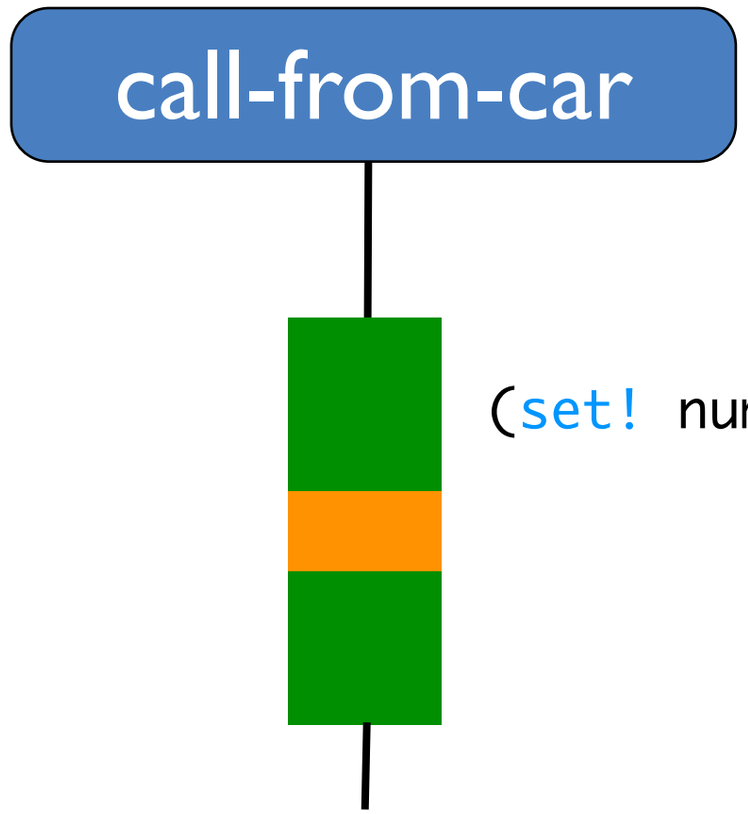
`restart` The execution is restarted from the beginning.

`resume` The execution is resumed from where it left off.

Interruption and Resumption Strategies in Flute

		Resumption Strategies	
Interruption Strategies		`restart`	`resume`
	`abort`	✔	✘
	`suspend`	✔	✔

Scoping of State Changes to Ordinary Variables in Flute



`immediate` Changes are immediately visible to other executions.

`deferred` Changes become visible to other executions on completion.

`isolated` Changes remain locally visible to the execution.

Semantics and Validation

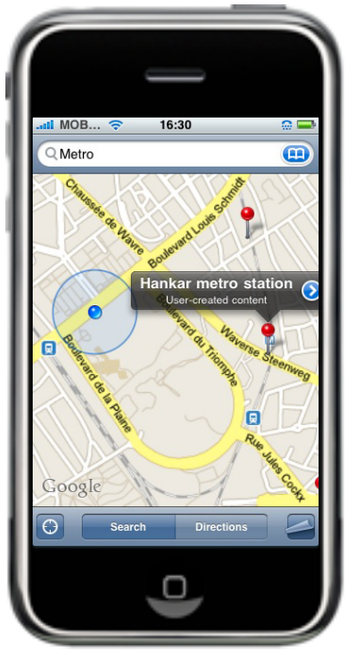
Semantics and Validation

iScheme

An Executable Semantics for Flute

Validation

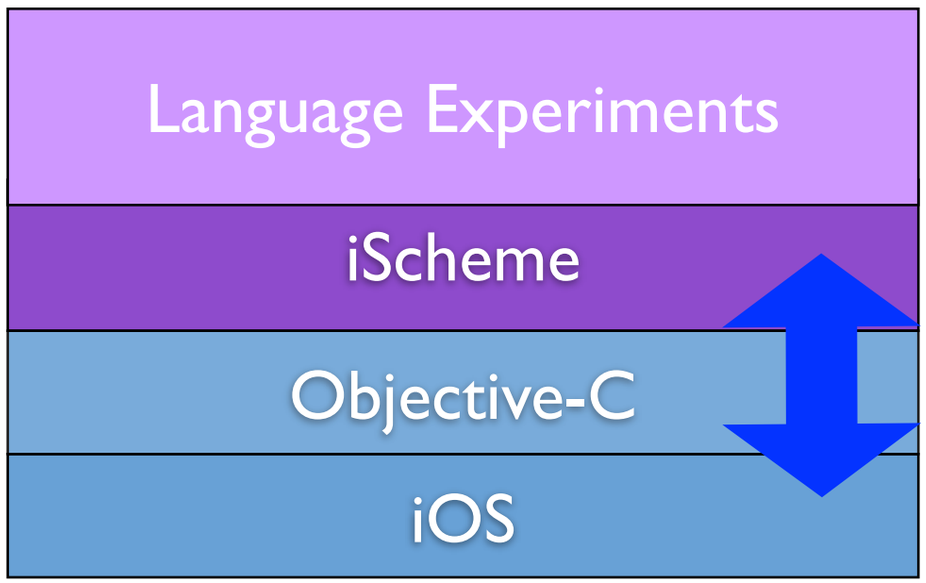
iScheme: A Mobile Language Laboratory



Access to iOS APIs (Sensors, GUI, ...)

Ambient-Oriented Programming

iScheme



Linguistic Symbiosis

Bainomugisha, E. *et.al*. (2012). Bringing Scheme Programming to the iPhone - Experience. *Software: Practice and Experience*, 42(3):331–356.

iScheme: A Mobile Language Laboratory

Language construct	Description
`OBJC-INSTANCE`	For instantiating an Objective-C class from within Scheme.
`OBJC-SEND`	Performing message sends to Objective-C instances.
`OBJC-CLASS`	Getting a reference to an Objective-C class.
`OBJC_TYPE`	A generic representation of Objective-C values in Scheme.
`SCHEME_CALL`	Calling Scheme procedures from Objective-C.
`service-type`	For creating a topic to publish or discover a procedure.
`export-service`	For exporting a procedure as a service.
`cancel-publication`	For cancelling a publication.
`when-discovered`	For discovering a procedure under a specified service type.
`cancel-subscription`	For cancelling a subscription..
`remote-send!`	For performing an asynchronous remote invocation without a return value.
`remote-send`	An asynchronous invocation with a return value.
`when-resolved`	For handling return values of remote invocations.
`due-in`	For specifying a maximum time to wait for a return value.
`catch`	For handling exceptions raised during an asynchronous invocation.

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OBJC_TYPE	A generic representati cheme.
SCHEME_CALL	Calling Scheme procedure
service-type	For creating a topic to publish or discover a procedure.
export-service	For exporting a procedure as a service.
cancel-publication	For cancelling a publication.
when-discovered	For discovering a procedure under a specified service type.
cancel-subscription	For cancelling a subscription..
remote-send!	For performing an asynchronous remote invocation without a return value.
remote-send	An asynchronous invocation with a return value.
when-resolved	For handling return values of remote invocations.
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Linguistic symbiosis constructs

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`cancel-publication`	For cancelling a publicati
`when-discovered`	For discovering a proce e type.
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Distribution constructs

Semantics and Validation

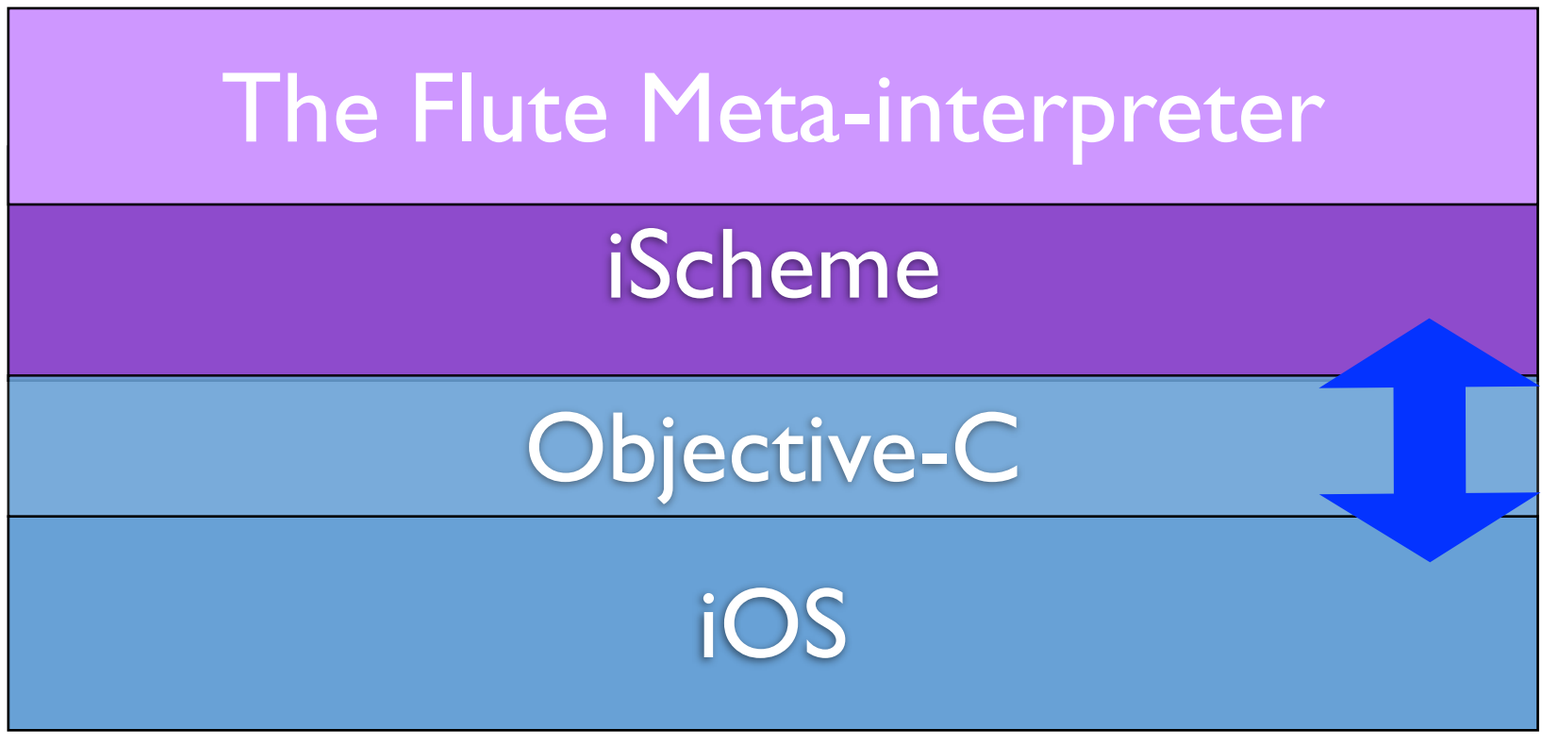
Semantics and Validation

An Executable Semantics for Flute

Validation

An Executable Semantics for Flute

- Flute is implemented as a meta-interpreter on top of iScheme.
- Context sources: GPS, proximity sensor, accelerometer on the iOS.



Bainomugisha, E. *et.al*. (2012). Bringing Scheme Programming to the iPhone - Experience. *Software: Practice and Experience*, 42(3):331–356.

An Executable Semantics for Flute

Mode eval

```
(define (eval-mode modal-expr pred-expr value-expr . exprs)
  (lambda (continue env tailcall)
    (define modal-binding (assoc (car modal-expr) env))

    (define (continue-after-value-expr variable-value env-after-value-expr)
      (define modal (cdr modal-binding))
      (let* ((params      '())
             (modal-envt (modal-env modal))
             (mode-envt  (append modal-envt env))
             (mode-proc  (make-proc params (list value-expr) mode-envt))
             (mode       (make-mode pred-expr mode-proc mode-envt)))
        (add-mode! modal mode)
        (continue mode-proc env)))

    (define (continue-after-config mode-config env-after-value-expr)
      (define (mode-params exprs)
        (car (cdr (car exprs))))
      (define (mode-exprs exprs)
        (cdr (cdr (car exprs))))
      (define modal (cdr modal-binding))
      (let* ((params       (mode-params exprs))
             (body-exprs   (mode-exprs exprs))
             (event-sources (modal-event-sources modal))
             (modal-envt   (modal-env modal))
             (mode-envt    (append modal-envt env))
             (mode-proc    (make-c-proc params
                                        (cons event-sources pred-expr)
                                        mode-config body-exprs mode-envt))
             (mode         (make-mode pred-expr mode-proc mode-envt)))
        (add-mode! modal mode)
        (continue mode-proc env)))

    (if (pair? exprs)
        (eval (car value-expr) continue-after-config  env #f)
        (eval value-expr continue-after-value-expr  env #f))))
```

Contextual and reactive dispatch eval

```
(define (eval-seq pred-expr config body-exprs args continue env tailcall)
 (define head                (car body-exprs))
 (define tail                (cdr body-exprs))
 (define context-sources     (car pred-expr))
 (define context-pred        (cdr pred-expr))

 (define (continue-with-seq value env-after-seq)
   (eval-seq pred-expr config tail args continue env-after-seq tailcall))

 (define (continue-after-context-pred boolean env-after-pred)
   (if (equal? boolean #f)
       (begin
         (save-execution resume-evaluation context-sources)
         (continue interrupted env-after-pred))
       (if (null? tail)
           (eval head continue env-after-pred tailcall)
           (eval head continue-with-seq env-after-pred #f))))

 (eval context-pred continue-after-context-pred env #f))
```

Procedure's body eval

```
(define (eval-seq pred-expr config body-exprs args continue env tailcall)
 (define head                (car body-exprs))
 (define tail                (cdr body-exprs))
 (define context-sources     (car pred-expr))
 (define context-pred        (cdr pred-expr))

 (define (continue-with-seq value env-after-seq)
   (eval-seq pred-expr config tail args continue env-after-seq tailcall))

 (define (continue-after-context-pred boolean env-after-pred)
   (if (equal? boolean #f)
       (begin
         (save-execution resume-evaluation context-sources)
         (continue interrupted env-after-pred))
       (if (null? tail)
           (eval head continue env-after-pred tailcall)
           (eval head continue-with-seq env-after-pred #f))))

 (eval context-pred continue-after-context-pred env #f))
```

Modal eval

```
(define (eval-modal . exprs)
  (lambda (continue env tailcall)
    (define empty-envt '())
    (define (lookup variable)
      (define binding (assoc variable env))
      (if (pair? binding)
          (cdr binding)
          (meta-level-eval variable (interaction-env))))

    (if (pair? exprs)
        (let* ((params       (car exprs))
               (args         (map lookup params))
               (event-sources args)
               (modal-envt   (bind-params params args empty-envt)))
          (define (continue-after-modal-exprs value env-after-modal-exprs)
            (continue (make-modal event-sources env-after-modal-exprs) env))
          (if (pair? (cdr exprs))
              (eval-seq (cdr exprs)
                        continue-after-modal-exprs
                        modal-envt tailcall)
              (continue-after-modal-exprs '()  modal-envt)))
        (continue (make-modal '() empty-envt) env))))
```

Main eval

```
(define (eval expr continue env tailcall)
  (cond
    ((symbol? expr)
     (eval-variable expr continue env))
    ((pair? expr)
     (let ((operator (car expr))
           (operands (cdr expr)))
       ((apply
         (case operator
           ((begin)            eval-begin       )
           ((define)           eval-define      )
           ((if)               eval-if          )
           ((lambda)           eval-lambda      )
           ((quote)            eval-quote       )
           ((set!)             eval-set!        )
           ((while)            eval-while       )
           ((let)              eval-let         )
           ((c-let)            eval-c-let       )
           ((let*)             eval-let*        )
           ((continuous)       eval-continuous  )
           ((c-set!)           eval-c-set!      )
           ((c-ref)            eval-c-ref       )
           ((modal)            eval-modal       )
           ((mode)             eval-mode        )
           ((OBJC-SEND)        eval-objc-send   )
           ((OBJC-CLASS)       eval-objc-class  )
           ((OBJC-INSTANCE)    eval-objc-instance)
           (else               (eval-application operator)))
         operands) continue env tailcall)))
    (else (continue expr env))))
```

Reactive values eval

```
(define (eval-modal . exprs)
  (lambda (continue env tailcall)
    (define empty-envt '())
    (define (lookup variable)
      (define binding (assoc variable env))
      (if (pair? binding)
          (cdr binding)
          (meta-level-eval variable (interaction-env))))

    (if (pair? exprs)
        (let* ((params       (car exprs))
               (args         (map lookup params))
               (event-sources args)
               (modal-envt   (bind-params params args empty-envt)))
          (define (continue-after-modal-exprs value env-after-modal-exprs)
            (continue (make-modal event-sources env-after-modal-exprs) env))
          (if (pair? (cdr exprs))
              (eval-seq (cdr exprs)
                        continue-after-modal-exprs
                        modal-envt tailcall)
              (continue-after-modal-exprs '()  modal-envt)))
        (continue (make-modal '() empty-envt) env))))
```

Modal invocation eval

```
(define (eval-modal . exprs)
  (lambda (continue env tailcall)
    (define empty-envt '())
    (define (lookup variable)
      (define binding (assoc variable env))
      (if (pair? binding)
          (cdr binding)
          (meta-level-eval variable (interaction-env))))

    (if (pair? exprs)
        (let* ((params       (car exprs))
               (args         (map lookup params))
               (event-sources args)
               (modal-envt   (bind-params params args empty-envt)))
          (define (continue-after-modal-exprs value env-after-modal-exprs)
            (continue (make-modal event-sources env-after-modal-exprs) env))
          (if (pair? (cdr exprs))
              (eval-seq (cdr exprs)
                        continue-after-modal-exprs
                        modal-envt tailcall)
              (continue-after-modal-exprs '()  modal-envt)))
        (continue (make-modal '() empty-envt) env))))
```

Variable modal access eval

```
(define (eval-modal . exprs)
  (lambda (continue env tailcall)
    (define empty-envt '())
    (define (lookup variable)
      (define binding (assoc variable env))
      (if (pair? binding)
          (cdr binding)
          (meta-level-eval variable (interaction-env))))

    (if (pair? exprs)
        (let* ((params       (car exprs))
               (args         (map lookup params))
               (event-sources args)
               (modal-envt   (bind-params params args empty-envt)))
          (define (continue-after-modal-exprs value env-after-modal-exprs)
            (continue (make-modal event-sources env-after-modal-exprs) env))
          (if (pair? (cdr exprs))
              (eval-seq (cdr exprs)
                        continue-after-modal-exprs
                        modal-envt tailcall)
              (continue-after-modal-exprs '()  modal-envt)))
        (continue (make-modal '() empty-envt) env))))
```

Scoped assignments eval

```
(define (eval-modal . exprs)
  (lambda (continue env tailcall)
    (define empty-envt '())
    (define (lookup variable)
      (define binding (assoc variable env))
      (if (pair? binding)
          (cdr binding)
          (meta-level-eval variable (interaction-env))))

    (if (pair? exprs)
        (let* ((params       (car exprs))
               (args         (map lookup params))
               (event-sources args)
               (modal-envt   (bind-params params args empty-envt)))
          (define (continue-after-modal-exprs value env-after-modal-exprs)
            (continue (make-modal event-sources env-after-modal-exprs) env))
          (if (pair? (cdr exprs))
              (eval-seq (cdr exprs)
                        continue-after-modal-exprs
                        modal-envt tailcall)
              (continue-after-modal-exprs '()  modal-envt)))
        (continue (make-modal '() empty-envt) env))))
```

An Executable Semantics for Flute

Mode eval

```
(define (eval-mode modal-expr pred-expr value-expr . exprs)
  (lambda (continue env tailcall)
    (define modal-binding (assoc (car modal-expr) env))

    (define (continue-after-value-expr variable-value env-after-value-expr)
      (define modal (cdr modal-binding))
      (let* ((params      '())
             (modal-envt (modal-env modal))
             (mode-envt  (append modal-envt env))
             (mode-proc  (make-proc params (list value-expr) mode-envt))
             (mode       (make-mode pred-expr mode-proc mode-envt)))
        (add-mode! modal mode)
        (continue mode-proc env)))

    (define (continue-after-config mode-config env-after-value-expr)
      (define (mode-params exprs)
        (car (cdr (car exprs))))
      (define (mode-exprs exprs)
        (cdr (cdr (car exprs))))
      (define modal (cdr modal-binding))
      (let* ((params        (mode-params exprs))
             (body-exprs    (mode-exprs exprs))
             (event-sources (modal-event-sources modal))
             (modal-envt    (modal-env modal))
             (mode-envt     (append modal-envt env))
             (mode-proc     (make-c-proc params
                                         (cons event-sources pred-expr)
                                         mode-config body-exprs mode-envt))
             (mode          (make-mode pred-expr mode-proc mode-envt)))
        (add-mode! modal mode)
        (continue mode-proc env)))

    (if (pair? exprs)
        (eval (car value-expr) continue-after-config  env #f)
        (eval value-expr continue-after-value-expr  env #f))))
```

Contextual and reactive dispatch eval

```
(define (eval-seq pred-expr config body-exprs args continue env tailcall)
  (define head                (car body-exprs))
  (define tail                (cdr body-exprs))
  (define context-sources     (car pred-expr))
  (define context-pred        (cdr pred-expr))

  (define (continue-with-seq value env-after-seq)
    (eval-seq pred-expr config tail args continue env-after-seq tailcall))

  (define (continue-after-context-pred boolean env-after-pred)
    (if (equal? boolean #f)
        (begin
          (save-execution resume-evaluation context-sources)
          (continue interrupted env-after-pred))
        (if (null? tail)
            (eval head continue env-after-pred tailcall)
            (eval head continue-with-seq env-after-pred #f))))

  (eval context-pred continue-after-context-pred env #f))
```

Procedure's body eval

```
(define (eval-seq pred-expr config body-exprs args continue env tailcall)
  (define head                (car body-exprs))
  (define tail                (cdr body-exprs))
  (define context-sources     (car pred-expr))
  (define context-pred        (cdr pred-expr))

  (define (continue-with-seq value env-after-seq)
    (eval-seq pred-expr config tail args continue env-after-seq tailcall))

  (define (continue-after-context-pred boolean env-after-pred)
    (if (equal? boolean #f)
        (begin
          (save-execution resume-evaluation context-sources)
          (continue interrupted env-after-pred))
        (if (null? tail)
            (eval head continue env-after-pred tailcall)
            (eval head continue-with-seq env-after-pred #f))))

  (eval context-pred continue-after-context-pred env #f))
```

Modal eval

```
(define (eval-modal . exprs)
  (lambda (continue env tailcall)
    (define empty-envt '())
    (define (lookup variable)
      (define binding (assoc variable env))
      (if (pair? binding)
          (cdr binding)
          (meta-level-eval variable (interaction-env))))

    (if (pair? exprs)
        (let* ((params        (car exprs))
               (args          (map lookup params))
               (event-sources args)
               (modal-envt    (bind-params params args empty-envt)))
          (define (continue-after-modal-exprs value env-after-modal-exprs)
            (continue (make-modal event-sources env-after-modal-exprs) env))
          (if (pair? (cdr exprs))
              (eval-seq (cdr exprs)
                        continue-after-modal-exprs
                        modal-envt tailcall)
              (continue-after-modal-exprs '()  modal-envt)))
        (continue (make-modal '() empty-envt) env))))
```

Main eval

```
(define (eval expr continue env tailcall)
  (cond
    ((symbol? expr)
     (eval-variable expr continue env))
    ((pair? expr)
     (let ((operator (car expr))
           (operands (cdr expr)))
       ((apply
         (case operator
           ((begin)            eval-begin       )
           ((define)           eval-define      )
           ((if)               eval-if          )
           ((lambda)           eval-lambda      )
           ((quote)            eval-quote       )
           ((set!)             eval-set!        )
           ((while)            eval-while       )
           ((let)              eval-let         )
           ((c-let)            eval-c-let       )
           ((let*)             eval-let*        )
           ((continuous)       eval-continuous  )
           ((c-set!)           eval-c-set!      )
           ((c-ref)            eval-c-ref       )
           ((modal)            eval-modal       )
           ((mode)             eval-mode        )
           ((OBJC-SEND)        eval-objc-send   )
           ((OBJC-CLASS)       eval-objc-class  )
           ((OBJC-INSTANCE)    eval-objc-instance)
           (else               (eval-application operator)))
         operands) continue env tailcall)))
    (else (continue expr env))))
```

Reactive values eval

```
(define (eval-modal . exprs)
  (lambda (continue env tailcall)
    (define empty-envt '())
    (define (lookup variable)
      (define binding (assoc variable env))
      (if (pair? binding)
          (cdr binding)
          (meta-level-eval variable (interaction-env))))

    (if (pair? exprs)
        (let* ((params        (car exprs))
               (args          (map lookup params))
               (event-sources args)
               (modal-envt    (bind-params params args empty-envt)))
          (define (continue-after-modal-exprs value env-after-modal-exprs)
            (continue (make-modal event-sources env-after-modal-exprs) env))
          (if (pair? (cdr exprs))
              (eval-seq (cdr exprs)
                        continue-after-modal-exprs
                        modal-envt tailcall)
              (continue-after-modal-exprs '()  modal-envt)))
        (continue (make-modal '() empty-envt) env))))
```

Modal invocation eval

```
(define (eval-modal . exprs)
  (lambda (continue env tailcall)
    (define empty-envt '())
    (define (lookup variable)
      (define binding (assoc variable env))
      (if (pair? binding)
          (cdr binding)
          (meta-level-eval variable (interaction-env))))

    (if (pair? exprs)
        (let* ((params        (car exprs))
               (args          (map lookup params))
               (event-sources args)
               (modal-envt    (bind-params params args empty-envt)))
          (define (continue-after-modal-exprs value env-after-modal-exprs)
            (continue (make-modal event-sources env-after-modal-exprs) env))
          (if (pair? (cdr exprs))
              (eval-seq (cdr exprs)
                        continue-after-modal-exprs
                        modal-envt tailcall)
              (continue-after-modal-exprs '()  modal-envt)))
        (continue (make-modal '() empty-envt) env))))
```

Variable modal access eval

```
(define (eval-modal . exprs)
  (lambda (continue env tailcall)
    (define empty-envt '())
    (define (lookup variable)
      (define binding (assoc variable env))
      (if (pair? binding)
          (cdr binding)
          (meta-level-eval variable (interaction-env))))

    (if (pair? exprs)
        (let* ((params        (car exprs))
               (args          (map lookup params))
               (event-sources args)
               (modal-envt    (bind-params params args empty-envt)))
          (define (continue-after-modal-exprs value env-after-modal-exprs)
            (continue (make-modal event-sources env-after-modal-exprs) env))
          (if (pair? (cdr exprs))
              (eval-seq (cdr exprs)
                        continue-after-modal-exprs
                        modal-envt tailcall)
              (continue-after-modal-exprs '()  modal-envt)))
        (continue (make-modal '() empty-envt) env))))
```

Scoped assignments eval

```
(define (eval-modal . exprs)
  (lambda (continue env tailcall)
    (define empty-envt '())
    (define (lookup variable)
      (define binding (assoc variable env))
      (if (pair? binding)
          (cdr binding)
          (meta-level-eval variable (interaction-env))))

    (if (pair? exprs)
        (let* ((params        (car exprs))
               (args          (map lookup params))
               (event-sources args)
               (modal-envt    (bind-params params args empty-envt)))
          (define (continue-after-modal-exprs value env-after-modal-exprs)
            (continue (make-modal event-sources env-after-modal-exprs) env))
          (if (pair? (cdr exprs))
              (eval-seq (cdr exprs)
                        continue-after-modal-exprs
                        modal-envt tailcall)
              (continue-after-modal-exprs '()  modal-envt)))
        (continue (make-modal '() empty-envt) env))))
```

Contextual and Reactive Dispatch Evaluation

```
(define (eval-modal-dispatch modal continue env)
  (define modes      (modal-modes modal))
  (define preds      (modal-preds modal))
  (define true-count-end   1)
  (define true-count-start 0)

  (define (iterate preds modes true-count mode-proc modes-after-dispatch)
    (if (null? preds)
        (if (= true-count true-count-end)
              (continue mode-proc env))
              (if (< true-count true-count-end)
                  (continue #f env)
                  (error "Ambiguous predicates for procedure modal" true-count)))
      (let* ((head-pred       (car preds))
             (tail-preds      (cdr preds))
             (head-mode       (car modes))
             (tail-modes      (cdr modes))
             (mode-envt       (mode-env head-mode))
             (remaining-modes (cons head-mode modes-after-dispatch))
             (head-mode-proc  (mode-proc head-mode)))
        (define (continue-after-pred value env)
          (if value
              (iterate tail-preds  tail-modes (+ true-count 1) head-mode-proc modes-after-dispatch)
              (iterate tail-preds  tail-modes true-count mode-proc remaining-modes)))
        (eval head-pred continue-after-pred  mode-envt #f))))
  (iterate preds modes true-count-start #f '()))
```

Contextual and Reactive Dispatch Evaluation

```
(define (eval-modal-dispatch modal continue env)
  (define modes      (modal-modes modal))
  (define preds      (modal-preds modal))
  (define true-count-end   1)
  (define true-count-start 0)

  (define (iterate preds modes true-count mode-proc modes-after-dispatch)
    (if (null? preds)
        (if (= true-count true-count-end)
              (continue mode-proc env))
              (if (< true-count true-count-end)
                  (continue #f env)
                  (error "Ambiguous predicates for procedure modal" true-count)))
      (let* ((head-pred       (car preds))
             (tail-preds      (cdr preds))
             (head-mode       (car modes))
             (tail-modes      (cdr modes))
             (mode-envt       (mode-env head-mode))
             (remaining-modes (cons head-mode modes-after-dispatch))
             (head-mode-proc  (mode-proc head-mode)))
        (define (continue-after-pred value env)
          (if value
              (iterate tail-preds  tail-modes (+ true-count 1) head-mode-proc modes-after-dispatch)
              (iterate tail-preds  tail-modes true-count mode-proc remaining-modes)))
        (eval head-pred continue-after-pred  mode-envt #f))))
  (iterate preds modes true-count-start #f '()))
```

Contextual and Reactive Dispatch Evaluation

```
(define (eval-modal-dispatch modal continue env)
  (define modes       (modal-modes modal))
  (define preds       (modal-preds modal))
  (define true-count-end   1)
  (define true-count-start 0)

  (define (iterate preds modes true-count mode-proc modes-after-dispatch)
    (if (null? preds)
        (if (= true-count true-count-end)
              (continue mode-proc env))
              (if (< true-count true-count-end)
                  (continue #f env)
                  (error "Ambiguous predicates for procedure modal" true-count)))
        (let* ((head-pred       (car preds))
               (tail-preds      (cdr preds))
               (head-mode       (car modes))
               (tail-modes      (cdr modes))
               (mode-envt       (mode-env head-mode))
               (remaining-modes (cons head-mode modes-after-dispatch))
               (head-mode-proc  (mode-proc head-mode)))
          (define (continue-after-pred value env)
            (if value
                (iterate tail-preds  tail-modes (+ true-count 1) head-mode-proc modes-after-dispatch)
                (iterate tail-preds  tail-modes true-count mode-proc remaining-modes)))
          (eval head-pred continue-after-pred  mode-envt #f))))
  (iterate preds modes true-count-start #f '()))
```

Contextual and Reactive Dispatch Evaluation

```
(define (eval-modal-dispatch modal continue env)
  (define modes      (modal-modes modal))
  (define preds      (modal-preds modal))
  (define true-count-end   1)
  (define true-count-start 0)

  (define (iterate preds modes true-count mode-proc modes-after-dispatch)
    (if (null? preds)
        (if (= true-count true-count-end)
              (continue mode-proc env))
              (if (< true-count true-count-end)
                  (continue #f env)
                  (error "Ambiguous predicates for procedure modal" true-count)))
        (let* ((head-pred       (car preds))
               (tail-preds      (cdr preds))
               (head-mode       (car modes))
               (tail-modes      (cdr modes))
               (mode-envt       (mode-env head-mode))
               (remaining-modes (cons head-mode modes-after-dispatch))
               (head-mode-proc  (mode-proc head-mode)))
          (define (continue-after-pred value env)
            (if value
                (iterate tail-preds  tail-modes (+ true-count 1) head-mode-proc modes-after-dispatch)
                (iterate tail-preds  tail-modes true-count mode-proc remaining-modes)))
          (eval head-pred continue-after-pred  mode-envt #f))))
  (iterate preds modes true-count-start #f '()))
```

Contextual and Reactive Dispatch Evaluation

```
(define (eval-modal-dispatch modal continue env)
  (define modes      (modal-modes modal))
  (define preds      (modal-preds modal))
  (define true-count-end   1)
  (define true-count-start 0)

  (define (iterate preds modes true-count mode-proc modes-after-dispatch)
    (if (null? preds)
        (if (= true-count true-count-end)
              (continue mode-proc env))
              (if (< true-count true-count-end)
                  (continue #f env)
                  (error "Ambiguous predicates for procedure modal" true-count)))
        (let* ((head-pred       (car preds))
               (tail-preds      (cdr preds))
               (head-mode       (car modes))
               (tail-modes      (cdr modes))
               (mode-envt       (mode-env head-mode))
               (remaining-modes (cons head-mode modes-after-dispatch))
               (head-mode-proc  (mode-proc head-mode)))
          (define (continue-after-pred value env)
            (if value
                (iterate tail-preds  tail-modes (+ true-count 1) head-mode-proc modes-after-dispatch)
                (iterate tail-preds  tail-modes true-count mode-proc remaining-modes)))
          (eval head-pred continue-after-pred  mode-envt #f))))
  (iterate preds modes true-count-start #f  ()))
```

Contextual and Reactive Dispatch Evaluation

```
(define (eval-modal-dispatch modal continue env)
  (define modes      (modal-modes modal))
  (define preds      (modal-preds modal))
  (define true-count-end   1)
  (define true-count-start 0)

  (define (iterate preds modes true-count mode-proc modes-after-dispatch)
    (if (null? preds)
        (if (= true-count true-count-end)
              (continue mode-proc env))
              (if (< true-count true-count-end)
                  (continue #f env)
                  (error "Ambiguous predicates for procedure modal" true-count)))
        (let* ((head-pred       (car preds))
               (tail-preds      (cdr preds))
               (head-mode       (car modes))
               (tail-modes      (cdr modes))
               (mode-envt       (mode-env head-mode))
               (remaining-modes (cons head-mode modes-after-dispatch))
               (head-mode-proc  (mode-proc head-mode)))
          (define (continue-after-pred value env)
            (if value
                (iterate tail-preds  tail-modes (+ true-count 1) head-mode-proc modes-after-dispatch)
                (iterate tail-preds  tail-modes true-count mode-proc remaining-modes)))
          (eval head-pred continue-after-pred  mode-envt #f))))
  (iterate preds modes true-count-start #f '()))
```

Contextual and Reactive Dispatch Evaluation

```
(define (eval-modal-dispatch modal continue env)
  (define modes      (modal-modes modal))
  (define preds      (modal-preds modal))
  (define true-count-end   1)
  (define true-count-start 0)

  (define (iterate preds modes true-count mode-proc modes-after-dispatch)
    (if (null? preds)
        (if (= true-count true-count-end)
            (continue mode-proc env))
            (if (< true-count true-count-end)
                (continue #f env)
                (error "Ambiguous predicates for procedure modal" true-count)))
        (let* ((head-pred       (car preds))
               (tail-preds      (cdr preds))
               (head-mode       (car modes))
               (tail-modes      (cdr modes))
               (mode-envt       (mode-env head-mode))
               (remaining-modes (cons head-mode modes-after-dispatch))
               (head-mode-proc  (mode-proc head-mode)))
          (define (continue-after-pred value env)
            (if value
                (iterate tail-preds  tail-modes (+ true-count 1) head-mode-proc modes-after-dispatch)
                (iterate tail-preds  tail-modes true-count mode-proc remaining-modes)))
          (eval head-pred continue-after-pred  mode-envt #f))))
  (iterate preds modes true-count-start #f '()))
```

Contextual and Reactive Dispatch Evaluation

```
(define (eval-modal-dispatch modal continue env)
  (define modes      (modal-modes modal))
  (define preds      (modal-preds modal))
  (define true-count-end   1)
  (define true-count-start 0)

  (define (iterate preds modes true-count mode-proc modes-after-dispatch)
    (if (null? preds)
        (if (= true-count true-count-end)
            (continue mode-proc env))
            (if (< true-count true-count-end)
                (continue #f env)
                (error "Ambiguous predicates for procedure modal" true-count)))
        (let* ((head-pred       (car preds))
               (tail-preds      (cdr preds))
               (head-mode       (car modes))
               (tail-modes      (cdr modes))
               (mode-envt       (mode-env head-mode))
               (remaining-modes (cons head-mode modes-after-dispatch))
               (head-mode-proc  (mode-proc head-mode)))
          (define (continue-after-pred value env)
            (if value
                (iterate tail-preds  tail-modes (+ true-count 1) head-mode-proc modes-after-dispatch)
                (iterate tail-preds  tail-modes true-count mode-proc remaining-modes)))
          (eval head-pred continue-after-pred  mode-envt #f))))
  (iterate preds modes true-count-start #f '()))
```

Contextual and Reactive Dispatch Evaluation

```
(define (eval-modal-dispatch modal continue env)
  (define modes      (modal-modes modal))
  (define preds      (modal-preds modal))
  (define true-count-end   1)
  (define true-count-start 0)

  (defin
    (if
```

```
(if (ormap event? context-sources)
    (let* ((dispatcher (ctx-event))
           (resumption-point
            (lambda ()
              (eval-modal-dispatch modal continue-after-dispatch env))))
      (set-thunk! dispatcher resumption-point)
      (for-each
       (lambda (context-source)
         (if (event? context-source)
             (register dispatcher context-source)))
       (listify context-sources))))
```

```
          (head-mode-proc  (mode-proc head-mode)))
      (define (continue-after-pred value env)
        (if value
            (iterate tail-preds  tail-modes (+ true-count 1) head-mode-proc modes-after-dispatch)
            (iterate tail-preds  tail-modes true-count mode-proc remaining-modes)))
      (eval head-pred continue-after-pred  mode-envt #f))))
(iterate preds modes true-count-start #f '()))
```

Contextual and Reactive Dispatch Evaluation

```
(define (eval-modal-dispatch modal continue env)
  (define modes      (modal-modes modal))
  (define preds      (modal-preds modal))
  (define true-count-end   1)
  (define true-count-start 0)

  (if (ormap event? context-sources)
      (let* ((dispatcher (ctx-event))
             (resumption-point
              (lambda ()
                (eval-modal-dispatch modal continue-after-dispatch env))))
        (set-thunk! dispatcher resumption-point)
        (for-each
         (lambda (context-source)
           (if (event? context-source)
               (register dispatcher context-source)))
         (listify context-sources))))

      (head-mode-proc  (mode-proc head-mode)))
    (define (continue-after-pred value env)
      (if value
          (iterate tail-preds  tail-modes (+ true-count 1) head-mode-proc modes-after-dispatch)
          (iterate tail-preds  tail-modes true-count mode-proc remaining-modes)))
    (eval head-pred continue-after-pred  mode-envt #f))))
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```

Contextual and Reactive Dispatch Evaluation

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(define (eval-modal-dispatch modal continue env)
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  (define preds      (modal-preds modal))
  (define true-count-end   1)
  (define true-count-start 0)

  (defin
    (if
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            (lambda ()
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      (set-thunk! dispatcher resumption-point)
      (for-each
       (lambda (context-source)
         (if (event? context-source)
             (register dispatcher context-source)))
       (listify context-sources))))
```

```
          (head-mode-proc  (mode-proc head-mode)))
      (define (continue-after-pred value env)
        (if value
            (iterate tail-preds  tail-modes (+ true-count 1) head-mode-proc modes-after-dispatch)
            (iterate tail-preds  tail-modes true-count mode-proc remaining-modes)))
      (eval head-pred continue-after-pred  mode-envt #f))))
(iterate preds modes true-count-start #f '()))
```

Contextual and Reactive Dispatch Evaluation

```
(define (eval-modal-dispatch modal continue env)
  (define modes      (modal-modes modal))
  (define preds      (modal-preds modal))
  (define true-count-end   1)
  (define true-count-start 0)

  (defin
    (if
```

```
(if (ormap event? context-sources)
    (let* ((dispatcher (ctx-event))
           (resumption-point
            (lambda ()
              (eval-modal-dispatch modal continue-after-dispatch env))))
      (set-thunk! dispatcher resumption-point)
      (for-each
       (lambda (context-source)
         (if (event? context-source)
             (register dispatcher context-source)))
       (listify context-sources))))
```

```
          (head-mode-proc  (mode-proc head-mode)))
      (define (continue-after-pred value env)
        (if value
            (iterate tail-preds  tail-modes (+ true-count 1) head-mode-proc modes-after-dispatch)
            (iterate tail-preds  tail-modes true-count mode-proc remaining-modes)))
      (eval head-pred continue-after-pred  mode-envt #f))))
(iterate preds modes true-count-start #f '()))
```

An Executable Semantics for Flute

Mode eval

```
(define (eval-mode modal-expr pred-expr value-expr . exprs)
  (lambda (continue env tailcall)
    (define modal-binding (assoc (car modal-expr) env))

    (define (continue-after-value-expr variable-value env-after-value-expr)
      (define modal (cdr modal-binding))
      (let* ((params      '())
             (modal-envt (modal-env modal))
             (mode-envt  (append modal-envt env))
             (mode-proc  (make-proc params (list value-expr) mode-envt))
             (mode       (make-mode pred-expr mode-proc mode-envt)))
        (add-mode! modal mode)
        (continue mode-proc env)))

    (define (continue-after-config mode-config env-after-value-expr)
      (define (mode-params exprs)
        (car (cdr (car exprs))))
      (define (mode-exprs exprs)
        (cdr (cdr (car exprs))))
      (define modal (cdr modal-binding))
      (let* ((params       (mode-params exprs))
             (body-exprs   (mode-exprs exprs))
             (event-sources (modal-event-sources modal))
             (modal-envt   (modal-env modal))
             (mode-envt    (append modal-envt env))
             (mode-proc    (make-c-proc params
                                        (cons event-sources pred-expr)
                                        mode-config body-exprs mode-envt))
             (mode         (make-mode pred-expr mode-proc mode-envt)))
        (add-mode! modal mode)
        (continue mode-proc env)))

    (if (pair? exprs)
        (eval (car value-expr) continue-after-config  env #f)
        (eval value-expr continue-after-value-expr  env #f))))
```

Contextual and reactive dispatch eval

```
(define (eval-seq pred-expr config body-exprs args continue env tailcall)
  (define head                (car body-exprs))
  (define tail                (cdr body-exprs))
  (define context-sources     (car pred-expr))
  (define context-pred        (cdr pred-expr))

  (define (continue-with-seq value env-after-seq)
    (eval-seq pred-expr config tail args continue env-after-seq tailcall))

  (define (continue-after-context-pred boolean env-after-pred)
    (if (equal? boolean #f)
        (begin
          (save-execution resume-evaluation context-sources)
          (continue interrupted env-after-pred))
        (if (null? tail)
            (eval head continue env-after-pred tailcall)
            (eval head continue-with-seq env-after-pred #f))))

  (eval context-pred continue-after-context-pred env #f))
```

Procedure's body eval

```
(define (eval-seq pred-expr config body-exprs args continue env tailcall)
  (define head                (car body-exprs))
  (define tail                (cdr body-exprs))
  (define context-sources     (car pred-expr))
  (define context-pred        (cdr pred-expr))

  (define (continue-with-seq value env-after-seq)
    (eval-seq pred-expr config tail args continue env-after-seq tailcall))

  (define (continue-after-context-pred boolean env-after-pred)
    (if (equal? boolean #f)
        (begin
          (save-execution resume-evaluation context-sources)
          (continue interrupted env-after-pred))
        (if (null? tail)
            (eval head continue env-after-pred tailcall)
            (eval head continue-with-seq env-after-pred #f))))

  (eval context-pred continue-after-context-pred env #f))
```

Modal eval

```
(define (eval-modal . exprs)
  (lambda (continue env tailcall)
    (define empty-envt '())
    (define (lookup variable)
      (define binding (assoc variable env))
      (if (pair? binding)
          (cdr binding)
          (meta-level-eval variable (interaction-env))))

    (if (pair? exprs)
        (let* ((params       (car exprs))
               (args         (map lookup params))
               (event-sources args)
               (modal-envt   (bind-params params args empty-envt)))
          (define (continue-after-modal-exprs value env-after-modal-exprs)
            (continue (make-modal event-sources env-after-modal-exprs) env))
          (if (pair? (cdr exprs))
              (eval-seq (cdr exprs)
                        continue-after-modal-exprs
                        modal-envt tailcall)
              (continue-after-modal-exprs '()  modal-envt)))
        (continue (make-modal '() empty-envt) env))))
```

Main eval

```
(define (eval expr continue env tailcall)
  (cond
    ((symbol? expr)
     (eval-variable expr continue env))
    ((pair? expr)
     (let ((operator (car expr))
           (operands (cdr expr)))
       ((apply
         (case operator
           ((begin)            eval-begin       )
           ((define)           eval-define      )
           ((if)               eval-if          )
           ((lambda)           eval-lambda      )
           ((quote)            eval-quote       )
           ((set!)             eval-set!        )
           ((while)            eval-while       )
           ((let)              eval-let         )
           ((c-let)            eval-c-let       )
           ((let*)             eval-let*        )
           ((continuous)       eval-continuous  )
           ((c-set!)           eval-c-set!      )
           ((c-ref)            eval-c-ref       )
           ((modal)            eval-modal       )
           ((mode)             eval-mode        )
           ((OBJC-SEND)        eval-objc-send   )
           ((OBJC-CLASS)       eval-objc-class  )
           ((OBJC-INSTANCE)    eval-objc-instance)
           (else               (eval-application operator)))
         operands) continue env tailcall)))
    (else (continue expr env))))
```

Reactive values eval

```
(define (eval-modal . exprs)
  (lambda (continue env tailcall)
    (define empty-envt '())
    (define (lookup variable)
      (define binding (assoc variable env))
      (if (pair? binding)
          (cdr binding)
          (meta-level-eval variable (interaction-env))))

    (if (pair? exprs)
        (let* ((params       (car exprs))
               (args         (map lookup params))
               (event-sources args)
               (modal-envt   (bind-params params args empty-envt)))
          (define (continue-after-modal-exprs value env-after-modal-exprs)
            (continue (make-modal event-sources env-after-modal-exprs) env))
          (if (pair? (cdr exprs))
              (eval-seq (cdr exprs)
                        continue-after-modal-exprs
                        modal-envt tailcall)
              (continue-after-modal-exprs '()  modal-envt)))
        (continue (make-modal '() empty-envt) env))))
```

Modal invocation eval

```
(define (eval-modal . exprs)
  (lambda (continue env tailcall)
    (define empty-envt '())
    (define (lookup variable)
      (define binding (assoc variable env))
      (if (pair? binding)
          (cdr binding)
          (meta-level-eval variable (interaction-env))))

    (if (pair? exprs)
        (let* ((params       (car exprs))
               (args         (map lookup params))
               (event-sources args)
               (modal-envt   (bind-params params args empty-envt)))
          (define (continue-after-modal-exprs value env-after-modal-exprs)
            (continue (make-modal event-sources env-after-modal-exprs) env))
          (if (pair? (cdr exprs))
              (eval-seq (cdr exprs)
                        continue-after-modal-exprs
                        modal-envt tailcall)
              (continue-after-modal-exprs '()  modal-envt)))
        (continue (make-modal '() empty-envt) env))))
```

Variable modal access eval

```
(define (eval-modal . exprs)
  (lambda (continue env tailcall)
    (define empty-envt '())
    (define (lookup variable)
      (define binding (assoc variable env))
      (if (pair? binding)
          (cdr binding)
          (meta-level-eval variable (interaction-env))))

    (if (pair? exprs)
        (let* ((params       (car exprs))
               (args         (map lookup params))
               (event-sources args)
               (modal-envt   (bind-params params args empty-envt)))
          (define (continue-after-modal-exprs value env-after-modal-exprs)
            (continue (make-modal event-sources env-after-modal-exprs) env))
          (if (pair? (cdr exprs))
              (eval-seq (cdr exprs)
                        continue-after-modal-exprs
                        modal-envt tailcall)
              (continue-after-modal-exprs '()  modal-envt)))
        (continue (make-modal '() empty-envt) env))))
```

Scoped assignments eval

```
(define (eval-modal . exprs)
  (lambda (continue env tailcall)
    (define empty-envt '())
    (define (lookup variable)
      (define binding (assoc variable env))
      (if (pair? binding)
          (cdr binding)
          (meta-level-eval variable (interaction-env))))

    (if (pair? exprs)
        (let* ((params       (car exprs))
               (args         (map lookup params))
               (event-sources args)
               (modal-envt   (bind-params params args empty-envt)))
          (define (continue-after-modal-exprs value env-after-modal-exprs)
            (continue (make-modal event-sources env-after-modal-exprs) env))
          (if (pair? (cdr exprs))
              (eval-seq (cdr exprs)
                        continue-after-modal-exprs
                        modal-envt tailcall)
              (continue-after-modal-exprs '()  modal-envt)))
        (continue (make-modal '() empty-envt) env))))
```

Interruptible Evaluation of a Procedure's Body

```
(define (eval-seq pred-expr config body-exprs args continue env tailcall)
 (define context-sources      (car pred-expr))
 (define context-pred         (cdr pred-expr))
 (define head                 (car body-exprs))
 (define tail                 (cdr body-exprs))

 (define (continue-with-seq value env-after-seq)
   (eval-seq pred-expr config tail args continue env-after-seq tailcall))

(define (continue-after-context-pred boolean env-after-pred)
  (if (equal? boolean #f)
      (begin
        (save-execution resume-evaluation context-sources)
        (continue interrupted env-after-pred))
      (if (null? tail)
          (eval head continue env-after-pred tailcall)
          (eval head continue-with-seq env-after-pred #f))))

(eval context-pred continue-after-context-pred env #f))
```

Interruptible Evaluation of a Procedure's Body

```
(define (eval-seq pred-expr config body-exprs args continue env tailcall)
 (define context-sources      (car pred-expr))
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 (define (continue-with-seq value env-after-seq)
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           (eval head continue env-after-pred tailcall)
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```

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(define (eval-seq pred-expr config body-exprs args continue env tailcall)
 (define context-sources      (car pred-expr))
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 (define head                 (car body-exprs))
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 (define (continue-with-seq value env-after-seq)
   (eval-seq pred-expr config tail args continue env-after-seq tailcall))

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      (if (null? tail)
          (eval head continue env-after-pred tailcall)
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```

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      (if (null? tail)
          (eval head continue env-after-pred tailcall)
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(eval context-pred continue-after-context-pred env #f))
```

Semantics and Validation

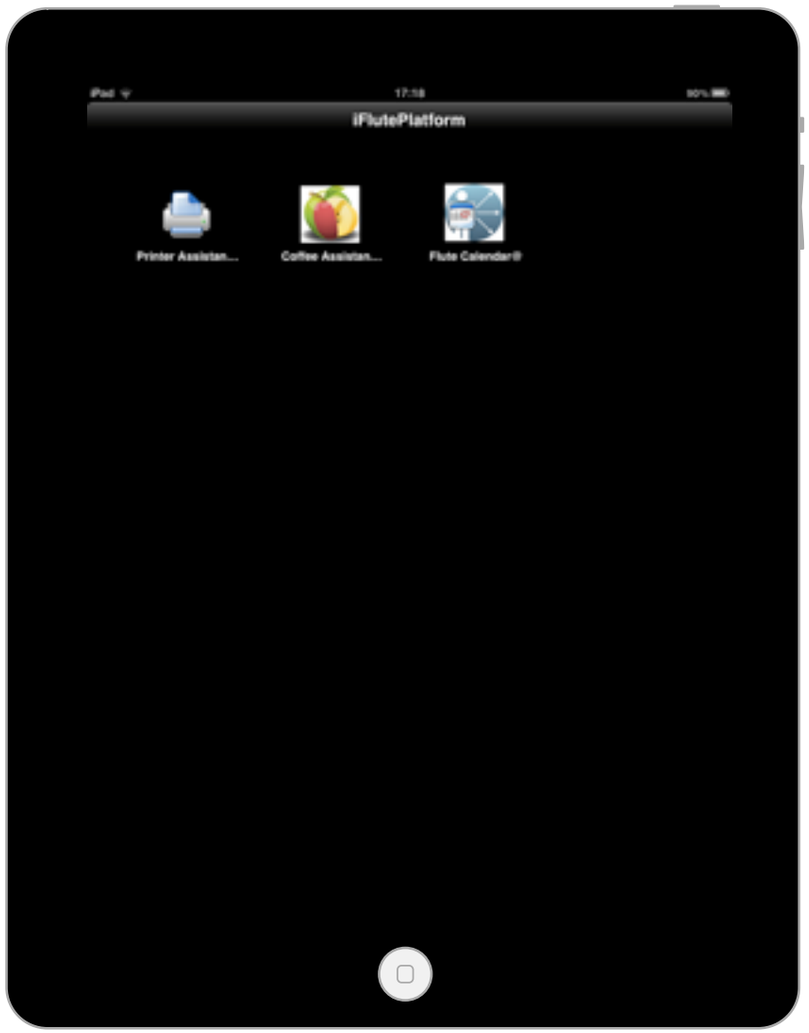
Semantics and Validation

iScheme

An Executable Semantics for Flute

Validation

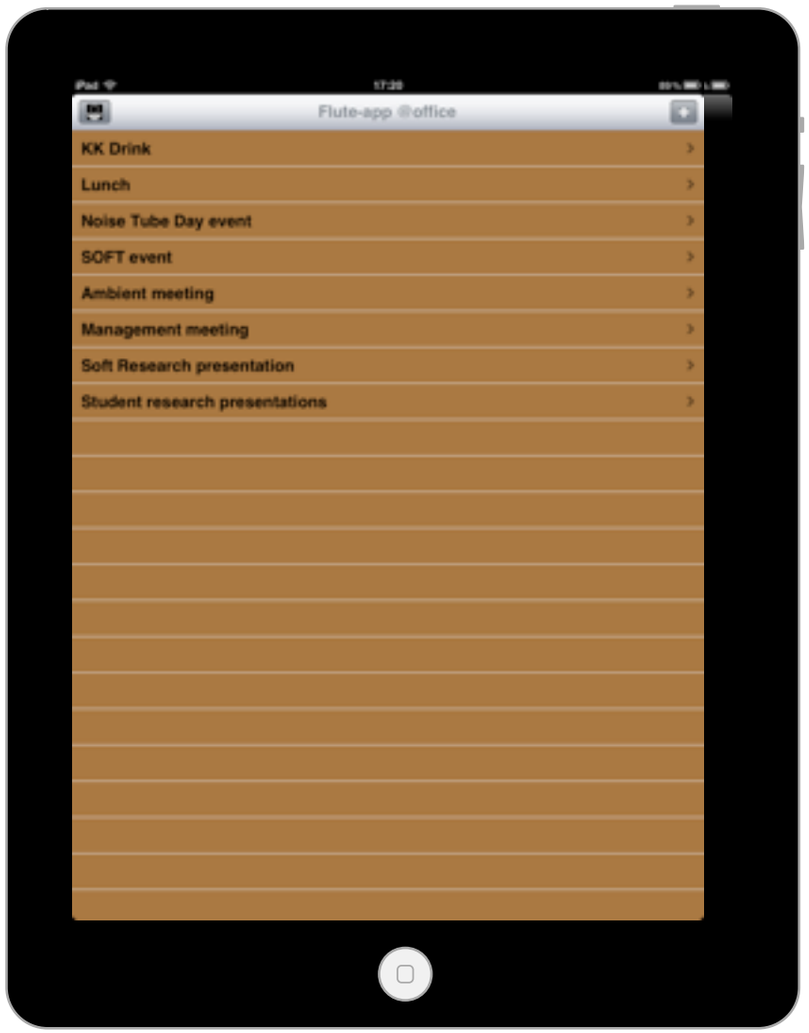
Validation: The iFlute Mobile Platform



Example apps on the iFlute mobile platform

1. *Kalenda:* a context-aware calendar assistant.
2. *Pulinta:* a context-aware printer assistant.
3. *Tasiki*: a context-aware task assistant.

Validation: The iFlute Mobile Platform



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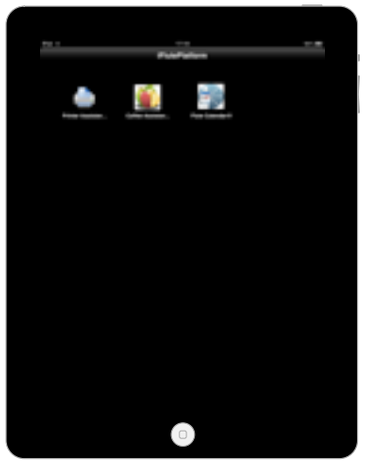

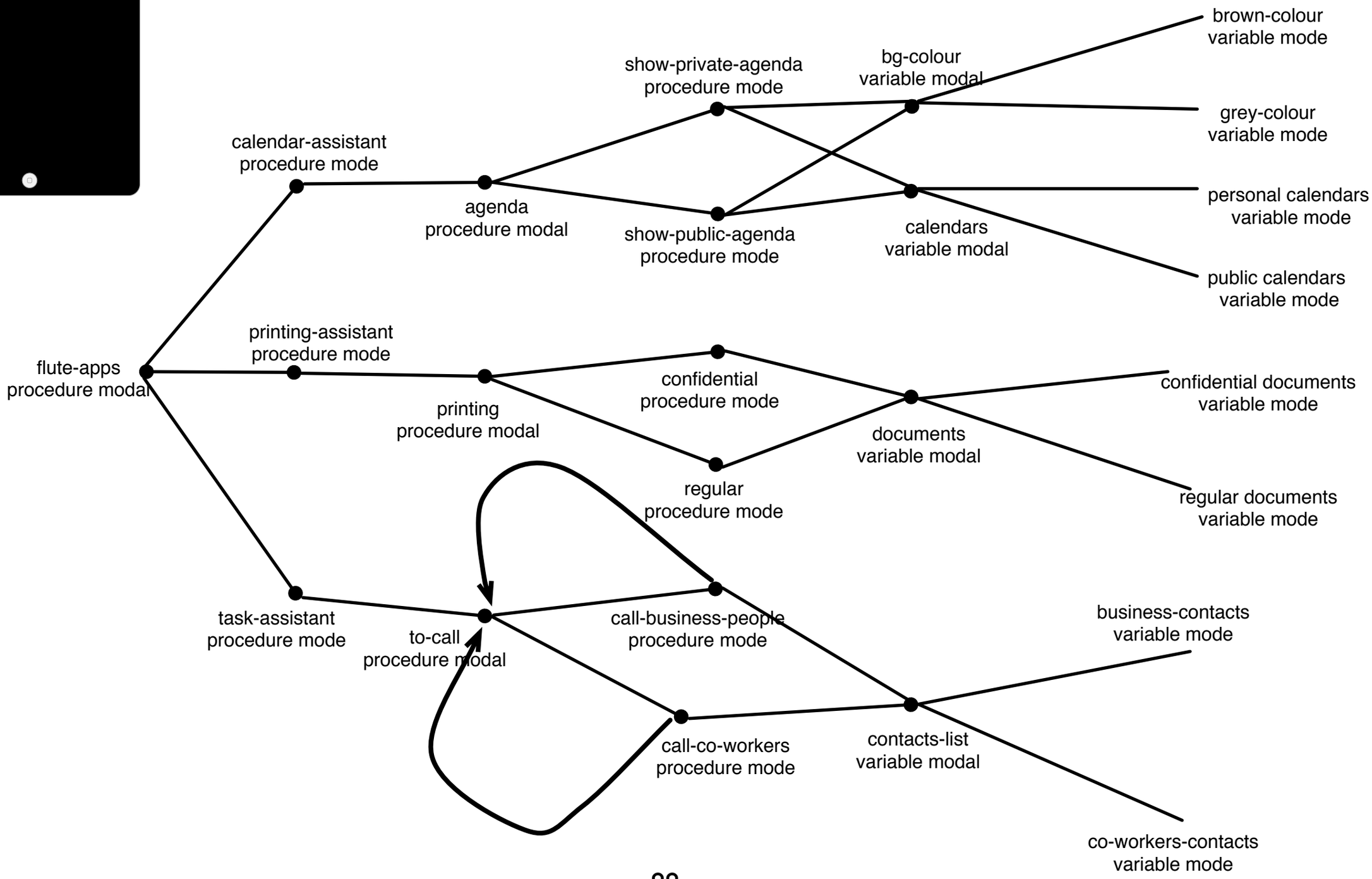

Evaluation

Language Construct	Satisfied Requirement
`ctx-event`	✓ Chained context reactions
`mode`	✓ Contextual dispatch
`modal`	✓ Reactive dispatch

`suspend`
`abort`
`resume`
`restart`
	✓ Context-dependent interruptions
	✓ Context-dependent resumptions

`deferred`
`immediate`
`isolated`
	✓ Reactive scope management

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`immediate`
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	✓ Reactive scope management

Limitations and Future Research Directions

- **Garbage collection of suspended executions.**
- **Flute programming language for the real world.**
- Ambiguous context predicates.
- Evaluation overhead.
- Data structure mutations for variable modals.
- Distributed interruptions.

Summarising the Contributions

1. The ICoDE model:
   - **Interruptible** and **resumable** executions.
   - Representation of context as **reactive** values.
   - **Contextual** and **reactive** dispatch.
   - **Reactive scope** management.

2. iScheme: a mobile language experimentation laboratory.

3. The Flute programming language and its executable semantics.

4. The iFlute Platform: a proof-of-concept mobile application platform for reactive context-aware applications.

Summarising the Contributions

1. The ICoDE model:
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   - **Contextual** and **reactive** dis
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Reactive Method Dispatch for Context-Oriented Programming

Supporting Publications

1. **Journal**: E. Bainomugisha, A. Lombide Carreton, T. Van Cutsem, S. Mostinckx, W. De Meuter. A Survey on Reactive Programming. To appear in *ACM Computing Surveys, 2012.*

2. **Conference**: E. Bainomugisha, J. Vallejos, C. De Roover, A. Lombide Carreton, W. De Meuter. Interruptible Context-dependent Executions: A Fresh Look at Programming Context-aware Applications. In *Proceedings of the ACM SPLASH/Onward! '12*, 2012.

3. **Journal**: E. Bainomugisha, J. Vallejos, E. Gonzalez Boix, P. Costanza, T. D'Hondt, W. De Meuter. Bringing Scheme Programming to the iPhone - Experience. In *Software: Practice and Experience*, 2012.

4. **Conference**: E. Bainomugisha, P. Koosha, J. Vallejos, Y. Berbers, W. De Meuter. Flexub: Dynamic Subscriptions for Publish/Subscribe Systems in MANETs. In *12th IFIP International Conference on Distributed Applications and Interoperable Systems*, Lecture Notes in Computer Science, 2012.

5. **Book chapter:** E. Bainomugisha, A. Cádiz, P. Costanza, W. De Meuter, S. Gonzalez, K. Mens, J. Vallejos, T. Van Cutsem. Language Engineering for Mobile Software. In *Handbook of Research on Mobile Software Engineering: Design Implementation and Emergent Applications*, IGI Global, 2011.