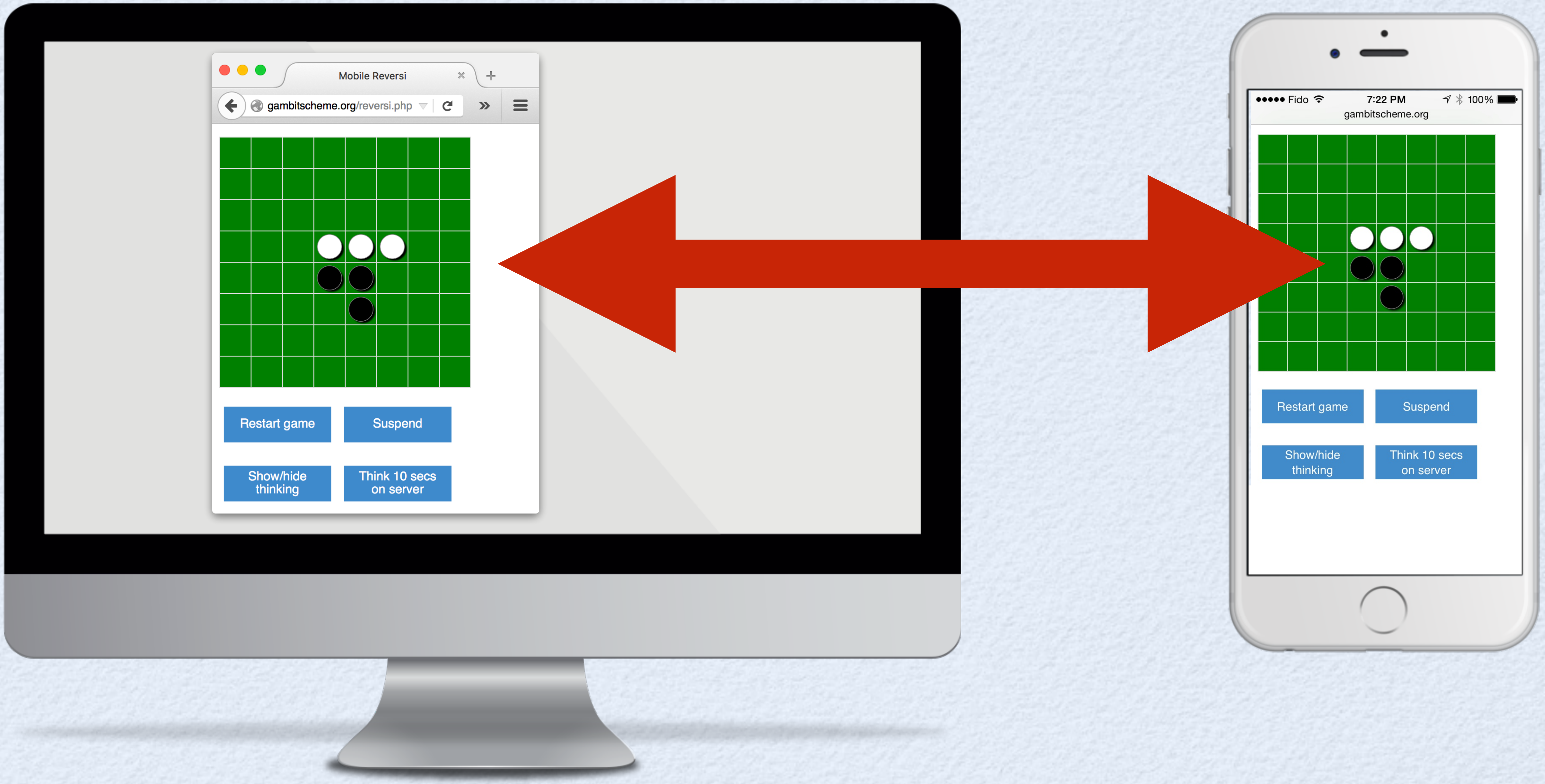
Universal Backend and Migration

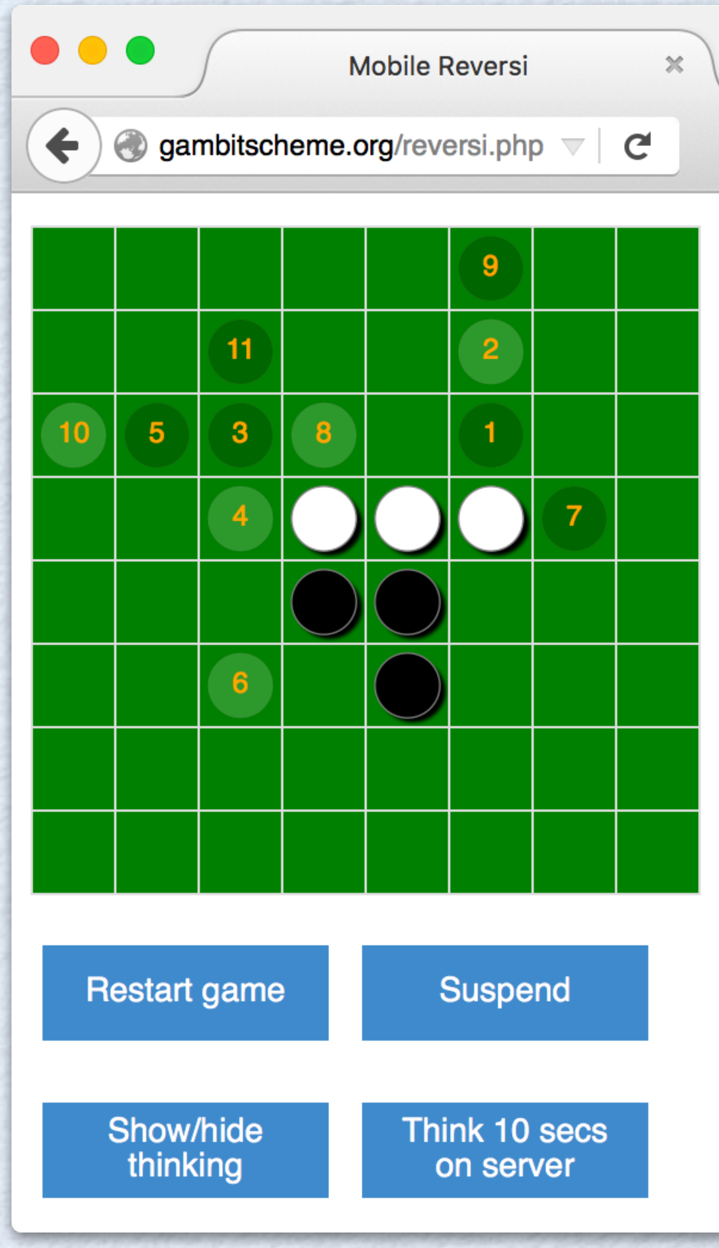
Task Migration

- Process of transferring a running computation to another computational node



Mobile Reversi Web App

- Reversi game against computer in browser
- **Continuous search for best replies** to human's legal moves while human is thinking (this allows instant response when human plays a move)
- **"Suspend"** button sends an email with a URL to **resume game on any other device**
- **"Think on server"** button migrates to web server for 10 secs and then back to browser (useful when using a powerful web server)



Start game

Implementation

- Program logic is implemented by a single **Scheme** program compiled to **JS** and **PHP**

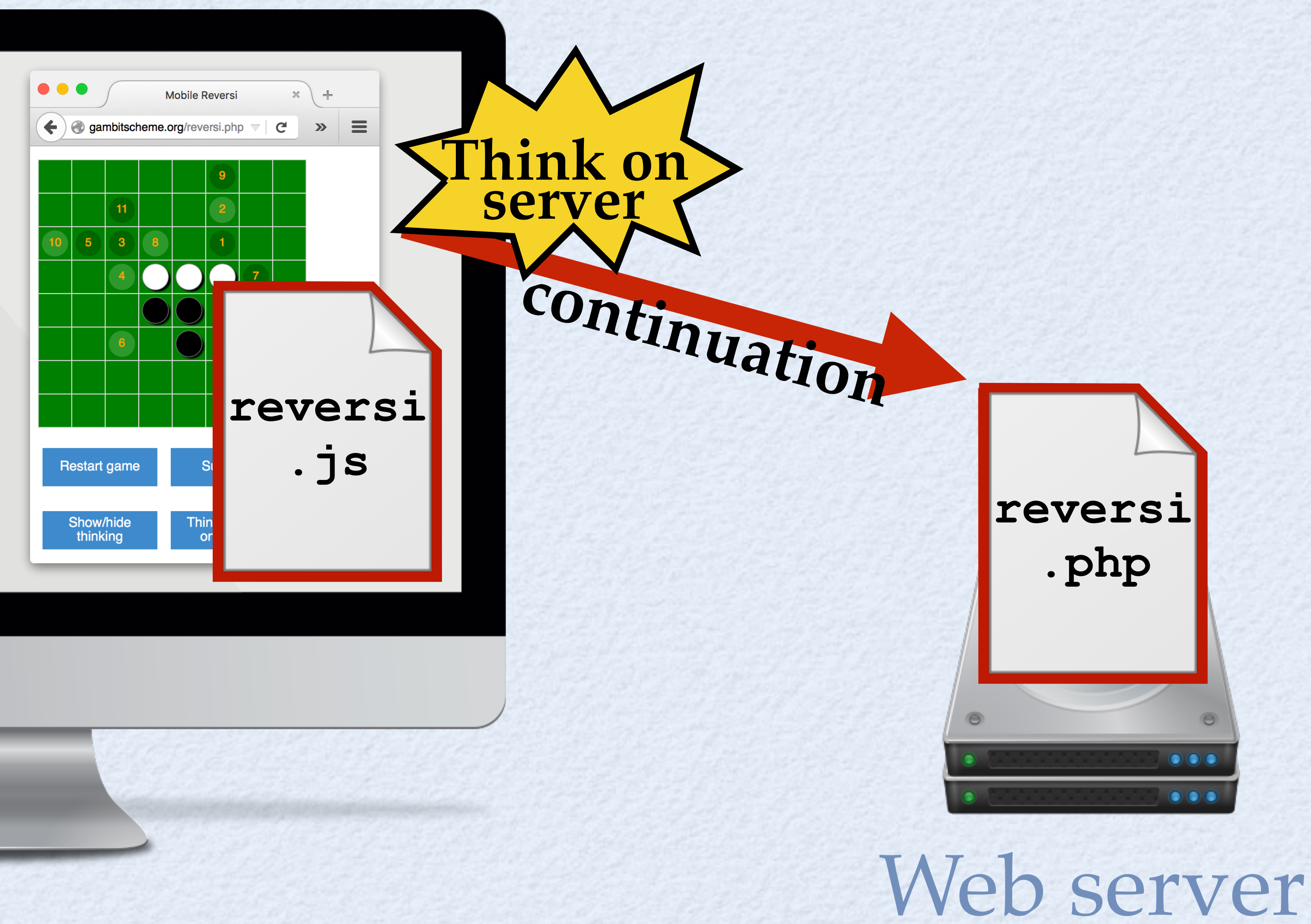
  `reversi.scm` → **`reversi.php`**
  `reversi.scm` → **`reversi.js`**

- To facilitate migration, browser and server run **same program** but at different entry points

- Task migration consists in sending the program's **current continuation** to the destination node and resuming it

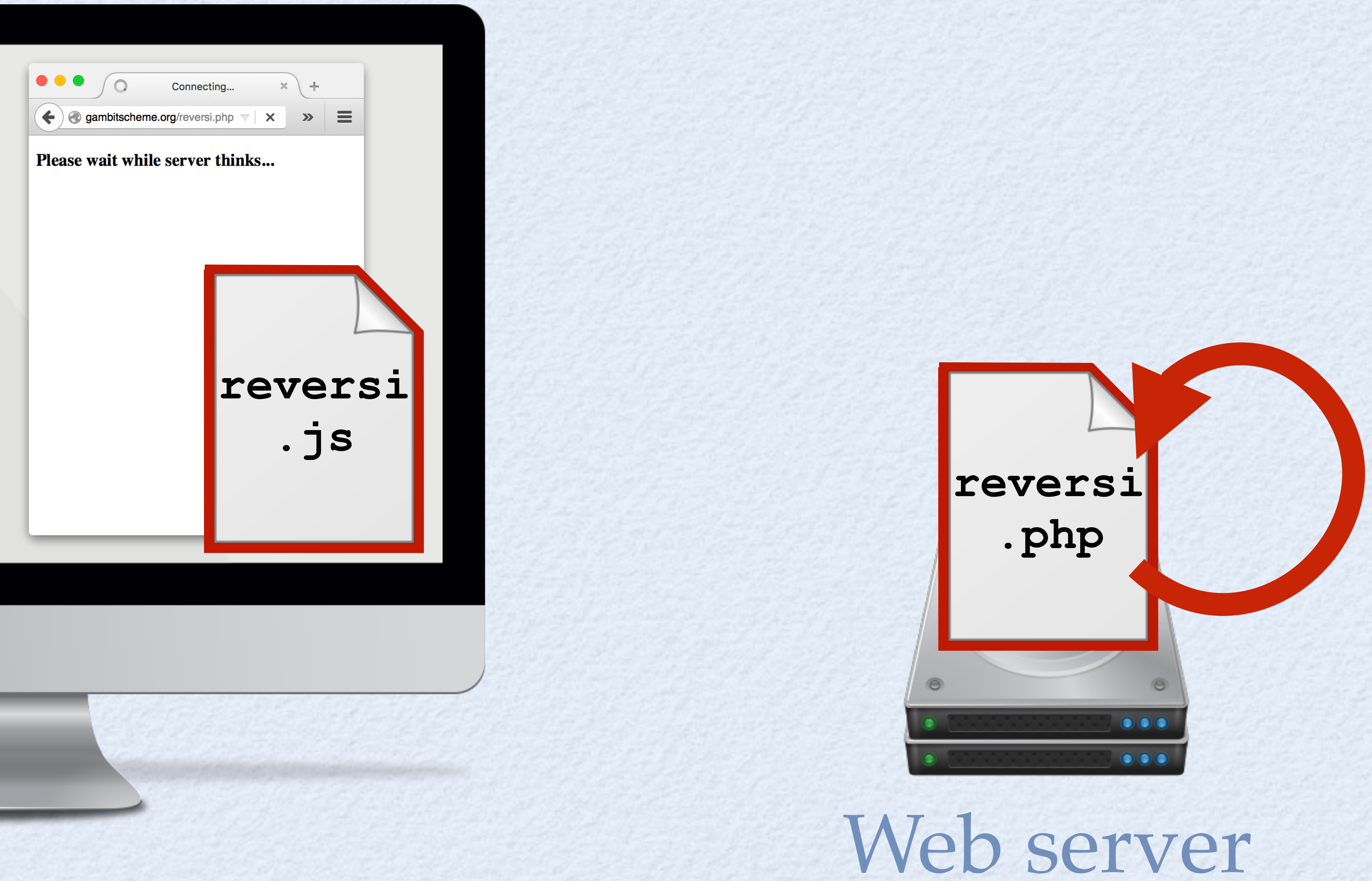
Trace for "Think on server" (1)

- Clicking **"Think on server"** sends the current continuation to the server



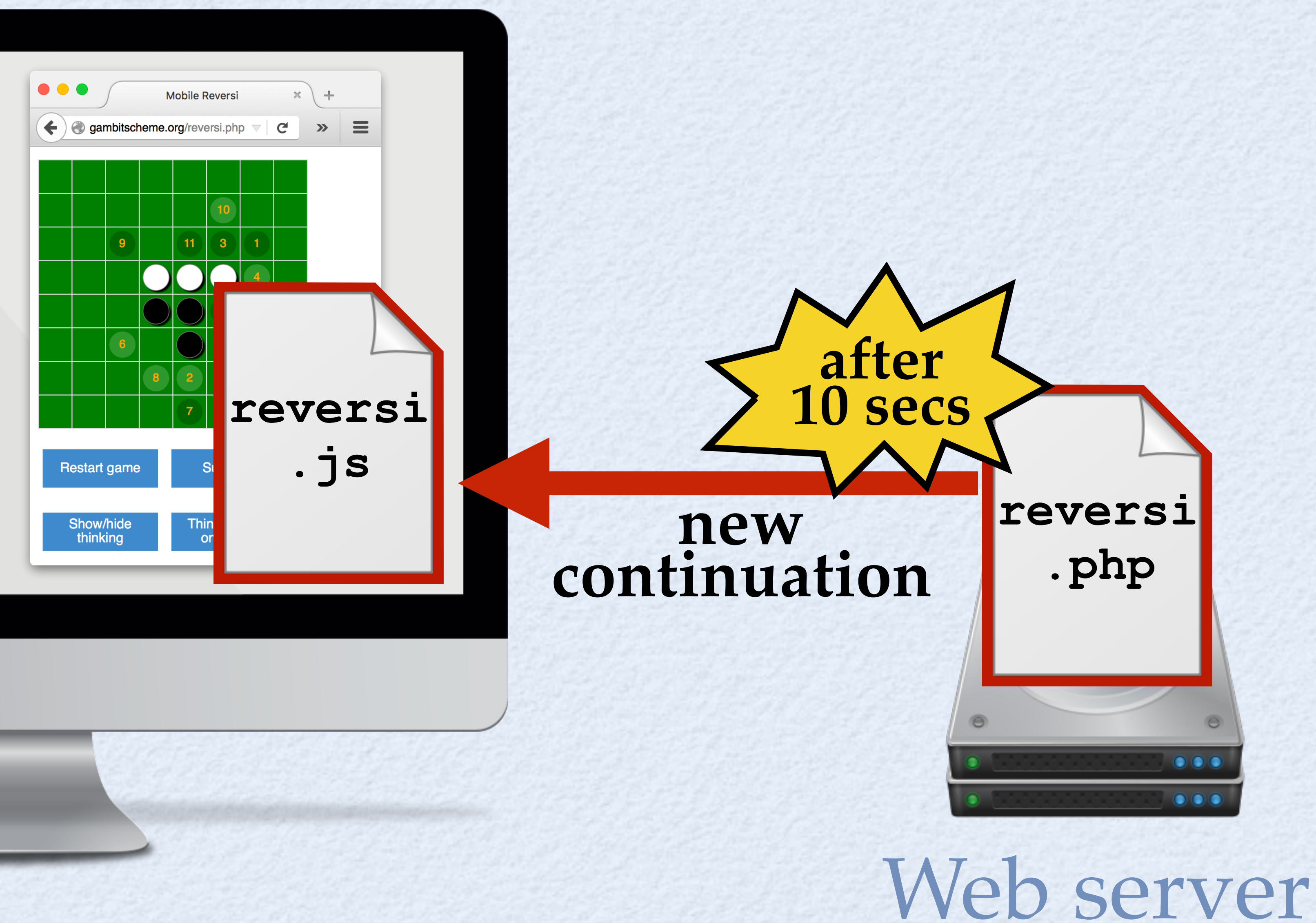
Trace for "Think on server" (2)

- The **server** resumes the continuation to continue searching for best replies



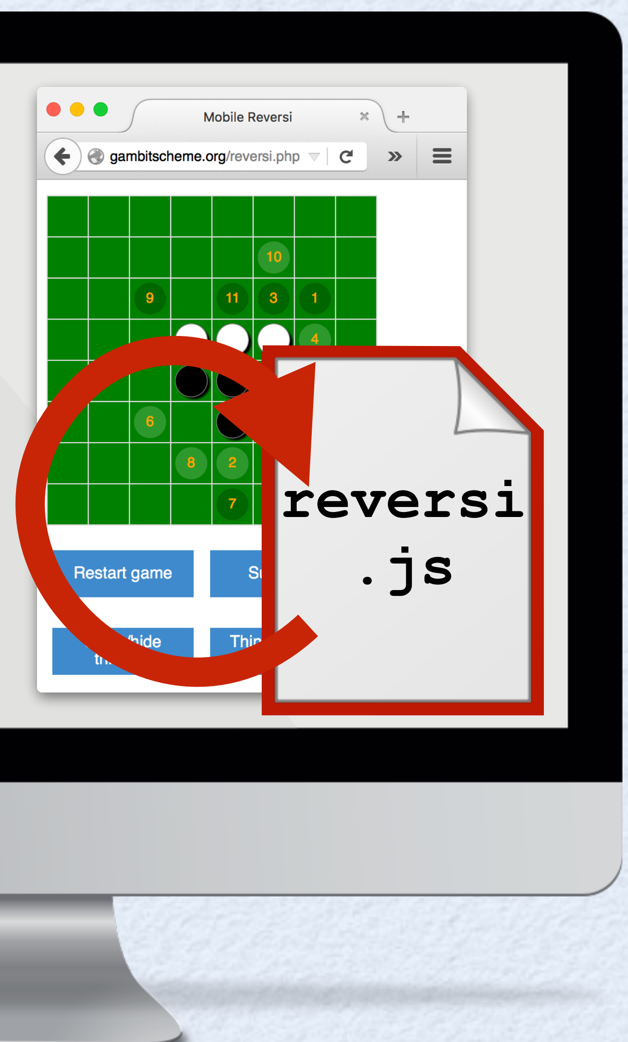
Trace for "Think on server" (3)

- After 10 seconds, the server sends its current continuation to the browser



Trace for "Think on server" (4)

- The **browser** resumes the continuation to continue searching for best replies



Web server

Migration

- Gist of **"Think on server"** implementation

runs on **browser**

runs on **server**

runs on **browser**

```
(define (search ...)
  .
  .
  .
  (migrate-task web-server) ;; click
  .
  .
  .
  (migrate-task web-browser) ;; 10 secs
  .
  .
  .
)
```

migrate-task

- Migration is performed with **`migrate-task`**:

```
(define (migrate-task dest)
  (call/cc
   (lambda (k)
     (send dest (make-request-resume-task k))
     (halt))))
```

- **Object serialization/deserialization** is hidden in the **`(send dest msg)`** operation that sends the message **`msg`** to the destination **`dest`**

- **`(halt)`** terminates task

Requirements

- To support this task migration approach, **continuations** (as well as the other data types) must be:
  - **serializable**
  - **compatible across the target languages**

Serialization/deserialization

```
> (define x (object->u8vector '#((1 . 2) (3 . 4))))

> x
#u8(34 100 81 82 100 83 84)

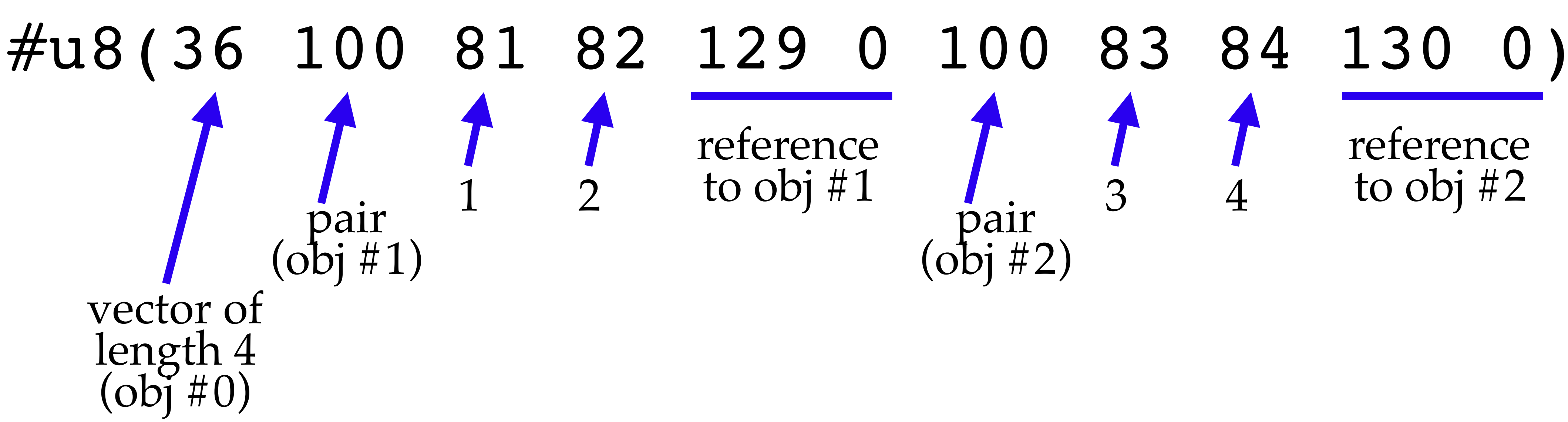
> (u8vector->object x)
#((1 . 2) (3 . 4))
```

```
#u8(34 100 81 82 100 83 84)
```

vector of length 2 — pair — 1 — 2 — pair — 3 — 4

Sharing

```
> (define a '(1 . 2))
> (define b '(3 . 4))
> (define x (object->u8vector (vector a a b b)))
> x
#u8(36 100 81 82 129 0 100 83 84 130 0)
> (define y (u8vector->object x))
> y
#((1 . 2) (1 . 2) (3 . 4) (3 . 4))
> (eq? (vector-ref y 0) (vector-ref y 1))
#t
```



Serialization encoding

- 0..15 : **symbol**, 16..31 : **string**, 32..47 : **vector**, 48..63 : **structure**, 64..79 : **subprocedure**, 80..96 : **integer**, etc
- How to serialize procedures? 2 cases:
  - "subprocedure" (a code address within a top-level procedure): encoded as the name of the top-level procedure and an index
  - closure: a flat representation is used, so a closure is just a kind of vector containing a reference to a subprocedure

Procedure Serialization

```
> (##subprocedure-id sqrt)
0

> (##subprocedure-parent sqrt)
#<procedure #2 sqrt>

> (##subprocedure-parent-name sqrt)
sqrt

> (object->u8vector sqrt)
#u8(64 92 171 61 6 4 115 113 114 116)
```

409003 Gambit version

sqrt

subprocedure with id=0

Closure Serialization

```
(declare (block))

(define (foo a b) (lambda (x) (list a x b)))

(define clo (foo 5 6))

(pp (##closure-length clo)) ;; 3
(pp (##subprocedure-id (##closure-code clo))) ;; 2
(pp (##closure-ref clo 1))  ;; 5
(pp (##closure-ref clo 2))  ;; 6
(pp (object->u8vector clo))

;;==>    #u8(106 2 92 171 61 6 3 102 111 111 85 86)
                  409003          foo
                                                5  6
      closure  subprocedure  Gambit
               with id=2     version
```

Continuation Serialization

- A continuation is a list (chain) of continuation frames (stack frames)
- Each continuation frame contains slots with Scheme values, one slot is the return address (which is a code point, i.e. a subprocedure)
- So serializing a continuation frame is similar to serializing a closure
- Only objects containing non-Scheme objects (such as pointers to foreign structures, ports, etc) can’t be serialized

Platform Independence

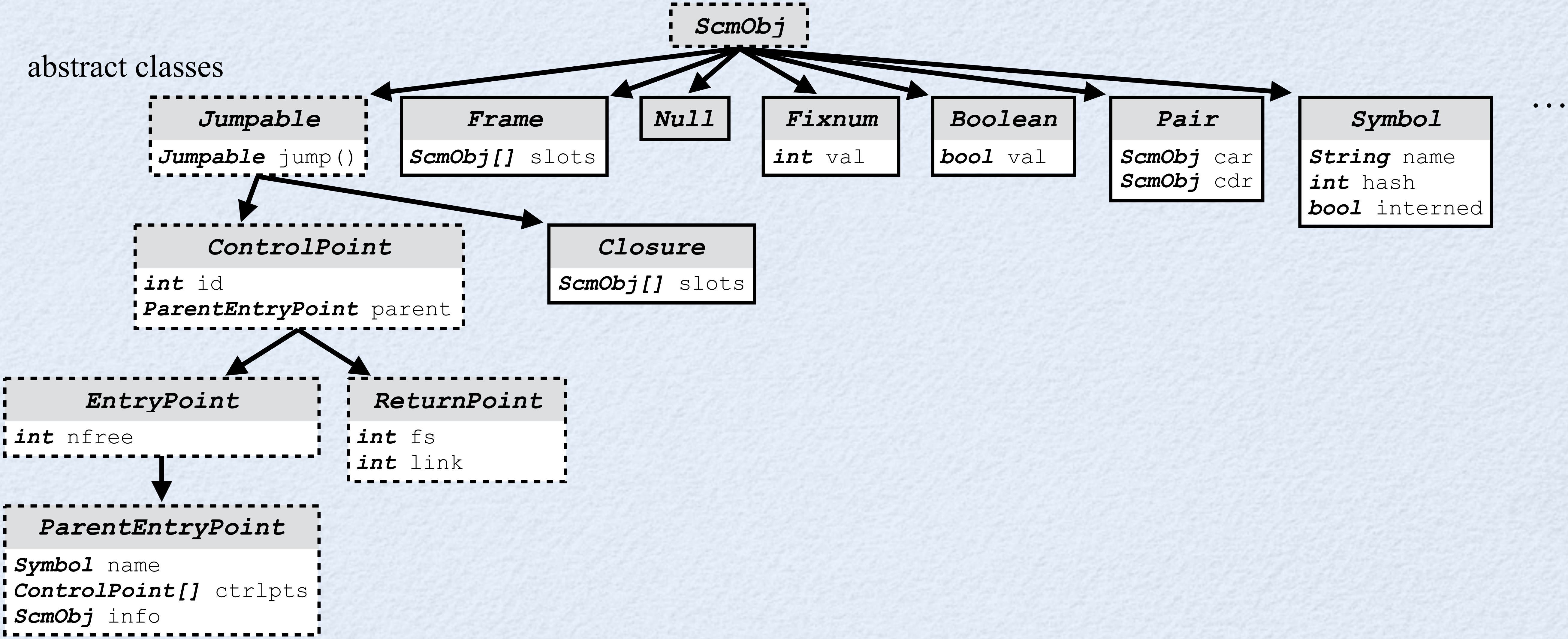
- Note that the encoding used for serialization of objects does not expose its low-level representation, so it could be represented differently at the deserializing end (32 vs 64 bits, endianness, etc)
- The same can be said of code (procedures, closures, continuations)… it does not depend on the low-level representation of that code (JS, PHP, C, x86, etc)
- The "code addresses" are symbolic in nature, and thus are portable to different host platforms

Virtual Machine Approach

- The variants of the universal backend use the same approach:
  - **Trampoline for tail calls**
  - **Explicit call stack management**
  - **Efficient incremental stack/heap implementation of continuations**
- This amounts to using the target language as a **high-level assembly language** to implement a virtual machine for Scheme

Abstract Object Representation

- Target language compatibility of data is achieved by a **common abstract representation** of Scheme objects that is serializable



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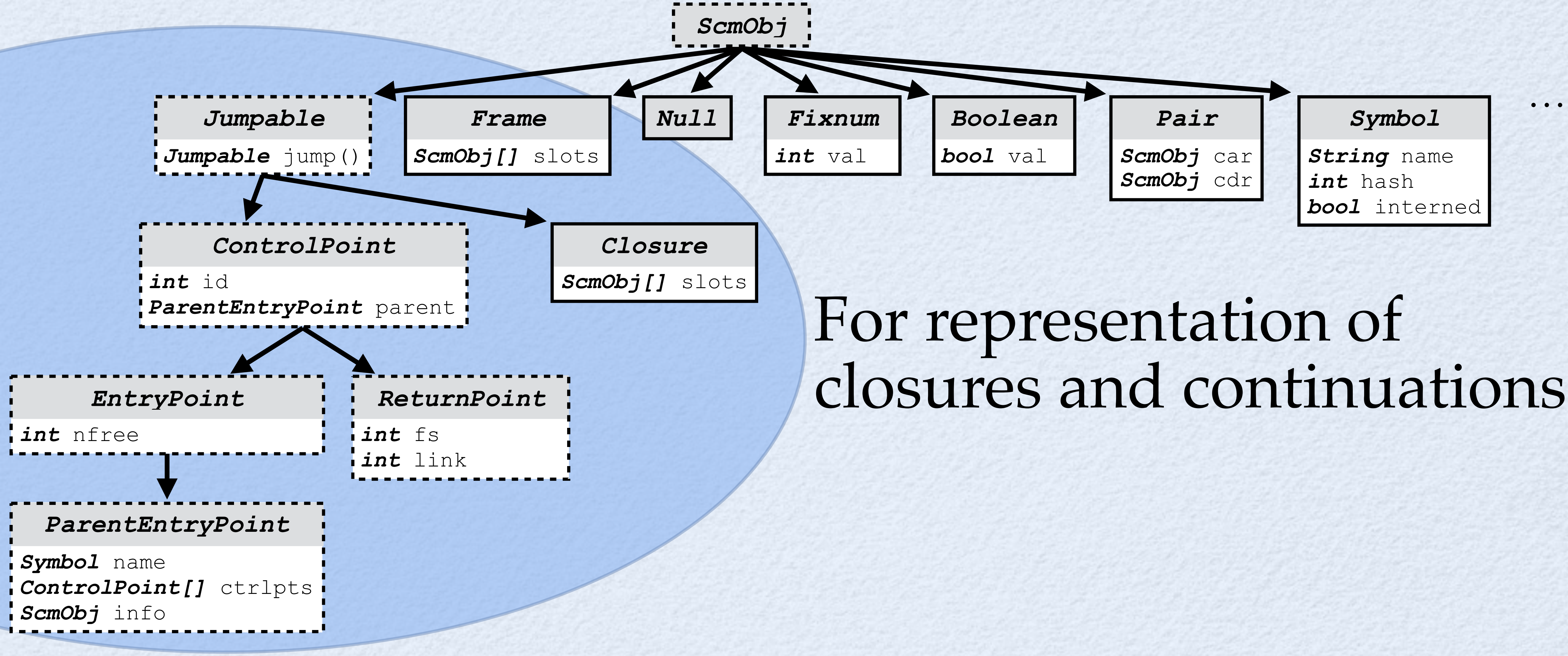


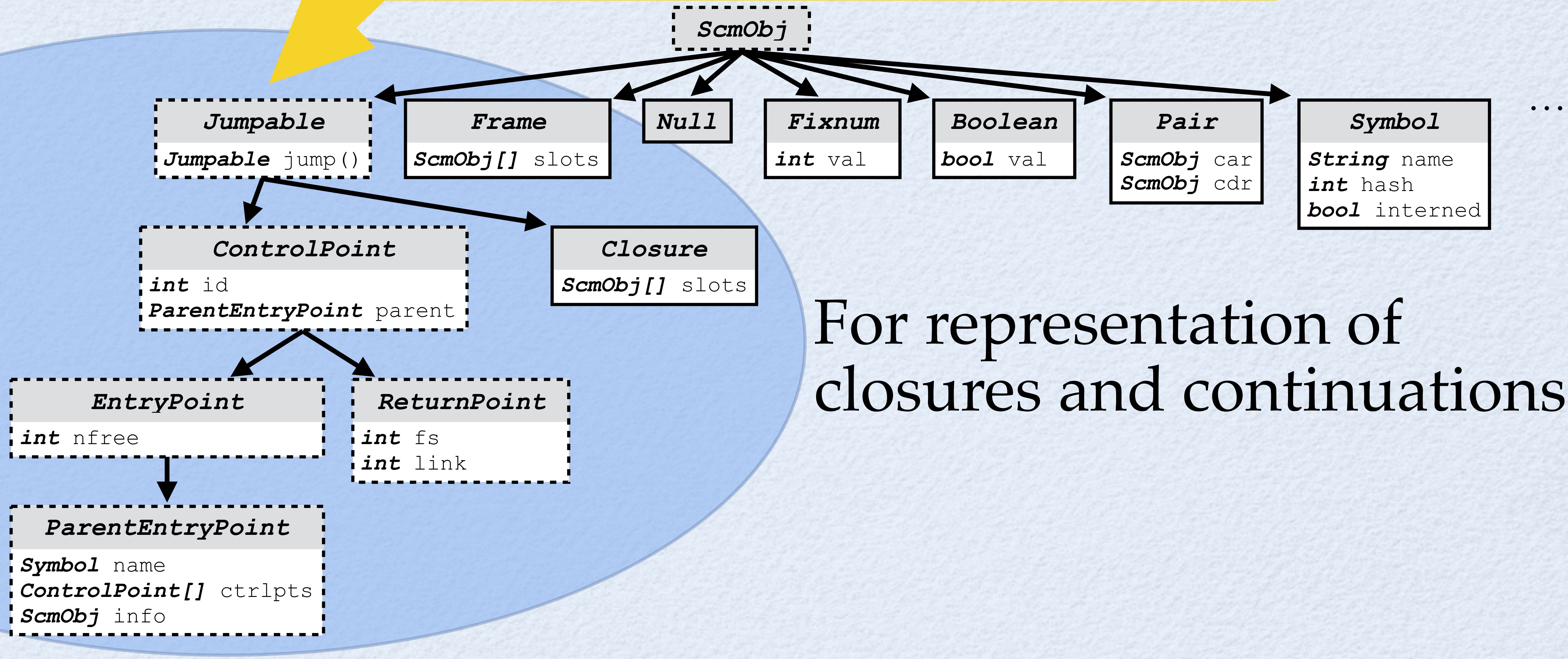
For representation of closures and continuations

Abstr… …tation

`Jumpable` is the type of objects that can be jumped to by the trampoline:

- **closures** and **continuations**
- **control points** in the code:
  - procedure **entry point**
  - non-tail call **return point**

- Target… …is achiev… …**sentation** of Sch…



For representation of closures and continuations

Mapping Object Representation

- The abstract object representation is **mapped to the target languages independently**
- Java uses **actual classes** for all object types
- For efficiency, dynamic languages use a **natural mapping** when possible, typically:
  - **`Boolean`** -> target language **Booleans**
  - **`Fixnum`** -> target language **numbers**
  - **`Vector`** -> target language **arrays**
  - **`Jumpable`** -> target language **functions**

Gambit Virtual Machine

- GVM is the intermediate code representation of the compiler (Scheme —> GVM —> target)
- A procedure's code is a **set of basic-blocks** with **explicit jump instructions** for local and global control flow
  - Each BB is a **control point** of the program
- The GVM has a set of general purpose **registers** and a **stack**, both used by the procedure call protocol

GVM Example

```
(define (foreach f lst)
  (let loop ((lst lst))
    (if (pair? lst)
        (begin
         (f (car lst))
         (loop (cdr lst)))
        #f)))
```

GVM basic blocks of **`foreach`**

```
#1 fs=0 entry-point nparams=2 ()
  jump fs=0 #3

#2 fs=3 return-point
  r2 = (cdr frame[3])
  r1 = frame[2]
  r0 = frame[1]
  jump/poll fs=0 #3

#3 fs=0
  if (pair? r2) jump fs=0 #4 else #5

#4 fs=0
  frame[1] = r0
  frame[2] = r1
  frame[3] = r2
  r1 = (car r2)
  r0 = #2
  jump fs=3 frame[2] nargs=1

#5 fs=0
  r1 = '#f
  jump fs=0 r0
```

tail call **`loop`**

non-tail call **`f`**

create continuation frame

pass return addr.

Call protocol of **`foreach`** and **`loop`**

`r0` = *return address*

`r1` = **`f`**

`r2` = **`lst`**

Call protocol of **`f`**

`r0` = *return address*

`r1` = *arg1*

Translating Jumps

- Except for jumps, GVM instructions are easily translated to the target language
- To implement jumps, each basic block is translated to a **parameter-less function** (in the case of Java a class derived from **`Jumpable`**)
- Their execution is chained by a **trampoline**

Translation to JS

Runtime system for JS

```
var r0, r1, r2, r3; // GVM registers
var nargs;          // argument count
var stack = [null]; // runtime stack
var sp = 0;         // stack pointer

function trampoline(pc) {
  while (pc !== null)
    pc = pc();
}

function poll(dest) {
  // ...check for interrupts here...
  return dest;
}
```

```
(define (foreach f lst)
  (let loop ((lst lst))
    (if (pair? lst)
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         (f (car lst))
         (loop (cdr lst)))
        #f)))
```

Generated JS code

```
function bb1_foreach() {
  if (nargs !== 2)
    return wrong_nargs(bb1_foreach);
  return bb3_foreach;
}

function bb2_foreach() {
  r2 = stack[sp].cdr;
  r1 = stack[sp-1];
  r0 = stack[sp-2];
  sp -= 3;
  return poll(bb3_foreach);
}

function bb3_foreach() {
  if (r2 instanceof Pair) {
    stack[sp+1] = r0;
    stack[sp+2] = r1;
    stack[sp+3] = r2;
    r1 = r2.car;
    r0 = bb2_foreach;
    sp += 3;
    nargs = 1;
    return stack[sp-1];
  } else {
    r1 = false;
    return r0;
  }
}
```

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function poll(dest) {
  // ...check for interrupts here...
  return dest;
}
```

`poll` function returns its argument after checking for interrupts

Generated JS code

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}

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    r0 = bb2_foreach;
    sp += 3;
    nargs = 1;
    return stack[sp-1];
  } else {
    r1 = false;
    return r0;
  }
}
```

inlined basic block #4

inlined basic block #5

Statically known jumps to **singly used or short** basic blocks are inlined

Translation to JS

Runtime system for JS

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function trampoline(pc) {
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}

function poll(dest) {
  // ...check for interrupts here...
  return dest;
}
```

Note: only basic control flow statements are used, namely `return` and `if` (no loops or exception handling or closures)

This makes optimization by the target VM easier

Generated JS code

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function bb1_foreach() {
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  }
}
```

Trace of call `trampoline(bb1_foreach)`

Runtime system for JS

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    sp += 3;
    nargs = 1;
    return stack[sp-1];
  } else {
    r1 = false;
    return r0;
  }
}
```

1 bb3_foreach

2 f

3 bb2_foreach

4

procedure **f**

Improvements

- This basic trampoline implementation has a relatively **high overhead**
- Each jump to a control point = 1 call + 1 return
- The single centralized function call dispatch in the trampoline **hinders inline caching by the target VM**
- This can be improved…

"Jump Destination Call" Optimization

`return` *X*`;` →* `return` *X*`();`

* except when *X* is **`poll(...)`**

- Allows the target VM to optimize the call to *X*:
  - **inlining and inline caching of functions**
  - **TCO**

- Target VM stack overflows are avoided because the calls to **`poll`** unwind the stack back to the trampoline at regular intervals

"Intermittent Polling" Optimization

```
return poll(X);
```

⇨

```
if (--pollcount === 0)
   return poll(X);
else
   return X();
```

- Lowers overhead of calling **`poll`**
- Exposes more call optimizations, such as inlining of *X*

Stack Space Leak Issue

- Target languages typically implement the stack using an array that **grows on demand**
- When a procedure returns, the data it saved on the stack is still there above **sp** => **space leak!**
- The `poll` function does the stack shrinking:

```
function poll(dest) {
  pollcount = 100;
  stack.length = sp+1;
  // …check for interrupts…
  return dest;
}
```

garbage on stack persists at most until next call to `poll`

Serialization

- For serializing closures and continuations, **meta information** is attached to control points:

- **Unique identifier** (parent + local id), used to recover the control point when deserializing it

- **`ReturnPoint`: size of frame** + **location of RA**, used by **`call/cc`** implementation

- **`EntryPoint`: number of free variables**

JS Code with Meta Information

```
function bb1_foreach() { ... } // ParentEntryPoint
function bb2_foreach() { ... } // ReturnPoint
function bb3_foreach() { ... } // Jumpable

bb1_foreach.id = 0;
bb1_foreach.parent = bb1_foreach;
bb1_foreach.nfree = -1; // not a closure
bb1_foreach.name = "foreach";
bb1_foreach.ctrlpts = [bb1_foreach,bb2_foreach];

bb2_foreach.id = 1;
bb2_foreach.parent = bb1_foreach;
bb2_foreach.fs = 3;
bb2_foreach.link = 1;

peps["foreach"] = bb1_foreach;
```

peps = table of parent entry points (used for deserialization)

.parent.name .id

Serialization: **`bb2_foreach`** —> **`<"foreach",1>`**

Deserialization: **`peps["foreach"].ctrlpts[1]`**

Evaluation

Other Systems

- No other Scheme system targets multiple languages and has serializable continuations
- The closest point of comparison is **Scheme2JS** and **Spock** that target JS and whose continuations could be made serializable with a moderate amount of work

Scheme Systems Compared

- **Scheme2JS** (Florian Loitsch):
  - **`call/cc`** based on Replay-C algorithm that uses exceptions to iterate over stack frames
- **Spock** (Felix Winkelman):
  - CPS conversion and exceptions to unwind stack
- **Gambit-JS** is our approach with JS backend

JS VMs Evaluated

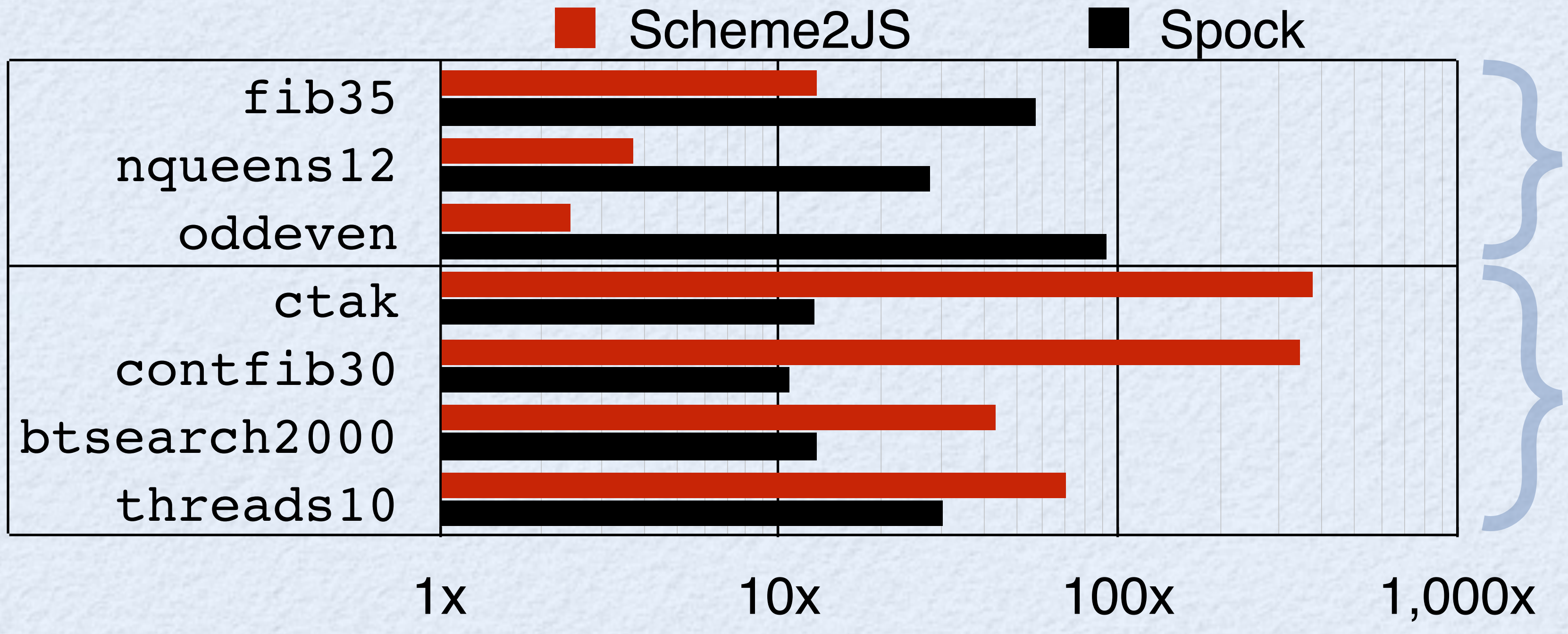
- **Microsoft Chakra**
- **Google V8**
- **Mozilla SpiderMonkey**
- **Apple Nitro**

Benchmarks

- Benchmarks without uses of **`call/cc`**
  - Recursive: **`fib35`**, **`nqueens12`**
  - Tail calls only: **`oddeven`**
- Benchmarks which use **`call/cc`**
  - Recursive: **`ctak`**, **`contfib30`**
  - Backtracking: **`btsearch2000`**
  - Threads: **`threads10`**

Execution Speed

- **Gambit-JS consistently faster** on all benchmarks and on all JS VMs
- Execution time relative to Gambit-JS averaged over the 4 JS VMs:



2-10x Scheme2JS
30-90x Spock

40-350x Scheme2JS
10-30x Spock

Performance Portability

- Execution speed difference between VMs: