Wasm/k: Delimited Continuations for WebAssembly

DLS 2020

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$$\begin{tikzcd}
C \arrow[dr] & & \\
& JS \arrow[r] & x86 \\
Go \arrow[ur] & &
\end{tikzcd}$$

+ Language preference
+ Code reuse

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+ Code reuse

? Fast & consistent performance
? Small code size

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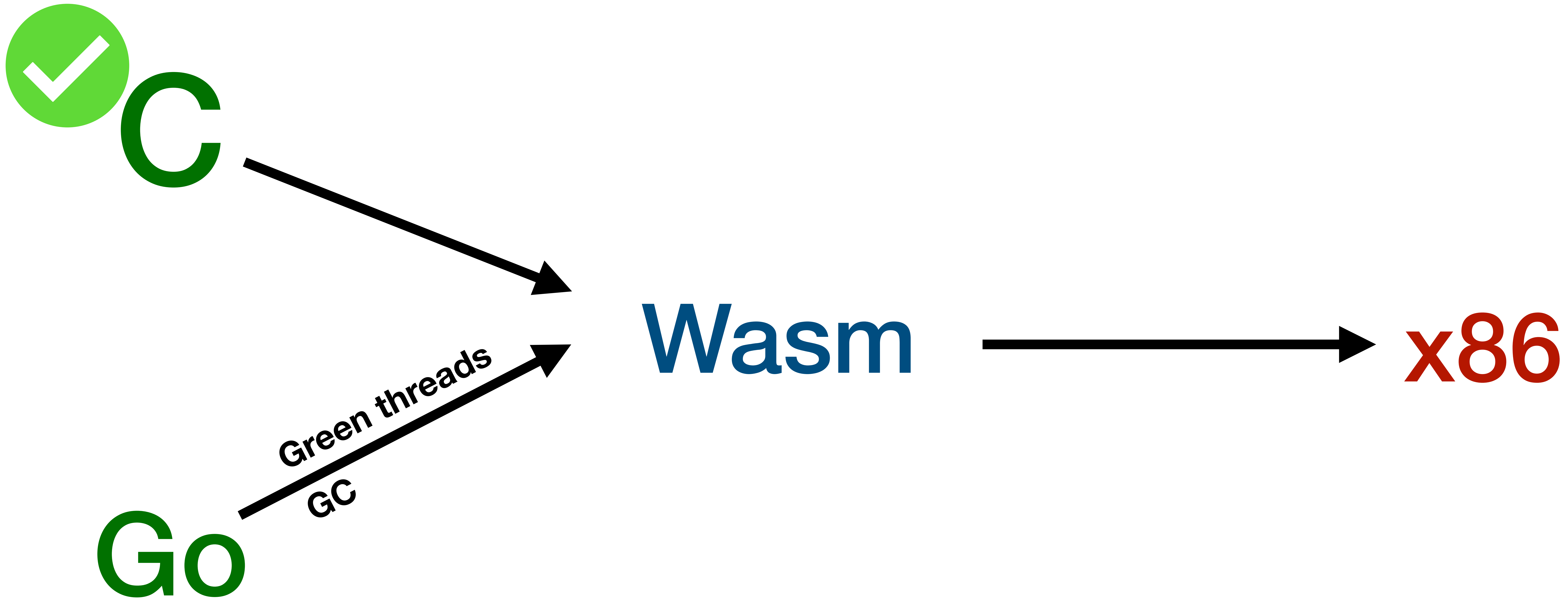

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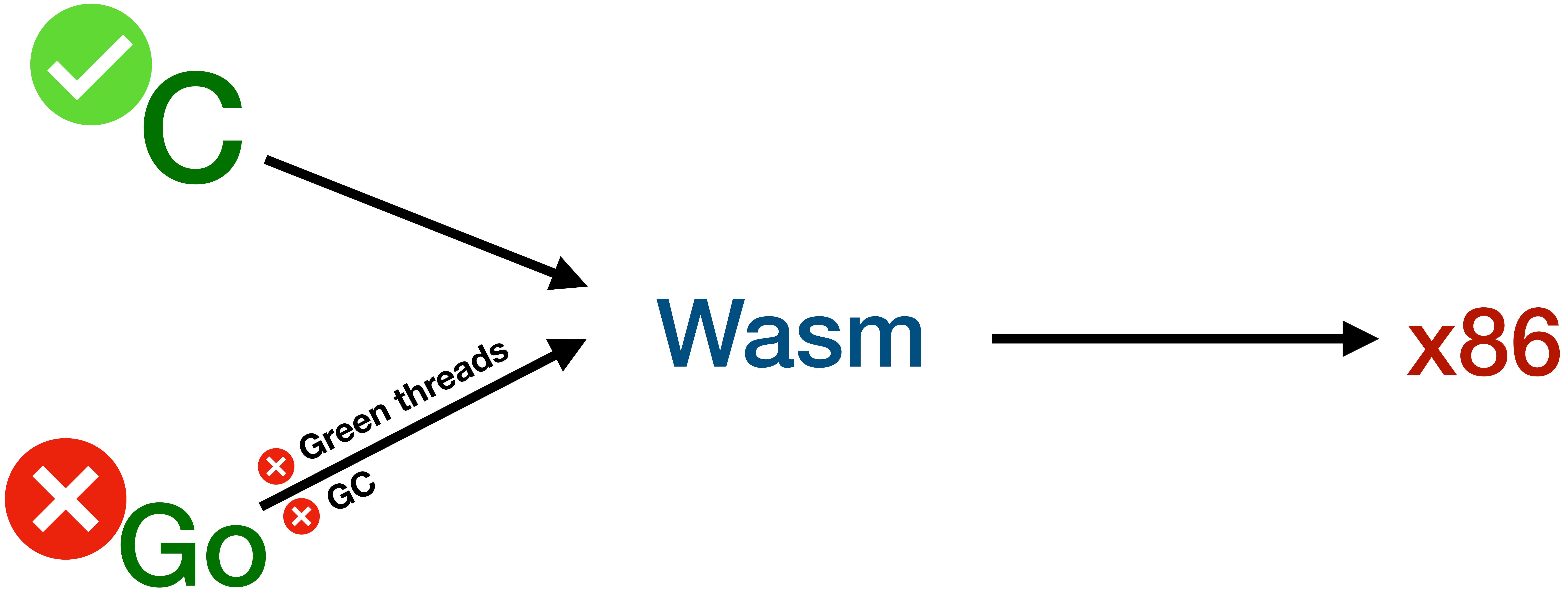

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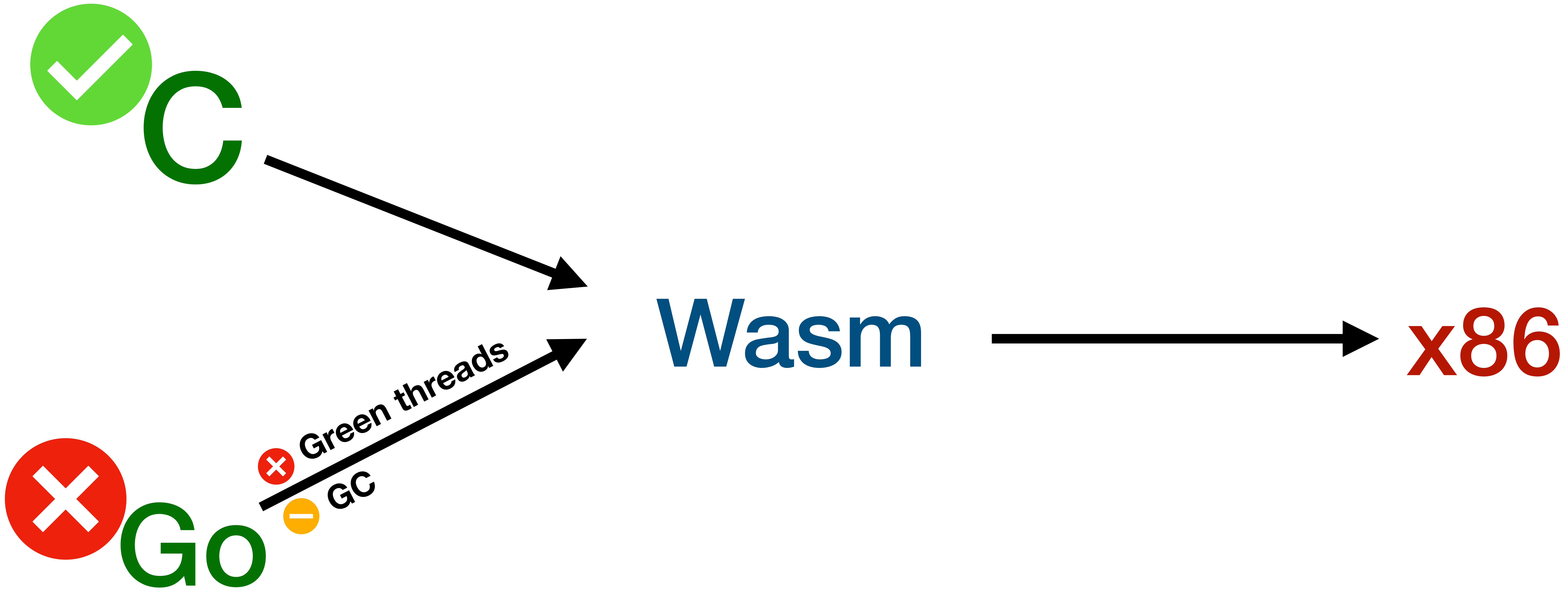

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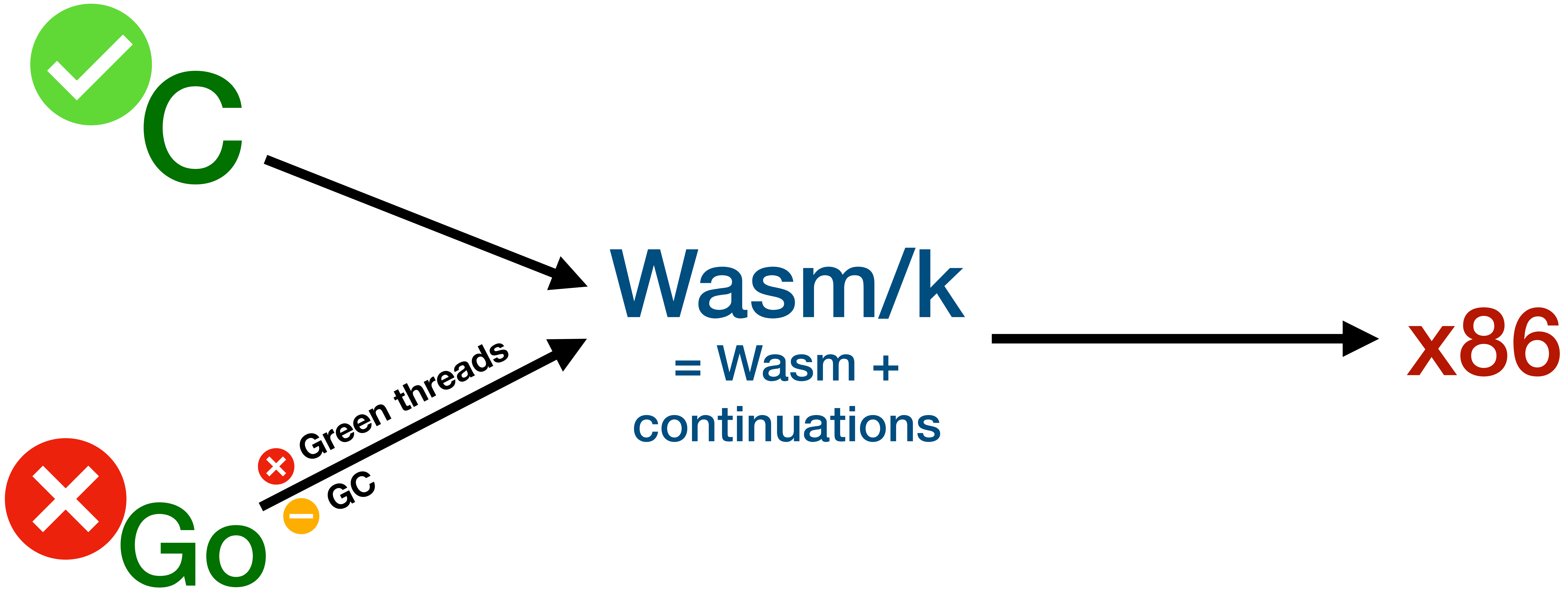

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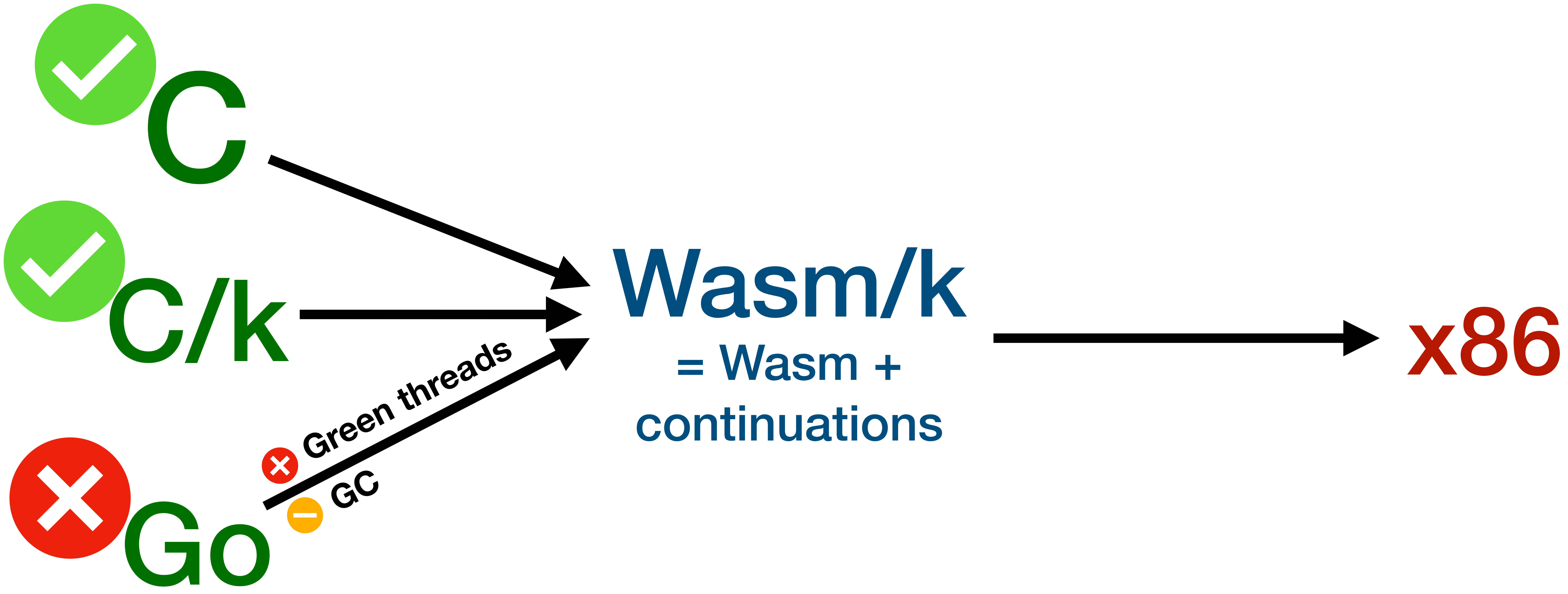

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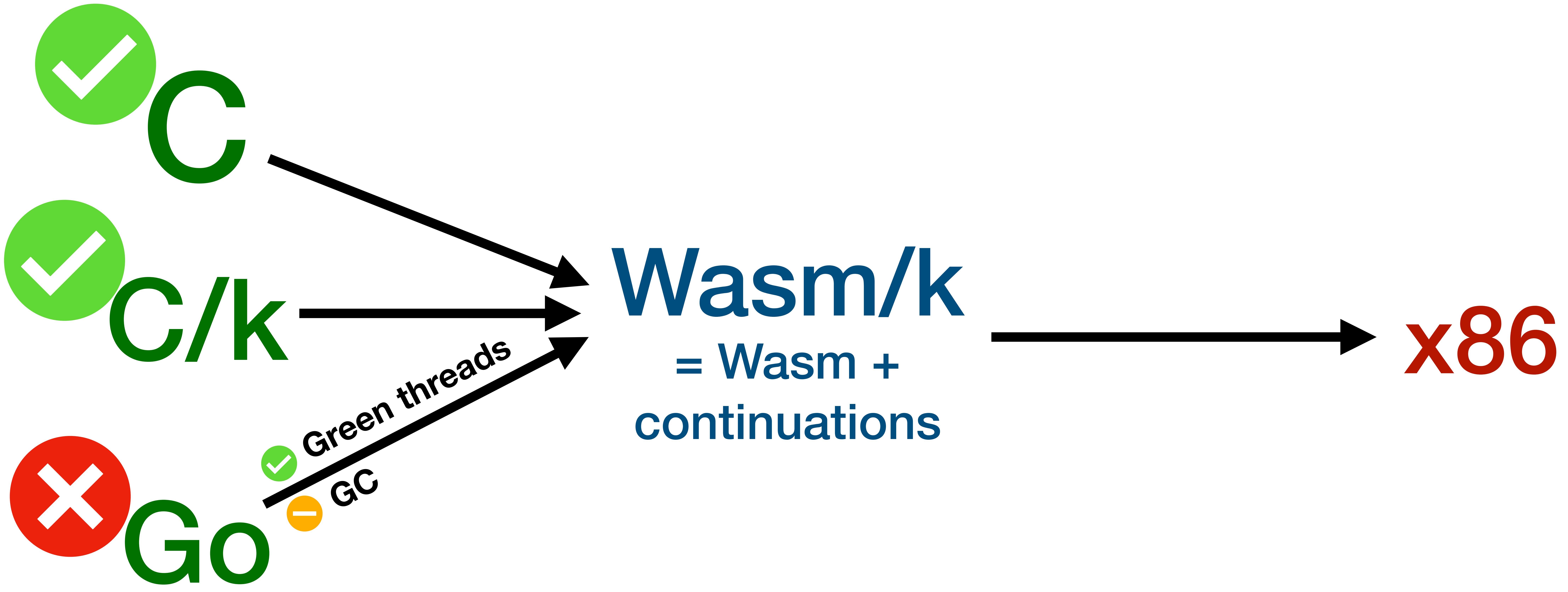

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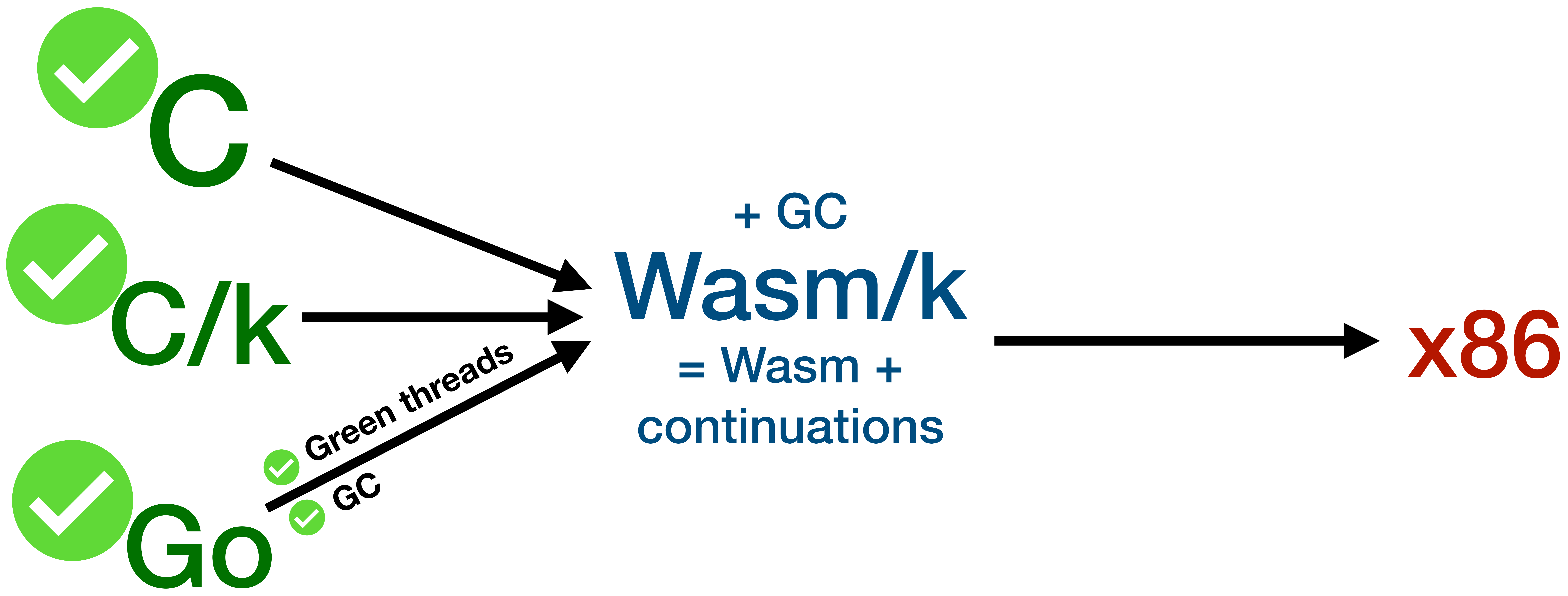

+ Language preference
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C $\longrightarrow$ Wasm

Expressions

Formal Stack

```
(5+3)*2
```

```
i32.const 5
i32.const 3
   i32.add
i32.const 2
   i32.mul
```

C $\longrightarrow$ Wasm

C

Functions +
Locals

```c
int f(int x) {
  int y = x;
  return g(y);
}
```

Wasm

Functions +
Locals

```wasm
(func $f (param $x i32)
         (local $y i32)
         (result i32)
  local.get $x
  local.set $y
  local.get $y
  call $g
)
```

$$\begin{tikzcd}\text{C} \arrow[r] & \text{Wasm} \arrow[r] & \text{x86}\end{tikzcd}$$

Expressions

Locals

Function Calls

malloc

Formal Stack

Locals

Function Calls

x86 Registers

Machine Stack

$$\begin{tikzcd}
\text{C} \arrow[r] & \text{Wasm} \arrow[r] & \text{x86} \\
\text{Expressions} \arrow[r] & \text{Formal Stack} & \text{x86 Registers} \\
\text{Locals} \arrow[r] & \text{Locals} & \text{Machine Stack} \\
\text{Function Calls} \arrow[r] & \text{Function Calls} & \\
\text{malloc} & &
\end{tikzcd}$$

$$\begin{tikzcd}
\text{C} \arrow[r] & \text{Wasm} \arrow[r] & \text{x86} \\
\text{Expressions} \arrow[r] & \text{Formal Stack} \arrow[dr] \arrow[dddr] & \\
 & & \text{x86 Registers} \\
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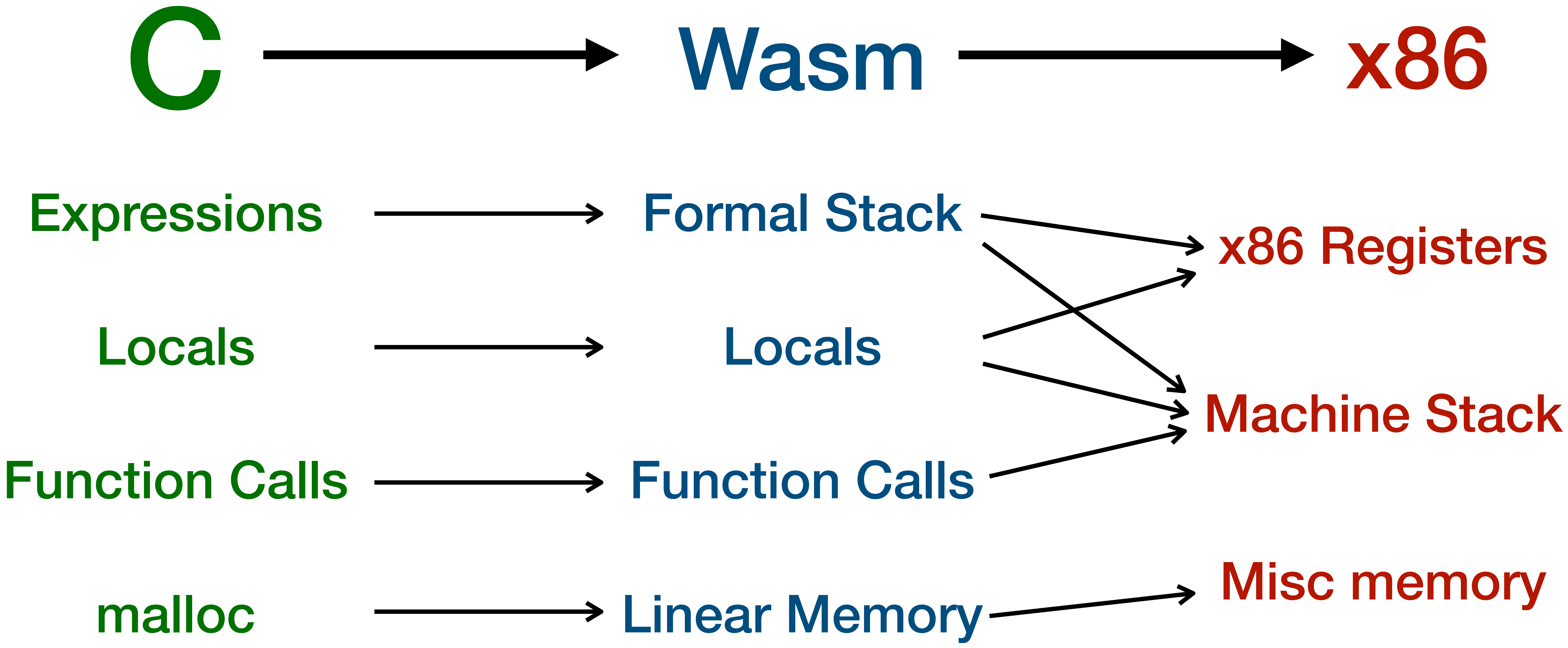

C
Wasm
x86
Expressions
Formal Stack
x86 Registers
Locals
Locals
Machine Stack
Function Calls
Function Calls
malloc
Linear Memory
Misc memory

C $\longrightarrow$ Wasm

Pointer to local

```
void f() {
  int x;
  g(&x);
}
```

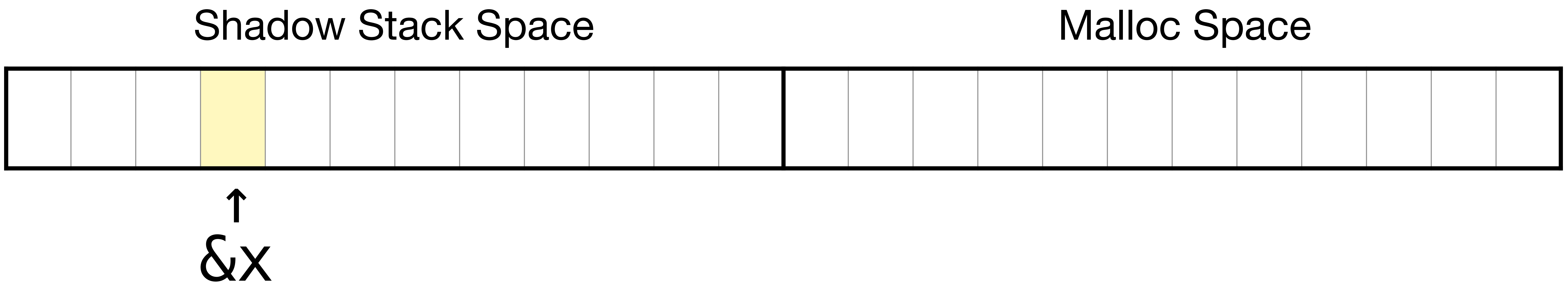
$$\text{C} \longrightarrow \text{Wasm}$$

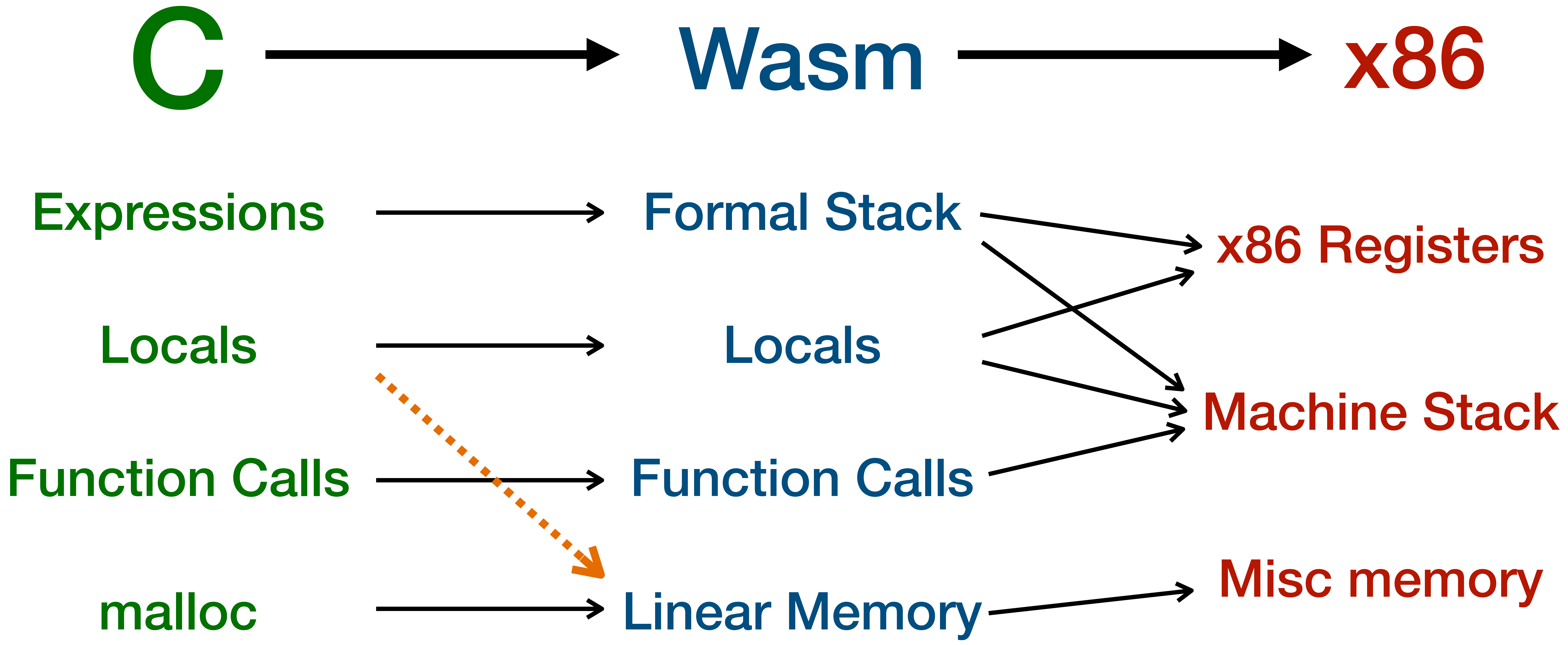
Pointer to local

```
void f() {
  int x;
  g(&x);
}
```

Local in Linear Memory

```
i32.const 4
call $shadow_stack_alloc
call $g
…
i32.const 4
call $shadow_stack_pop
```




C
Wasm
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Expressions
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Machine Stack
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Misc memory

Intro to WebAssembly

The Toolchain + Compilation

$$\begin{tikzcd}
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Intro to WebAssembly

The Toolchain + Compilation

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Intro to WebAssembly

The Toolchain + Compilation

$$\begin{tikzcd}
\text{Go} \arrow[r] & \text{Wasm} \arrow[r] & \text{x86}
\end{tikzcd}$$

Go → Wasm

```go
x := 0
for {

  x += 1

  f(x);

}
```

```wasm
local.get $x
i32.const 1
i32.add
local.set $x

local.get $x
call $f
```

Go ⟶ Wasm

```
x := 0
for {

  x += 1

  f(x);

}
```

← Might switch Goroutines / green threads!

```
local.get $x
i32.const 1
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```
local.get $x
call $f
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Go $\longrightarrow$ Wasm

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~~local.get $x~~
~~i32.const 1~~
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~~local.get $x~~
~~call $f~~

Go ⟶ Wasm

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x := 0
for {

  x += 1

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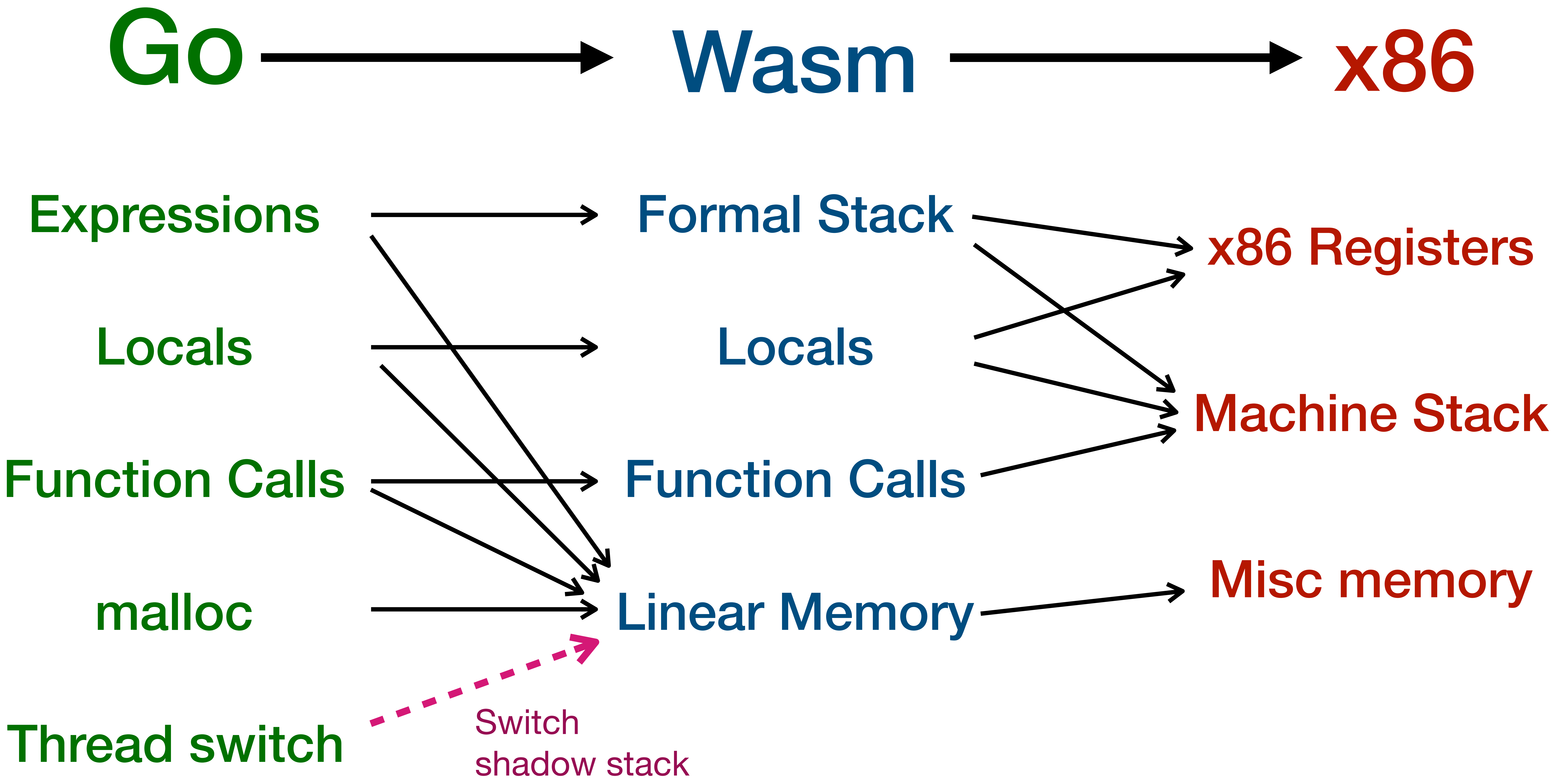
```

← Might switch Goroutines / green threads!

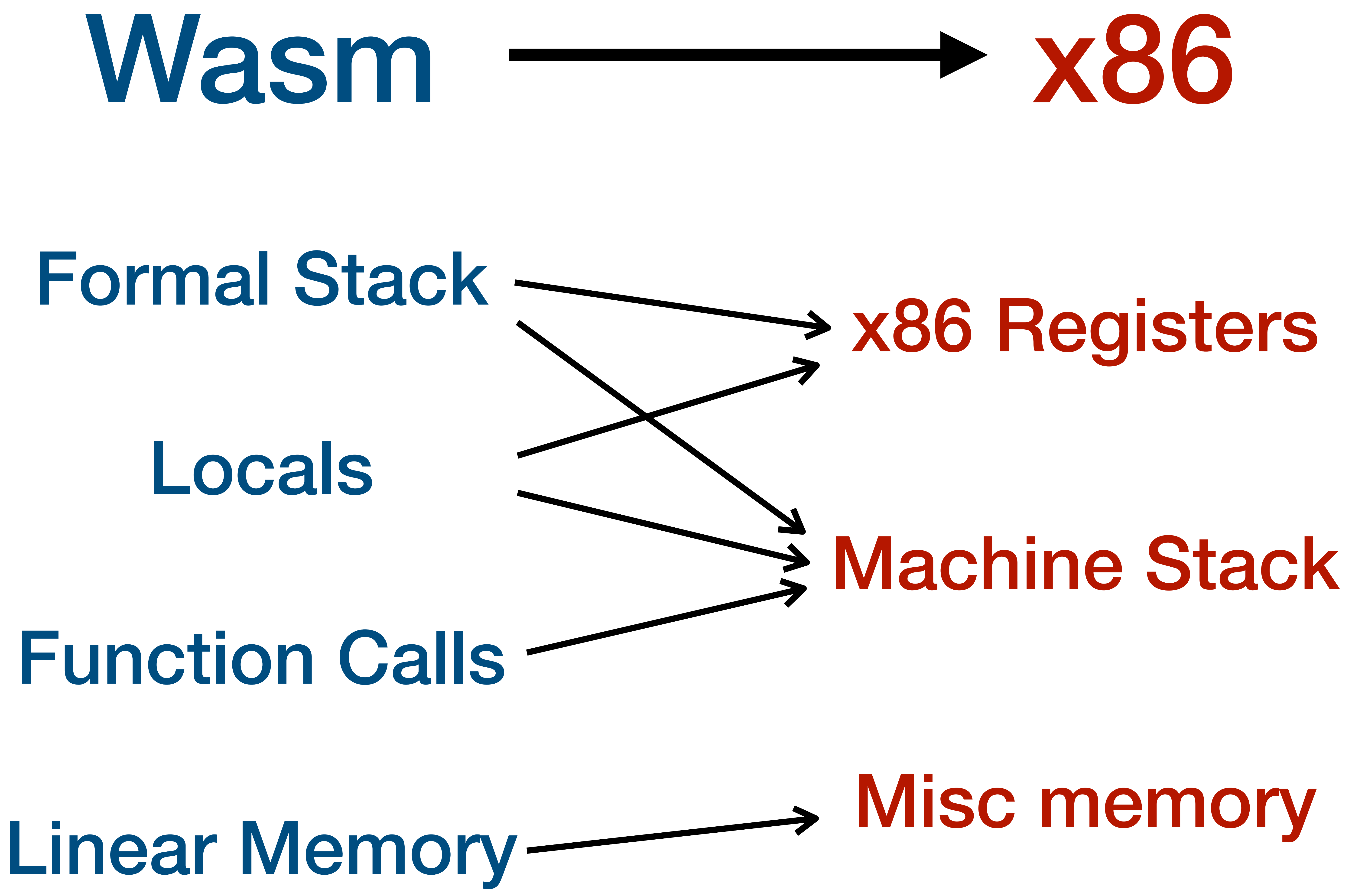
```wasm
local.get $x
i32.const 1
i32.add
local.set $x
```

```wasm
local.get $x
call $push_shadow_stack
local.get $x
call $f
call $pop_shadow_stack
local.set $x
```


Go
Wasm
x86
Expressions
Locals
Function Calls
malloc
Thread switch
Formal Stack
Locals
Function Calls
Linear Memory
x86 Registers
Machine Stack
Misc memory
Switch
shadow stack

Key Problem:

Go needs to manipulate the stack, but WebAssembly disallows manipulating the formal stack


Wasm
x86
Formal Stack
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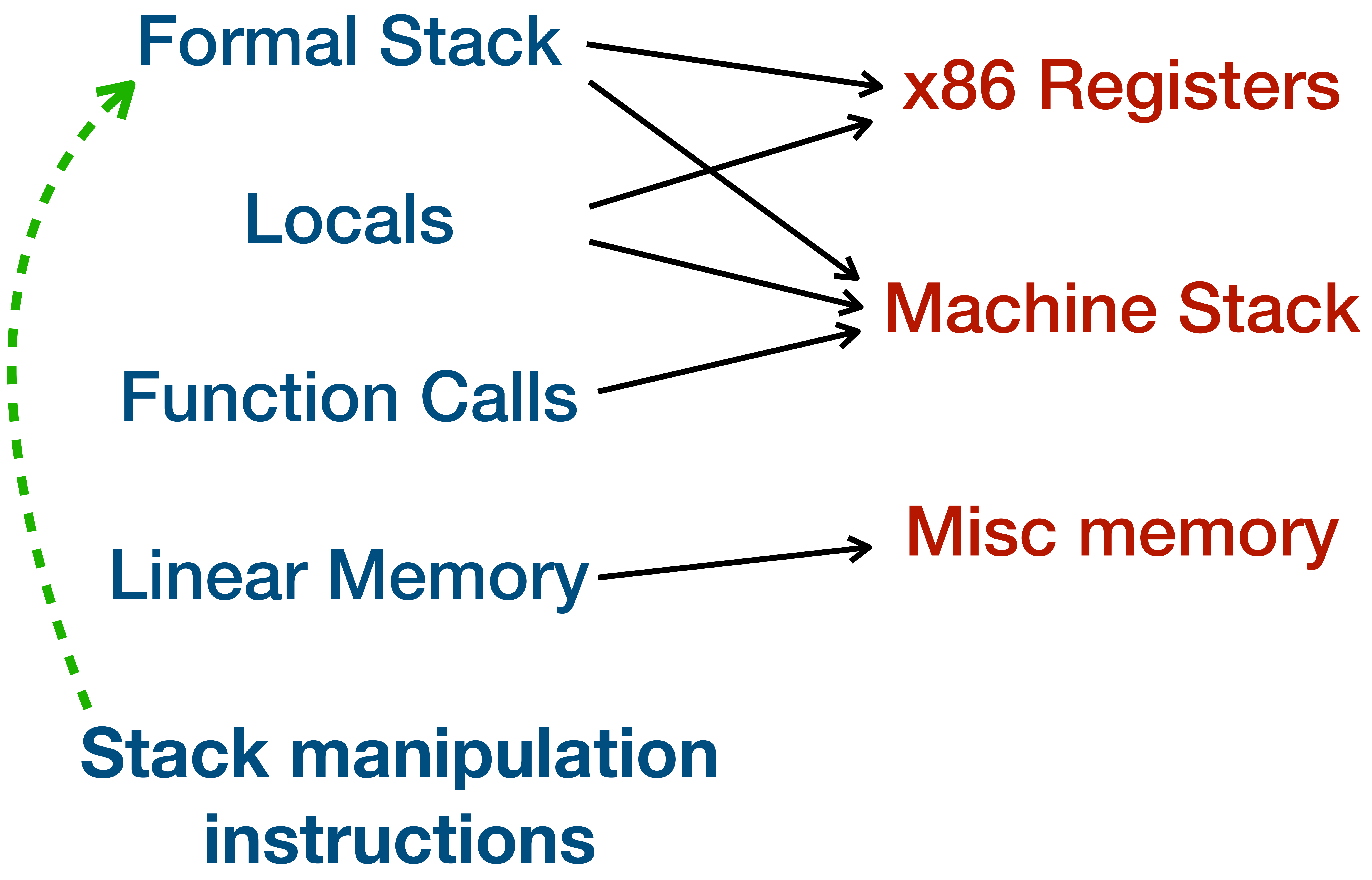
Wasm/k $\longrightarrow$ x86



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\text{malloc} \arrow[r] & \text{Linear Memory} \arrow[r] & \text{Misc memory} \\
\text{Stack manipulation functions} \arrow[r] & \text{Stack manipulation instructions} \arrow[uuuu, dashed, bend left] &
\end{tikzcd}$$

C/k = C +		**Wasm/k** = Wasm +
`control()`	→	`control`
`restore()`	→	`restore`
`continuation_copy()`	→	`continuation_copy`
`continuation_delete()`	→	`continuation_delete`
`prompt()`	→	`prompt … end`

Programming in C/k

Green threads: `control()` and `restore()`

```
std::vector<uint64_t> Q;

uint64_t dequeue() {
    uint64_t next_k = Q.back(); Q.pop_back();
    return next_k;
}

void yield_handler(uint64_t k, uint64_t arg) {
    Q.insert(Q.begin(), k);
    restore(dequeue(), 0);
}
void thread_yield() {
    control(yield_handler, 0);
}
```

```
void thread_main() {
    std::cout << "A" << std::endl;
    thread_yield();
    std::cout << "B" << std::endl;
}
int main() {
    thread_create(thread_main);
    thread_create(thread_main);
    join_all_threads();
}
```

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```

Programming in C/k

Generators: `continuation_delete()`

```c
void yield_handler(k_id k, Generator *g) {
    g->after_yield = k;
    restore(g->after_next, g->value);
}
void gen_yield(uint64_t v, Generator *g) {
    g->value = v;
    control(yield_handler, g);
}
// Next implementation
void next_handler(k_id k, Generator *g) {
    g->after_next = k;
    restore(g->after_yield, 0);
}
uint64_t gen_next(Generator *g) {
    return control(next_handler, g);
}
// Freeing a generator
void free_generator(Generator *g) {
    continuation_delete(g->after_yield); free(g);
}
```

```c
void example_generator(Generator *g) {
    uint64_t i = 0;
    while(1) { gen_yield(i++, g); }
}
int main() {
    Generator *g = make_generator(example_generator);
    for(int i = 0; i < 10; i++)
        printf("%llu\n", gen_next(g));
    free_generator(g);
    return 0;
}
```

Programming in C/k

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    free_generator(g);
    return 0;
}
```

Programming in C/k

Probabilistic Programming: `continuation_copy()`

```
struct ContinuationThunk {
    k_id continuation; // The continuation to resume
    uint64_t value; // The value to pass to the continuation
};
// vector of thunks which need to be executed
std::vector<ContinuationThunk *> to_execute;

std::map<uint64_t, double> *driver(uint64_t (*body)()) {
    auto *results = new std::vector<uint64_t>();
    results->push_back(body());
    if(rest.size() > 0) {
        ContinuationThunk *t = rest.back(); rest.pop_back();
        restore(t->continuation, t->value);
    }
    return count_probs(results);
}

void uniform_handler(k_id k, std::vector<uint64_t> *args) {
    for(auto it = std::next(args->begin());
        it != args->end(); ++it) {
        to_execute.push_back(new ContinuationThunk {
            .continuation=continuation_copy(k),
            .value=*it});
    }
    restore(k, args[0]);
}
uint64_t uniform(std::vector<uint64_t> *args) {
    return control(uniform_handler, args);
}
```

```
uint64_t sum_d6() {
    auto *d6 = new std::vector<uint64_t> {1, 2, 3, 4, 5, 6};
    return uniform(d6) + uniform(d6);
}
int main() {
    std::cout << *driver(sum_d6) << std::endl; return 0;
}
```

Programming in C/k

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    results->push_back(body());
    if(rest.size() > 0) {
        ContinuationThunk *t = rest.back(); rest.pop_back();
        restore(t->continuation, t->value);
    }
    return count_probs(results);
}

void uniform_handler(k_id k, std::vector<uint64_t> *args) {
    for(auto it = std::next(args->begin());
        it != args->end(); ++it) {
        to_execute.push_back(new ContinuationThunk {
            .continuation=continuation_copy(k),
            .value=*it});
    }
    restore(k, args[0]);
}
uint64_t uniform(std::vector<uint64_t> *args) {
    return control(uniform_handler, args);
}
```

```
uint64_t sum_d6() {
    auto *d6 = new std::vector<uint64_t> {1, 2, 3, 4, 5, 6};
    return uniform(d6) + uniform(d6);
}
int main() {
    std::cout << *driver(sum_d6) << std::endl; return 0;
}
```

Programming in C/k

Probabilistic Programming: `continuation_copy()`

```
struct ContinuationThunk {
    k_id continuation; // The continuation to resume
    uint64_t value; // The value to pass to the continuation
};
// vector of thunks which need to be executed
std::vector<ContinuationThunk *> to_execute;

std::map<uint64_t, double> *driver(uint64_t (*body)()) {
    auto *results = new std::vector<uint64_t>();
    results->push_back(body());
    if(rest.size() > 0) {
        ContinuationThunk *t = rest.back(); rest.pop_back();
        restore(t->continuation, t->value);
    }
    return count_probs(results);
}

void uniform_handler(k_id k, std::vector<uint64_t> *args) {
    for(auto it = std::next(args->begin());
        it != args->end(); ++it) {
        to_execute.push_back(new ContinuationThunk {
            .continuation=continuation_copy(k),
            .value=*it});
    }
    restore(k, args[0]);
}
uint64_t uniform(std::vector<uint64_t> *args) {
    return control(uniform_handler, args);
}
```

```
uint64_t sum_d6() {
    auto *d6 = new std::vector<uint64_t> {1, 2, 3, 4, 5, 6};
    return uniform(d6) + uniform(d6);
}
int main() {
    std::cout << *driver(sum_d6) << std::endl; return 0;
}
```

Programming in C/k

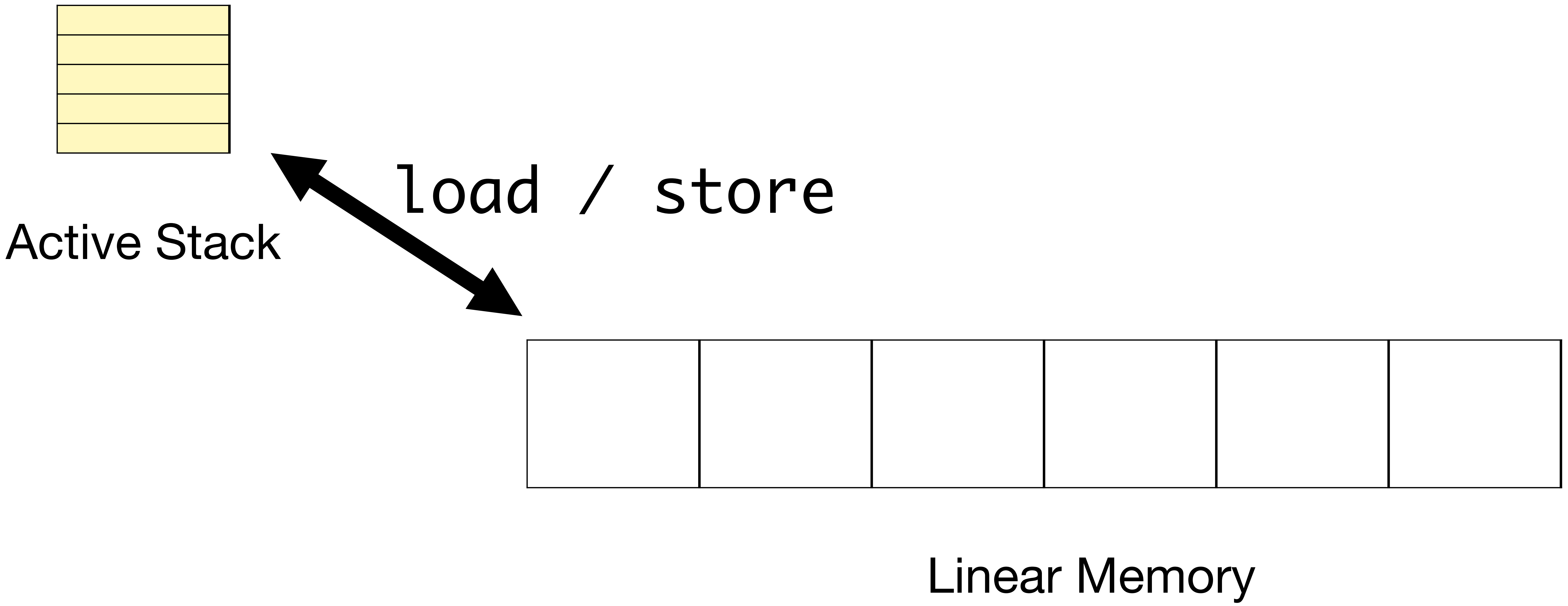
Probabilistic Programming: `continuation_copy()`

```
struct ContinuationThunk {
    k_id continuation; // The continuation to resume
    uint64_t value; // The value to pass to the continuation
};
// vector of thunks which need to be executed
std::vector<ContinuationThunk *> to_execute;

std::map<uint64_t, double> *driver(uint64_t (*body)()) {
    auto *results = new std::vector<uint64_t>();
    results->push_back(body());
    if(rest.size() > 0) {
        ContinuationThunk *t = rest.back(); rest.pop_back();
        restore(t->continuation, t->value);
    }
    return count_probs(results);
}

void uniform_handler(k_id k, std::vector<uint64_t> *args) {
    for(auto it = std::next(args->begin());
        it != args->end(); ++it) {
        to_execute.push_back(new ContinuationThunk {
            .continuation=continuation_copy(k),
            .value=*it});
    }
    restore(k, args[0]);
}
uint64_t uniform(std::vector<uint64_t> *args) {
    return control(uniform_handler, args);
}
```

```
uint64_t sum_d6() {
    auto *d6 = new std::vector<uint64_t> {1, 2, 3, 4, 5, 6};
    return uniform(d6) + uniform(d6);
}
int main() {
    std::cout << *driver(sum_d6) << std::endl; return 0;
}
```

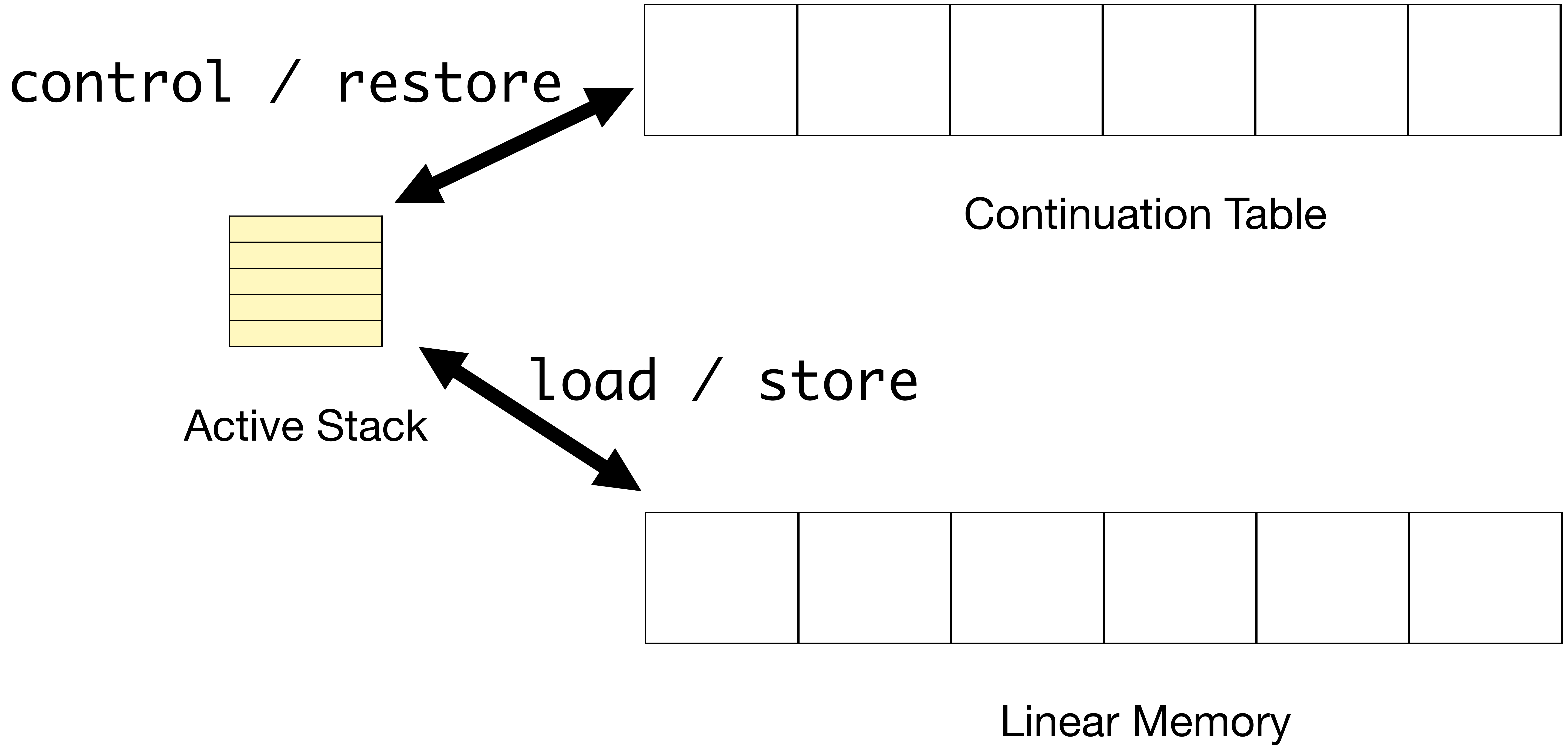
Wasm/k Semantics

The continuation table



Wasm/k Semantics

The continuation table

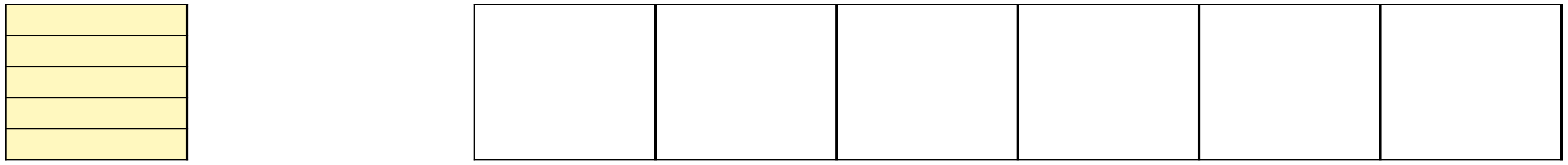


Wasm/k Semantics

`control` and `restore`

$$s;\ v_l^*;\ L^{\max}[(\mathbf{i64.const}\ v)\ (\mathbf{control}\ h)] \rightsquigarrow_i s';\ \epsilon;\ (\mathbf{i64.const}\ \kappa)\ (\mathbf{i64.const}\ v)\ (\mathbf{call}\ h)\ \mathbf{trap}$$

$$s;\ v_l^*;\ L^{\max}[(\mathbf{i64.const}\ \kappa)\ (\mathbf{i64.const}\ v)\ \mathbf{restore}] \rightsquigarrow_i s';\ v_l^{*\prime};\ L^{\max\prime}[(\mathbf{i64.const}\ v)]$$



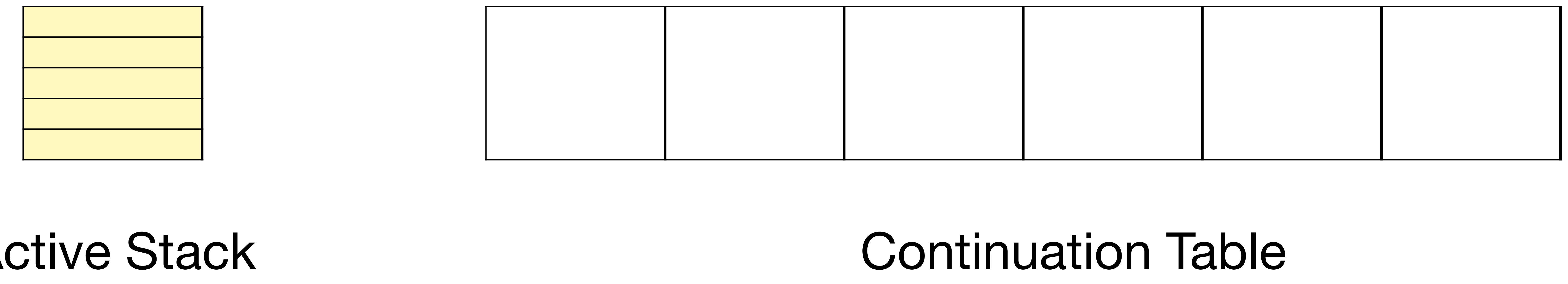
Wasm/k Semantics

`control` and `restore`

$$s;\ v_l^*;\ \boxed{L^{\max}}[(\mathbf{i64.const}\ v)\ (\mathbf{control}\ h)] \leadsto_i s';\ \epsilon;\ (\mathbf{i64.const}\ \kappa)\ (\mathbf{i64.const}\ v)\ (\mathbf{call}\ h)\ \mathbf{trap}$$

Capture the stack

$$s;\ v_l^*;\ L^{\max}[(\mathbf{i64.const}\ \kappa)\ (\mathbf{i64.const}\ v)\ \mathbf{restore}] \leadsto_i s';\ v_l^{*\prime};\ L^{\max\prime}[(\mathbf{i64.const}\ v)]$$



Wasm/k Semantics

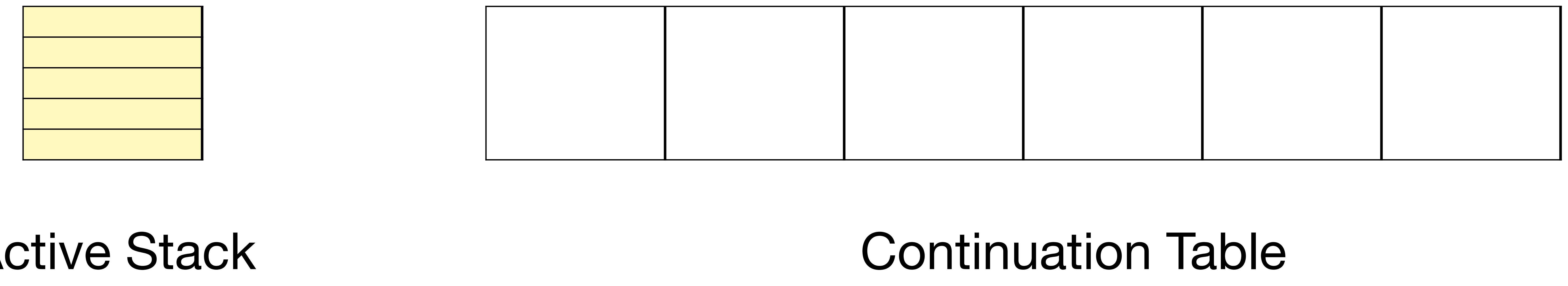
`control` and `restore`

$$s;\ v_l^*;\ \boxed{L^{\max}}[(\textbf{i64.const}\ v)\ (\textbf{control}\ h)] \rightsquigarrow_i \boxed{s';}\ \epsilon;\ (\textbf{i64.const}\ \kappa)\ (\textbf{i64.const}\ v)\ (\textbf{call}\ h)\ \textbf{trap}$$

Capture the stack

where s’ = s but with context L^{max} and v_l^* stored at index k

$$s;\ v_l^*;\ L^{\max}[(\textbf{i64.const}\ \kappa)\ (\textbf{i64.const}\ v)\ \textbf{restore}] \rightsquigarrow_i s';\ v_l^{*\prime};\ L^{\max\prime}[(\textbf{i64.const}\ v)]$$



Wasm/k Semantics

`control` and `restore`

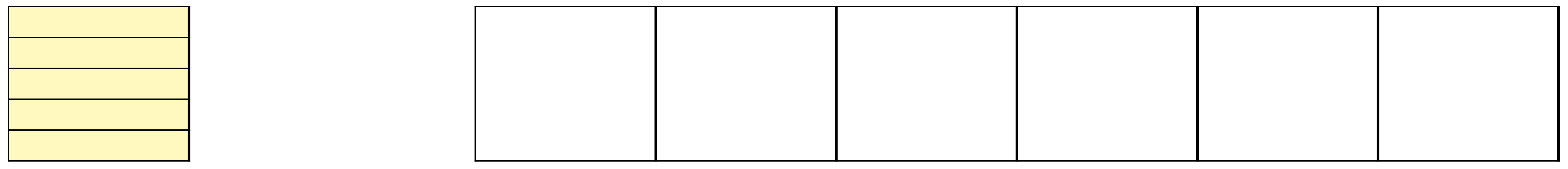
$$s;\ v_l^*;\ \boxed{L^{\max}}[(\mathbf{i64.const}\ v)\ (\mathbf{control}\ h)] \rightsquigarrow_i \boxed{s';}\ \boxed{\epsilon;\ (\mathbf{i64.const}\ \kappa)\ (\mathbf{i64.const}\ v)\ (\mathbf{call}\ h)}\ \mathbf{trap}$$

Capture the stack

where s' = s but with context L^{max} and v_l^* stored at index k

Execute h in fresh stack.
k is a new ID

$$s;\ v_l^*;\ L^{\max}[(\mathbf{i64.const}\ \kappa)\ (\mathbf{i64.const}\ v)\ \mathbf{restore}] \rightsquigarrow_i s';\ v_l^{*\prime};\ L^{\max\prime}[(\mathbf{i64.const}\ v)]$$



Active Stack

Continuation Table

Wasm/k Semantics

`control` and `restore`

$$s;\ v_l^*;\ \boxed{L^{\max}}[(\mathbf{i64.const}\ v)\ (\mathbf{control}\ h)] \rightsquigarrow_i \boxed{s';}\ \boxed{\epsilon;\ (\mathbf{i64.const}\ \kappa)\ (\mathbf{i64.const}\ v)\ (\mathbf{call}\ h)}\ \mathbf{trap}$$

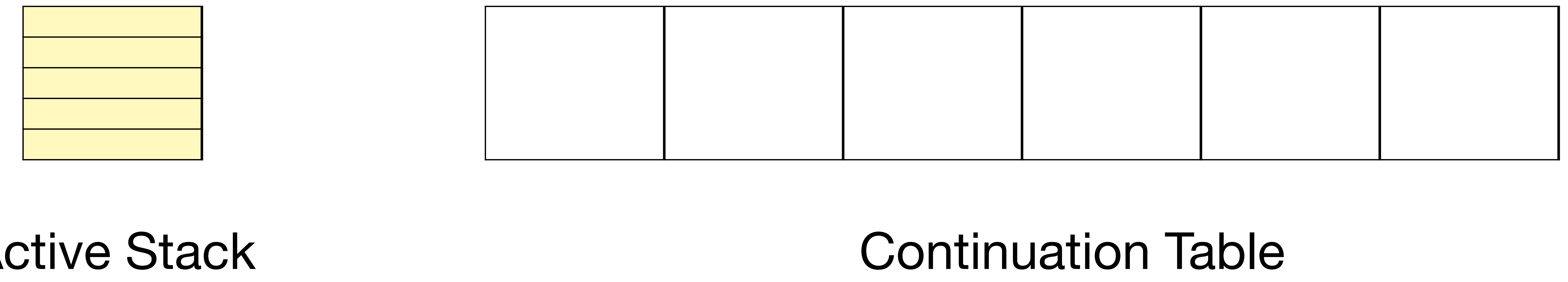
Capture the stack

where s’ = s but with context $L^{\max}$ and v_l^* stored at index k

Execute h in fresh stack. k is a new ID

Current stack is discarded

$$s;\ v_l^*;\ \boxed{L^{\max}}[(\mathbf{i64.const}\ \kappa)\ (\mathbf{i64.const}\ v)\ \mathbf{restore}] \rightsquigarrow_i s';\ v_l^{*\prime};\ L^{\max\prime}[(\mathbf{i64.const}\ v)]$$



Wasm/k Semantics

`control` and `restore`

$$s;\ v_l^*;\ \boxed{L^{\max}}[(\mathbf{i64.const}\ v)\ (\mathbf{control}\ h)] \leadsto_i \boxed{s';}\ \boxed{\epsilon;\ (\mathbf{i64.const}\ \kappa)\ (\mathbf{i64.const}\ v)\ (\mathbf{call}\ h)}\ \mathbf{trap}$$

Capture the stack

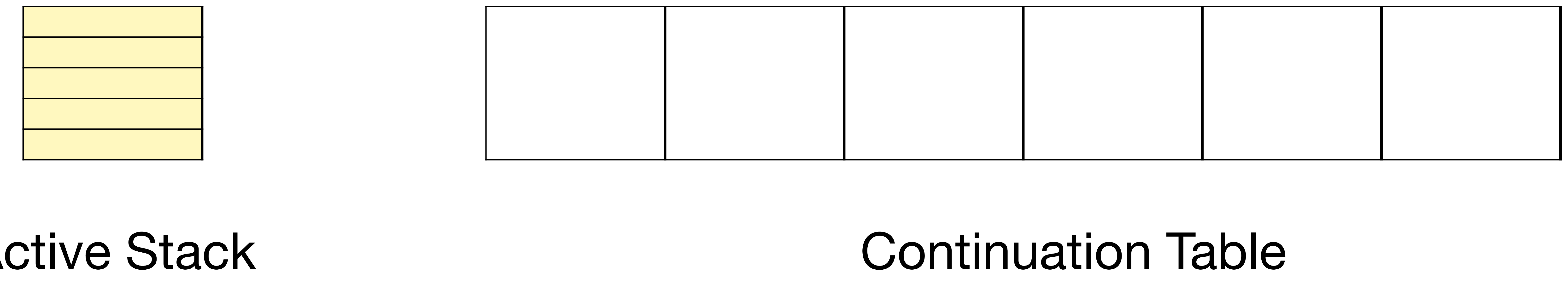
where s’ = s but with context L^{max} and v_l^* stored at index k

Execute h in fresh stack. k is a new ID

Current stack is discarded

Retrieved from s at index k

$$s;\ v_l^*;\ \boxed{L^{\max}}[(\mathbf{i64.const}\ \kappa)\ (\mathbf{i64.const}\ v)\ \mathbf{restore}] \leadsto_i s';\ v_l^{*\prime};\ \boxed{L^{\max\prime}}[(\mathbf{i64.const}\ v)]$$

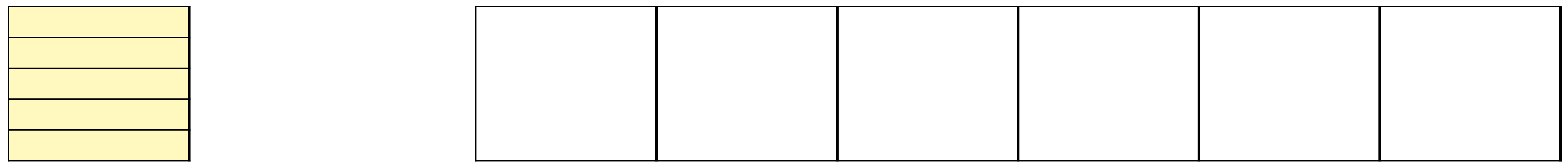


Wasm/k Semantics

`control` and `restore`

$$s;\ v_l^*;\ \underbrace{\boxed{L^{\max}}}_{\text{Capture the stack}}[(\mathbf{i64.const}\ v)\ (\mathbf{control}\ h)] \leadsto_i \underbrace{\boxed{s';}}_{\text{where s' = s but with context } L^{\max} \text{ and } v_l^{*} \text{ stored at index k}}\ \underbrace{\boxed{\epsilon;\ (\mathbf{i64.const}\ \kappa)\ (\mathbf{i64.const}\ v)\ (\mathbf{call}\ h)}}_{\text{Execute h in fresh stack. k is a new ID}}\ \mathbf{trap}$$

$$s;\ v_l^*;\ \overbrace{\boxed{L^{\max}}}^{\text{Current stack is discarded}}[(\mathbf{i64.const}\ \kappa)\ (\mathbf{i64.const}\ v)\ \mathbf{restore}] \leadsto_i \overbrace{\boxed{s';}}^{\text{Index k is marked as free}}\ v_l^{*\prime};\ \overbrace{\boxed{L^{\max\prime}}}^{\text{Retrieved from s at index k}}[(\mathbf{i64.const}\ v)]$$



Wasm/k Semantics

`control` and `restore`

$$s;\ v_l^*;\ \boxed{L^{\max}}[(\mathbf{i64.const}\ v)\ (\mathbf{control}\ h)] \leadsto_i \boxed{s';}\ \boxed{\epsilon;\ (\mathbf{i64.const}\ \kappa)\ (\mathbf{i64.const}\ v)\ (\mathbf{call}\ h)}\ \mathbf{trap}$$

Capture *entire* stack

where s' = s but with context L^{max} and v_l^* stored at index k

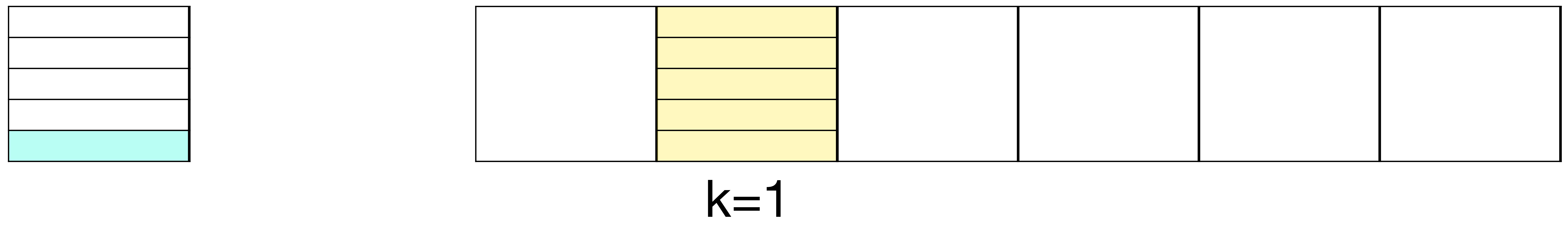
Execute h in fresh stack.
k is a new ID

Current stack is discarded

Index k is marked as free

Retrieved from s at index k

$$s;\ v_l^*;\ \boxed{L^{\max}}[(\mathbf{i64.const}\ \kappa)\ (\mathbf{i64.const}\ v)\ \mathbf{restore}] \leadsto_i \boxed{s';}\ v_l^{*\prime};\ \boxed{L^{\max\prime}}[(\mathbf{i64.const}\ v)]$$



Active Stack

Continuation Table

Wasm/k Semantics

`control` and `restore`

$$s;\ v_l^*;\ \boxed{L^{\max}}[(\textbf{i64.const}\ v)\ (\textbf{control}\ h)] \rightsquigarrow_i \boxed{s';}\ \boxed{\epsilon;\ (\textbf{i64.const}\ \kappa)\ (\textbf{i64.const}\ v)\ (\textbf{call}\ h)}\ \textbf{trap}$$

Capture the stack

where s’ = s but with context L^{max} and v_l^* stored at index k

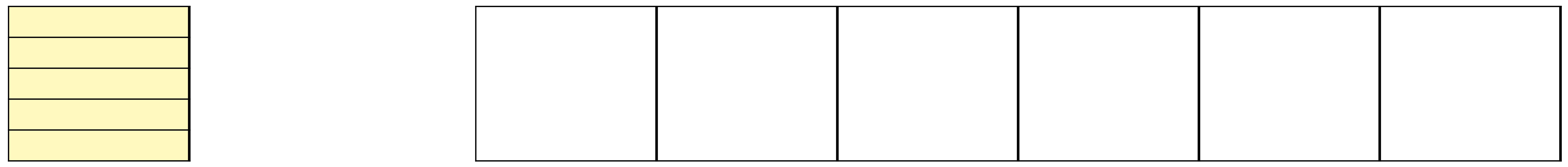
Execute h in fresh stack.
k is a new ID

Current stack is discarded

Index k is marked as free

Retrieved from s at index k

$$s;\ v_l^*;\ \boxed{L^{\max}}[(\textbf{i64.const}\ \kappa)\ (\textbf{i64.const}\ v)\ \textbf{restore}] \rightsquigarrow_i \boxed{s';}\ v_l^{*\prime};\ \boxed{L^{\max\prime}}[(\textbf{i64.const}\ v)]$$



Active Stack

Continuation Table

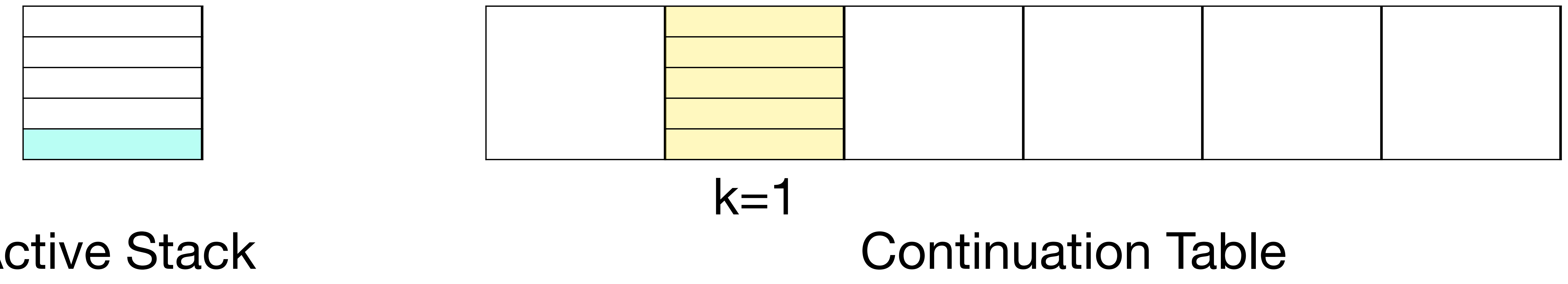
Wasm/k Semantics

`continuation_copy`

$$s;\ \boxed{(\text{i64.const}\ \kappa)}\ \text{continuation\_copy} \hookrightarrow_i \boxed{s';\ (\text{i64.const}\ \kappa')}$$

Stack at index k will be copied

Stack at k is copied to k', and k' is returned



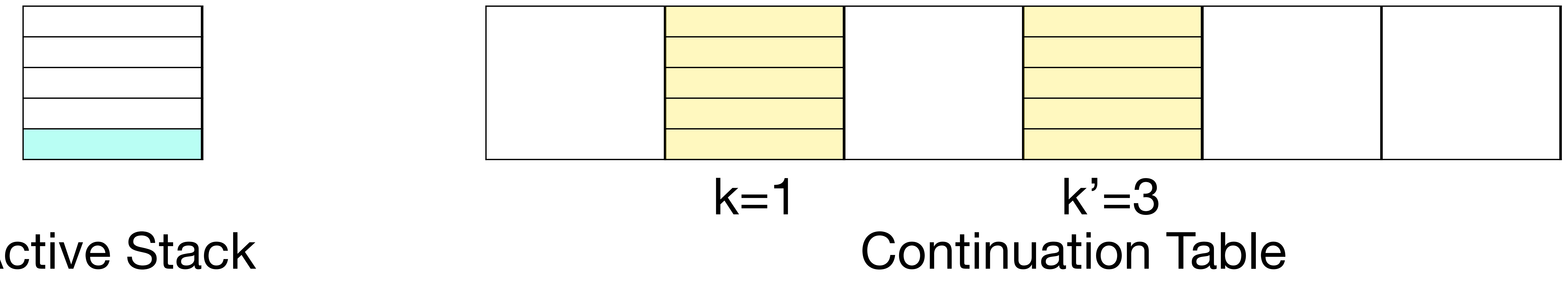
Wasm/k Semantics

`continuation_copy`

$$s;\ \boxed{(\text{i64.const}\ \kappa)}\ \text{continuation\_copy} \hookrightarrow_i \boxed{s';\ (\text{i64.const}\ \kappa')}$$

Stack at index k will be copied

Stack at k is copied to k', and k' is returned

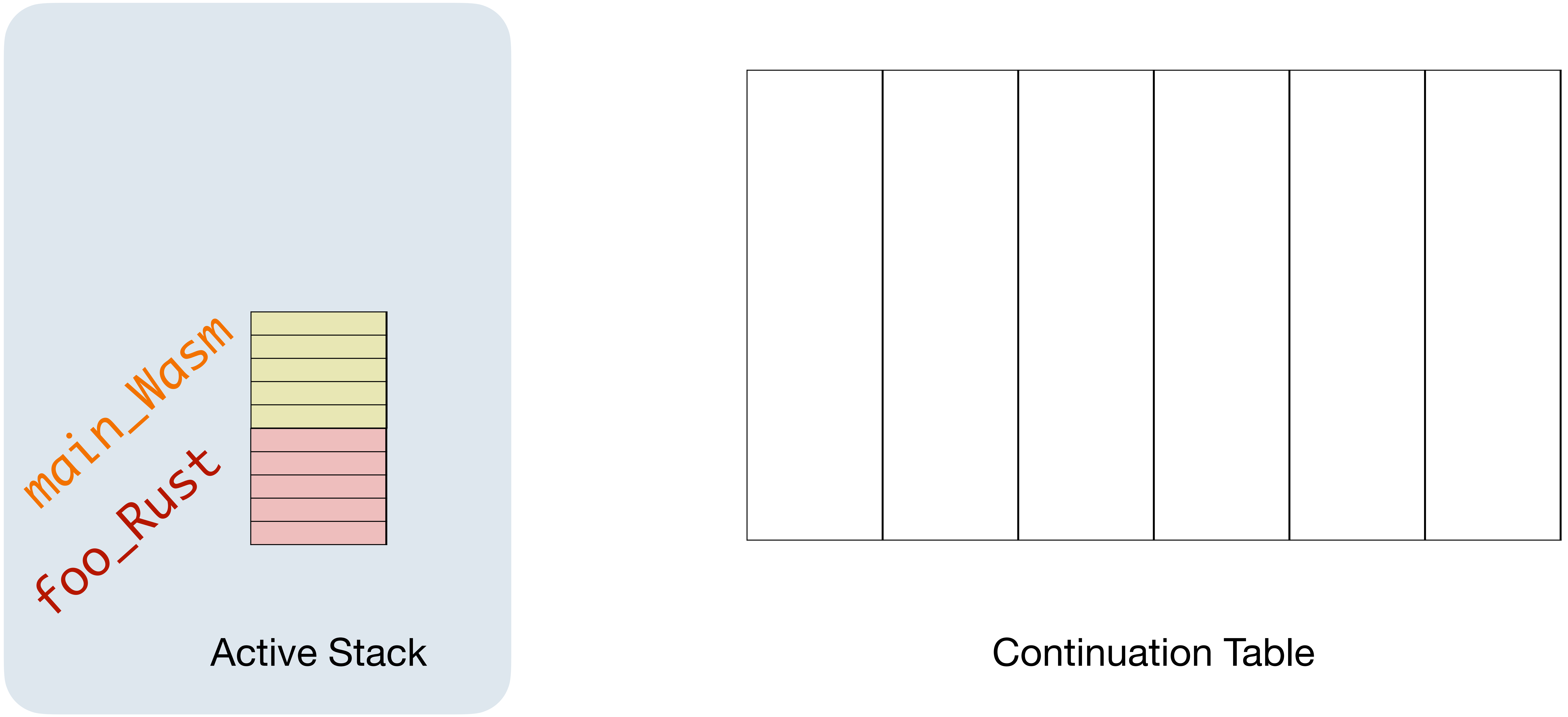


What We Have so Far

C/k = C +		Wasm/k = Wasm +
`control()`	$\longrightarrow$	`control`
`restore()`	$\longrightarrow$	`restore`
`continuation_copy()`	$\longrightarrow$	`continuation_copy`
`continuation_delete()`	$\longrightarrow$	`continuation_delete`
`prompt()`	$\longrightarrow$	`prompt … end`

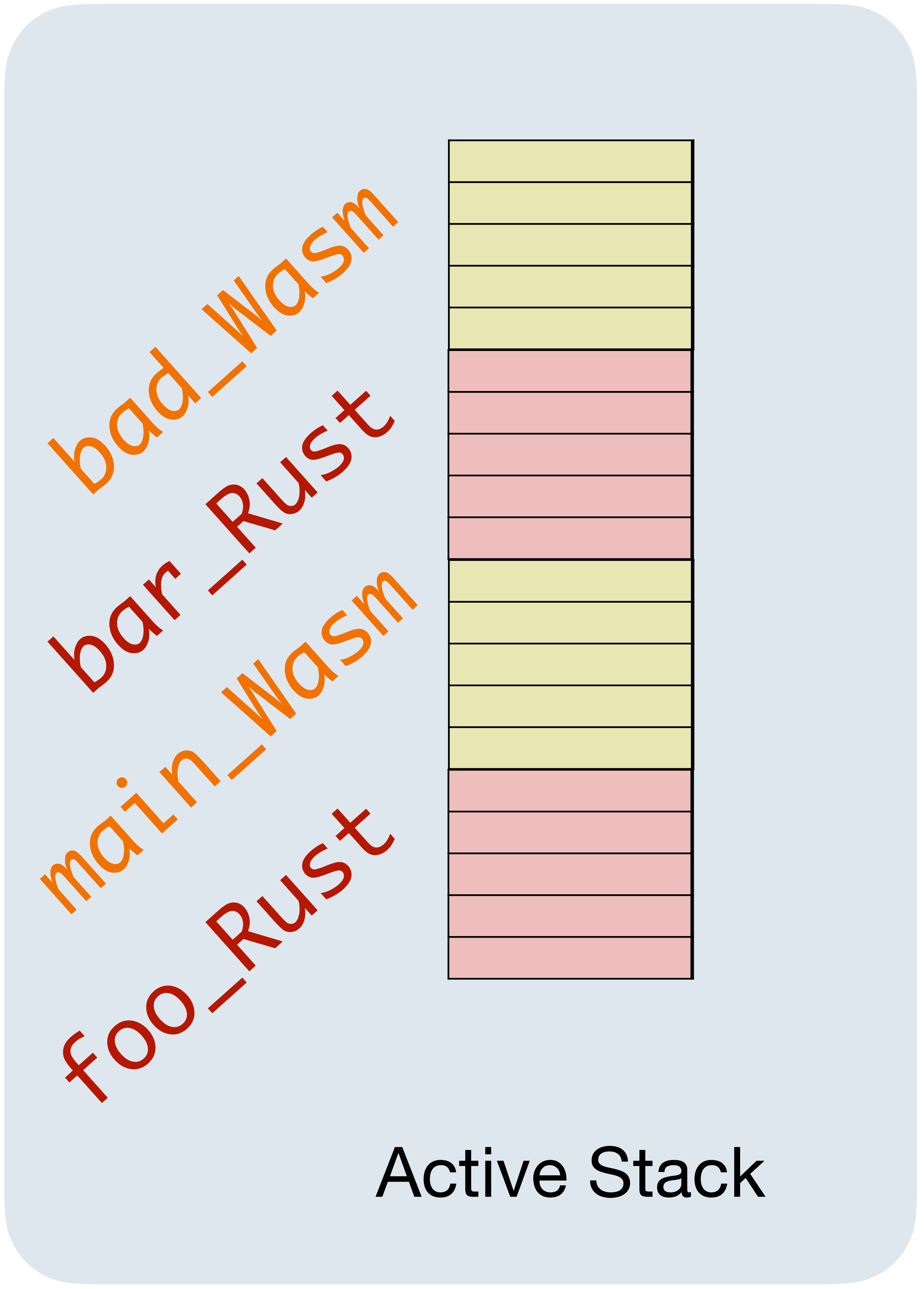
Is it Safe?

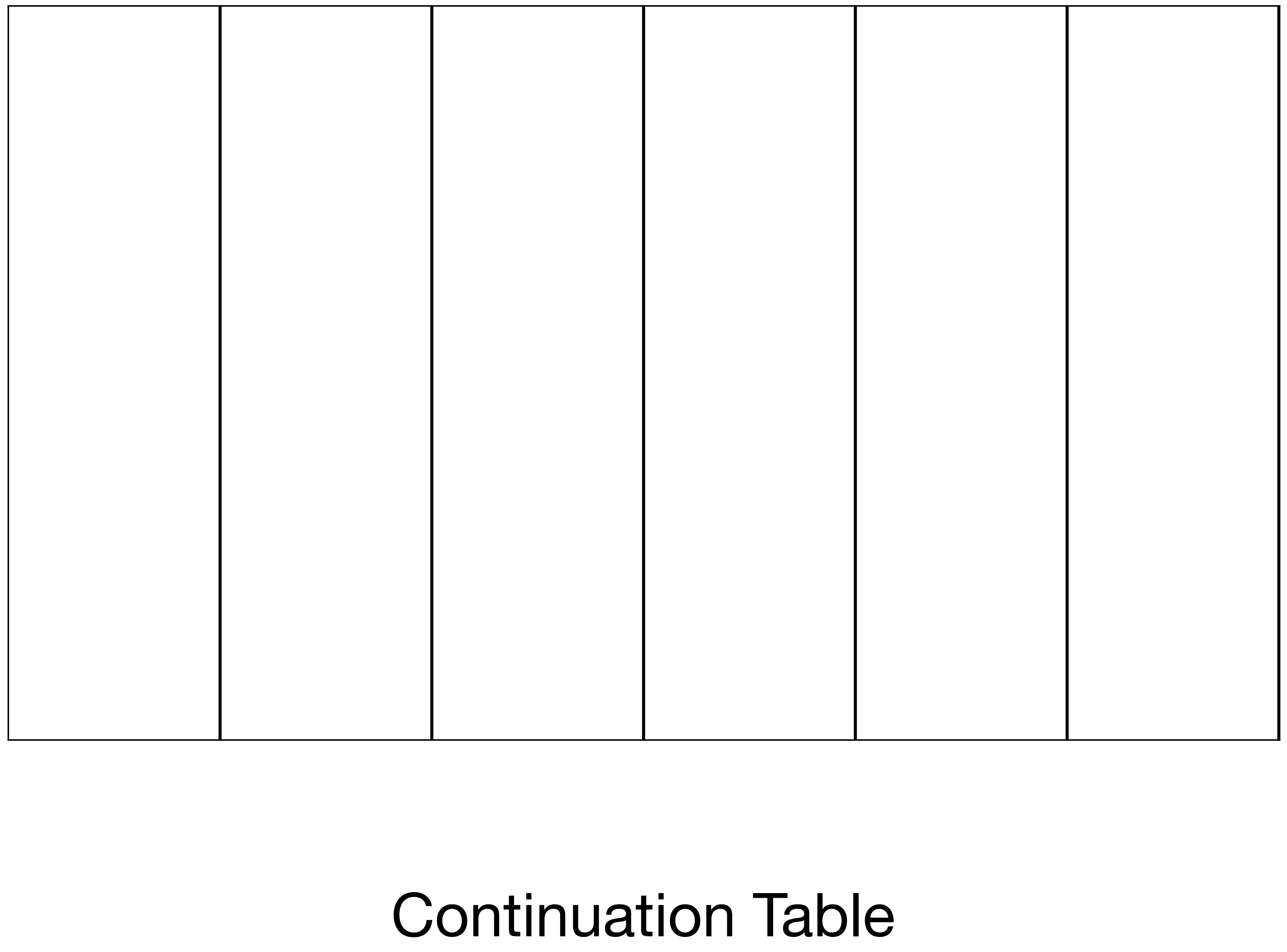
Almost… what about FFI?



Is it Safe?

Almost… what about FFI?





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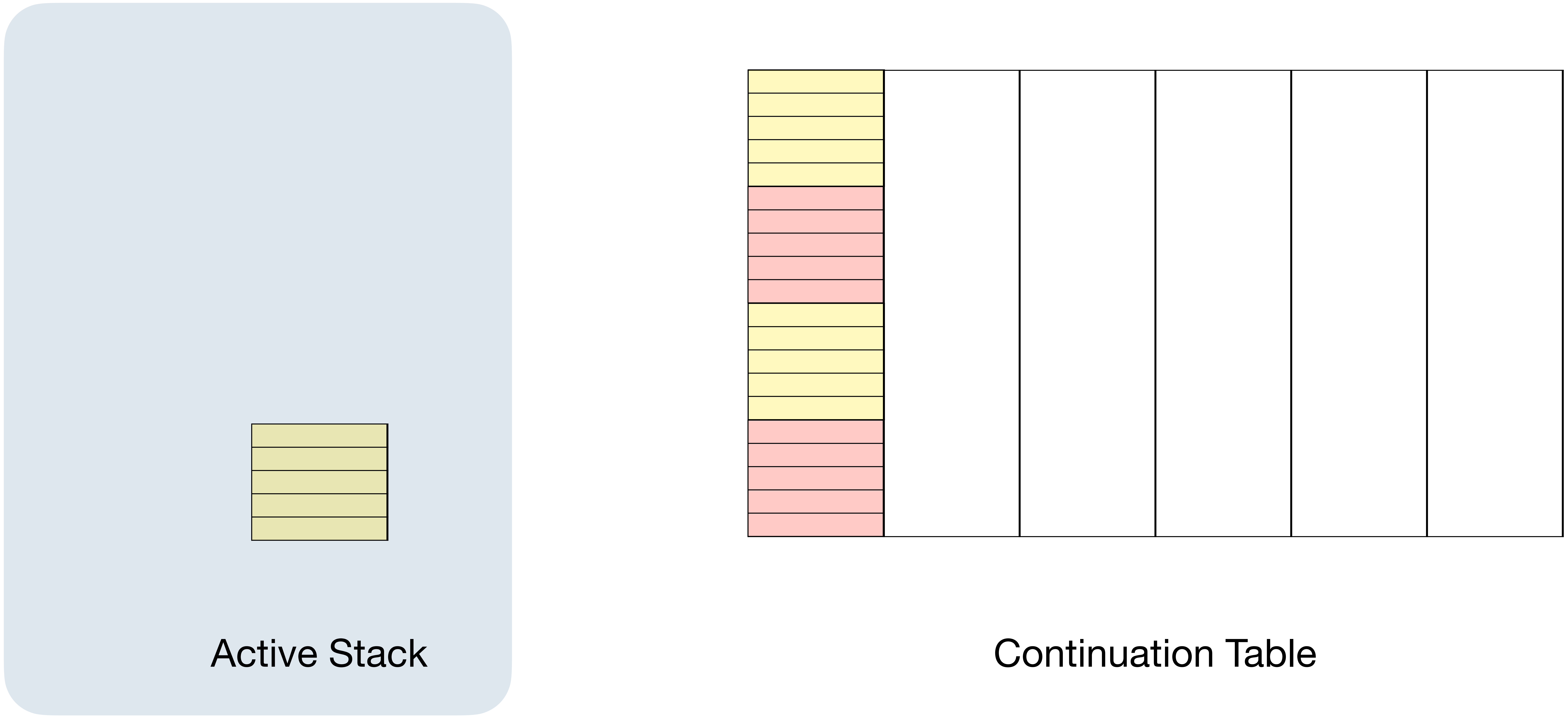
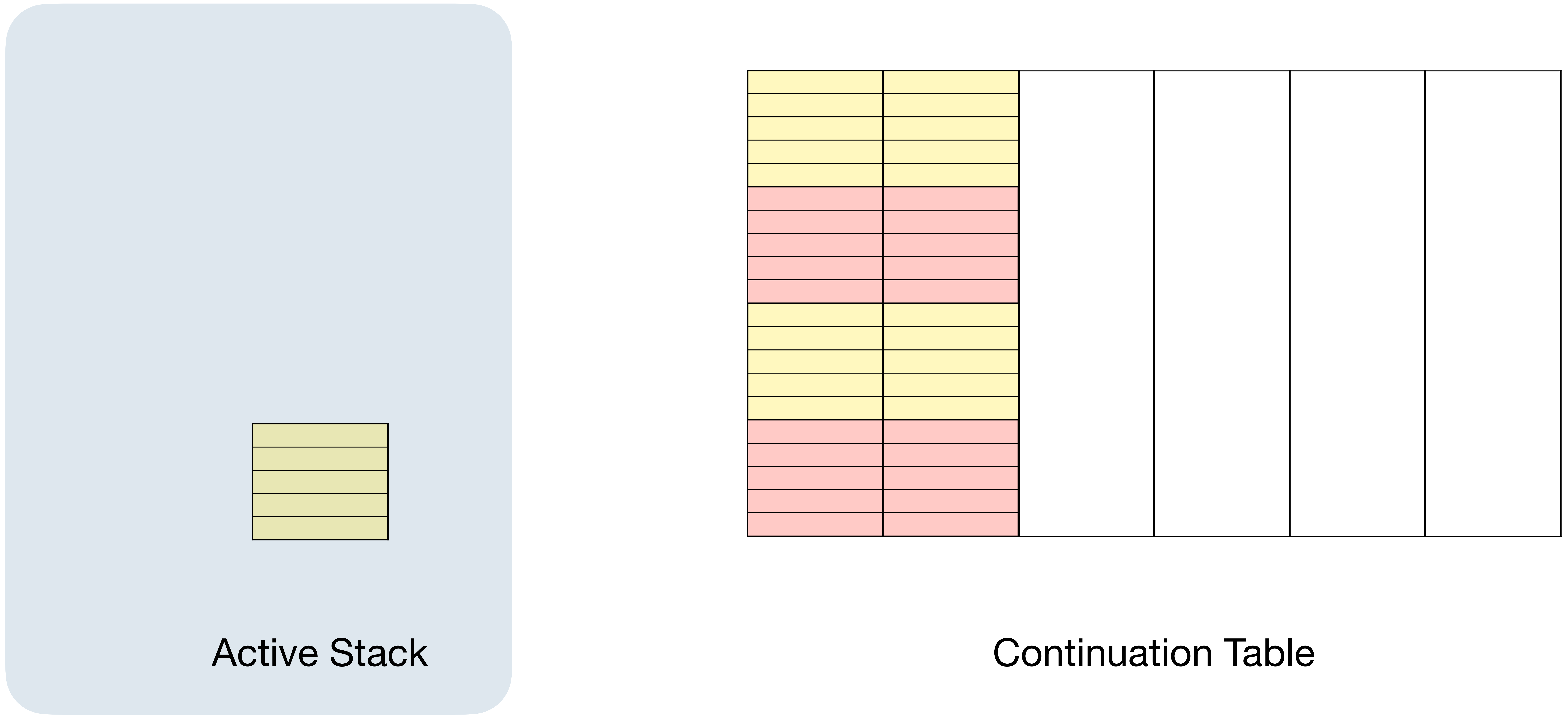


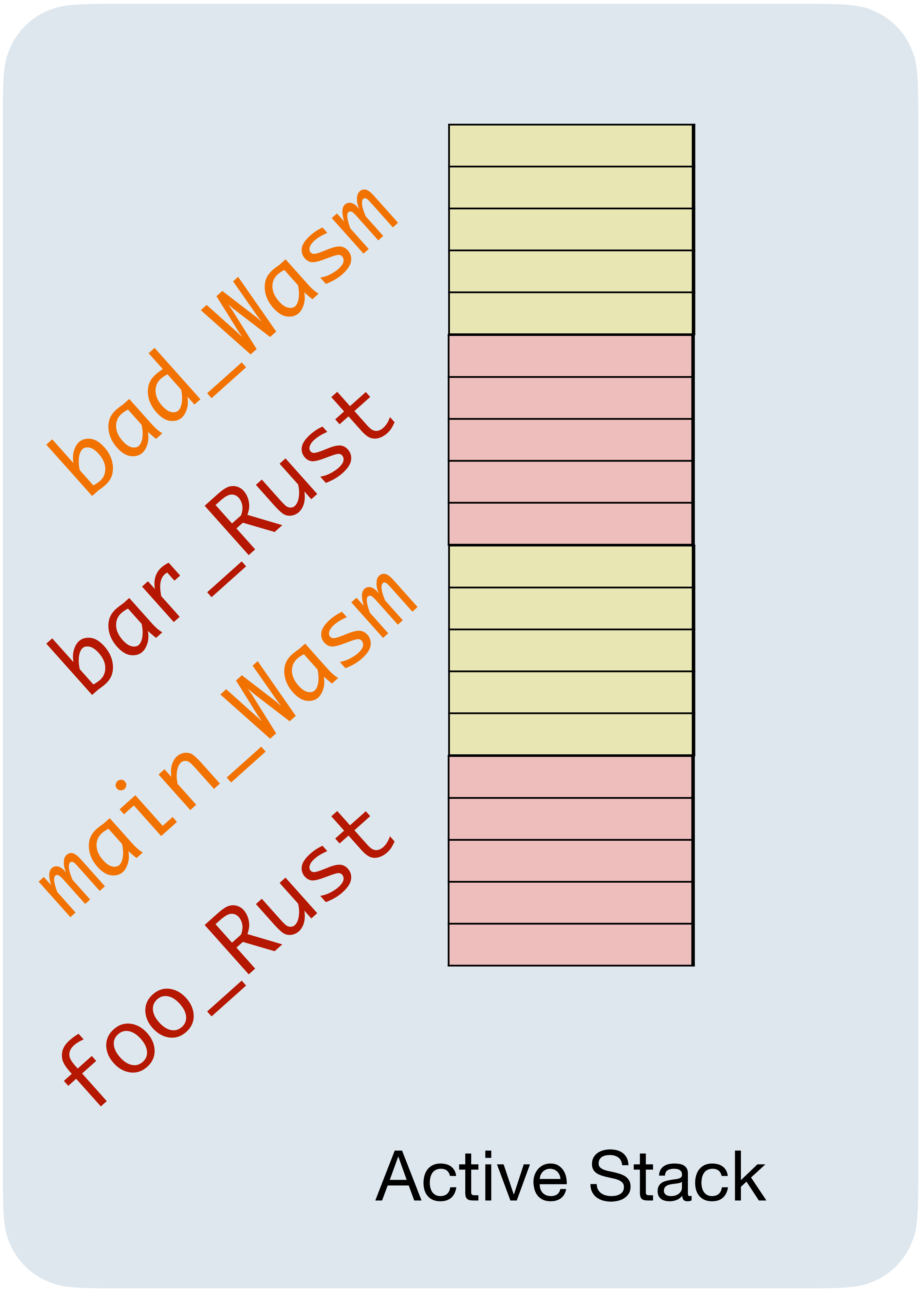
Is it Safe?

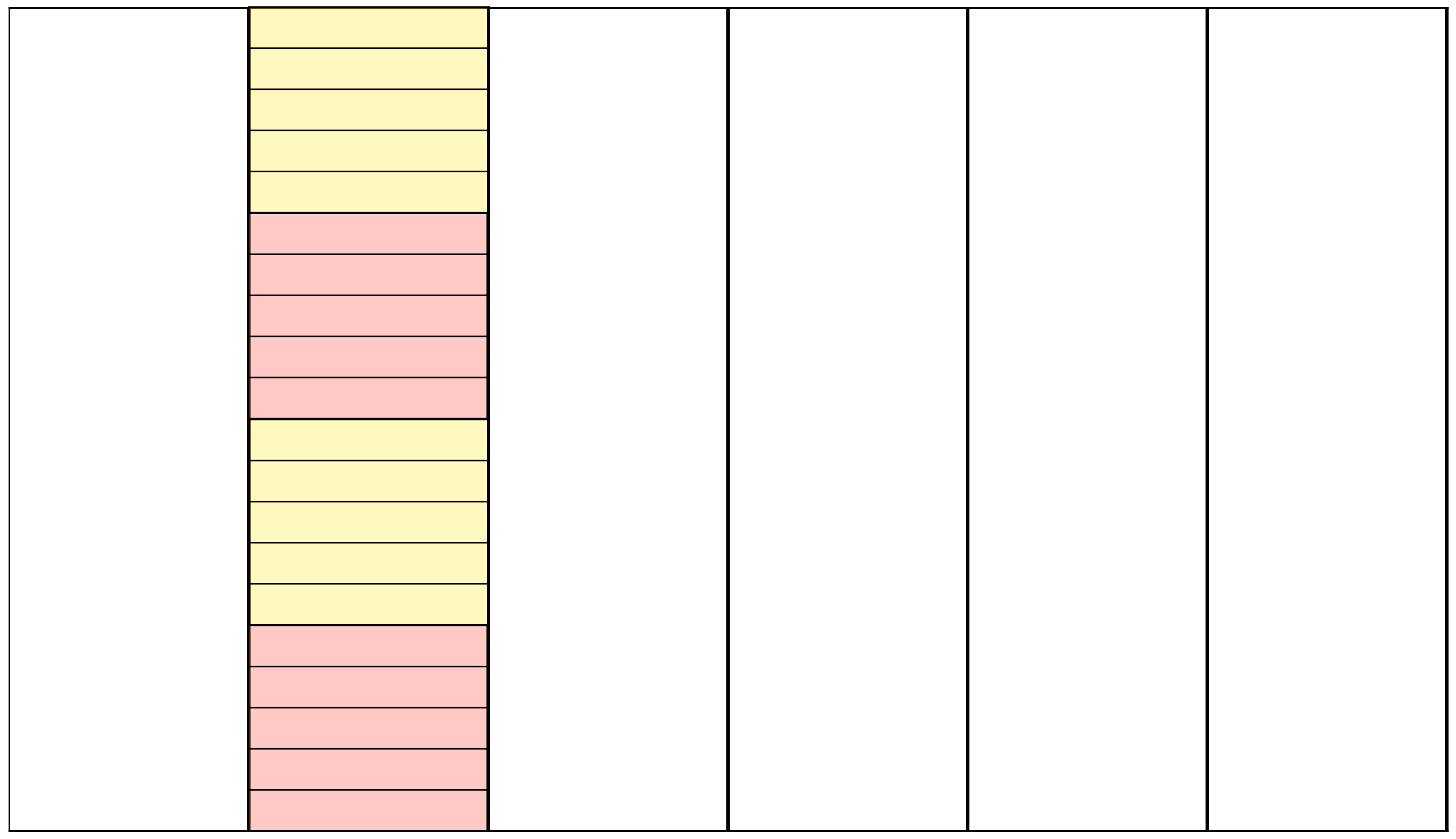
Almost… what about FFI?



Is it Safe?

Almost… what about FFI?

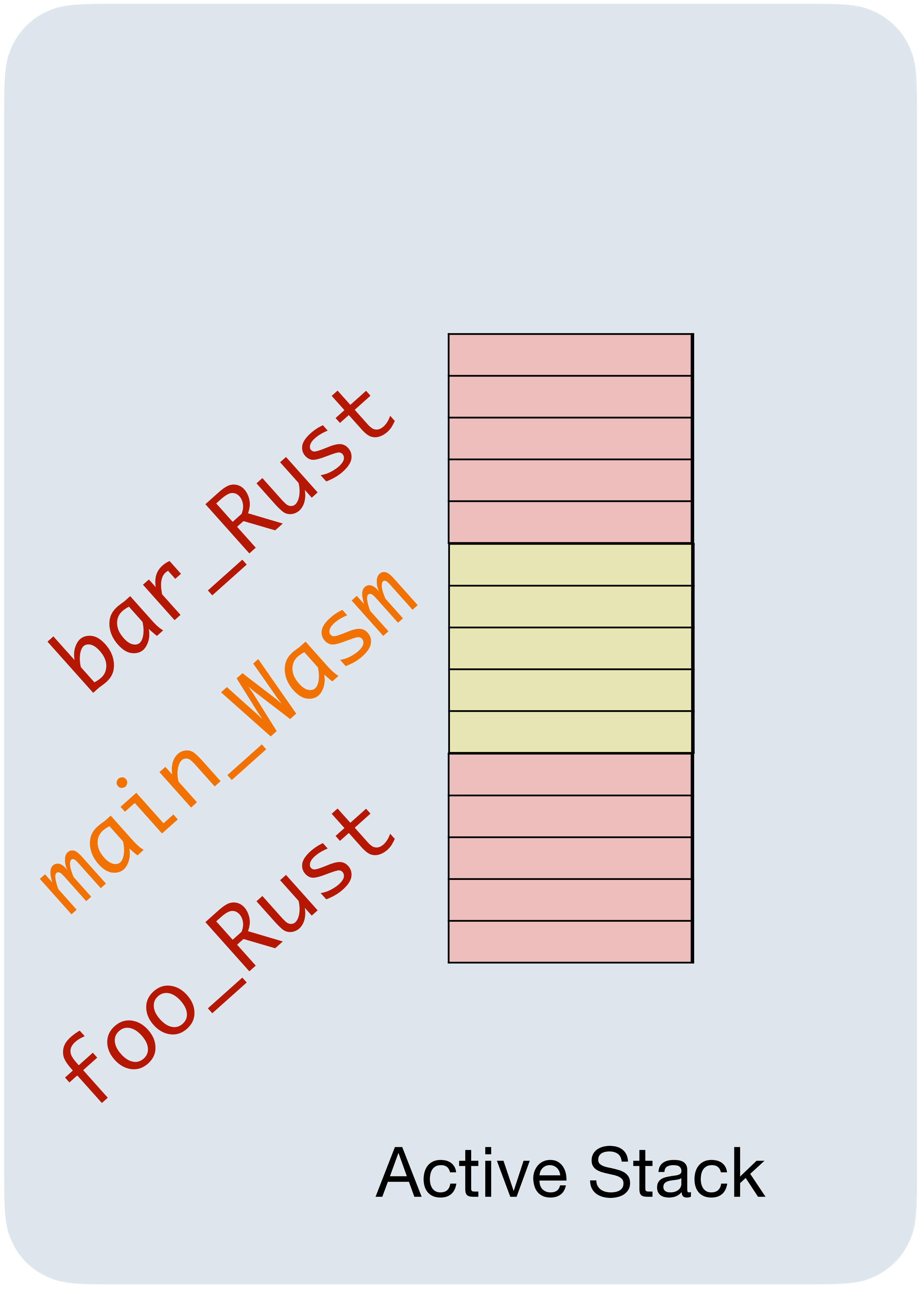


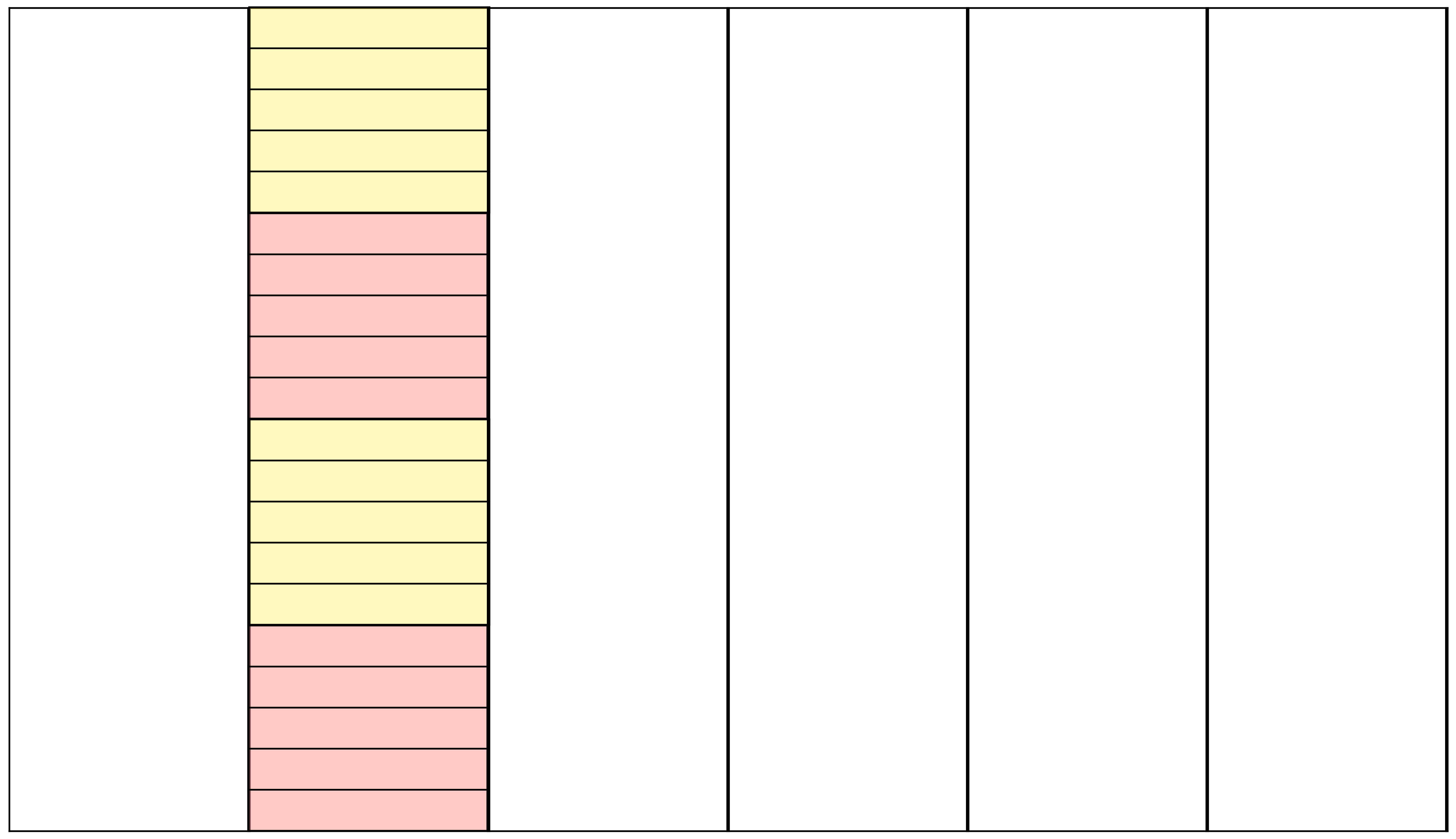


Continuation Table

Is it Safe?

Almost… what about FFI?





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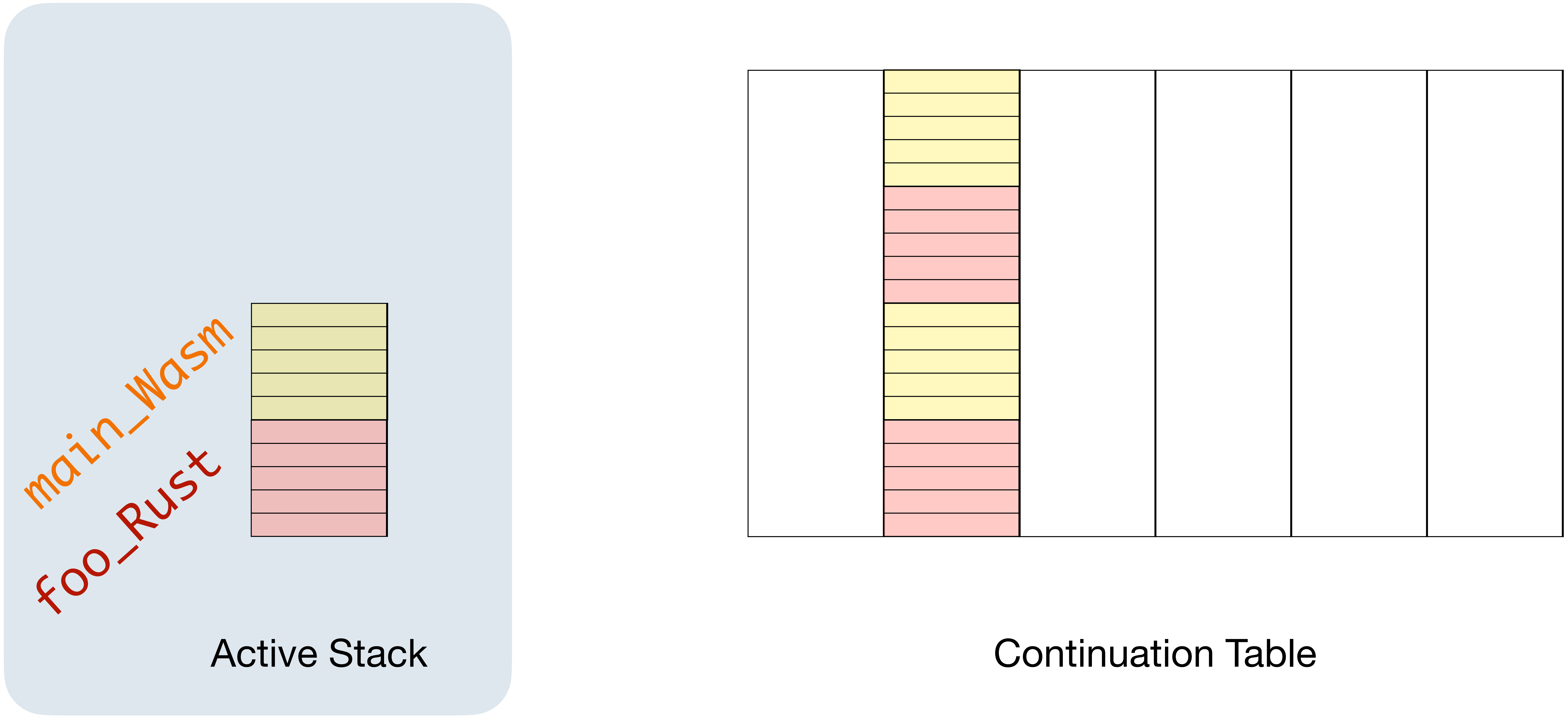
Almost… what about FFI?



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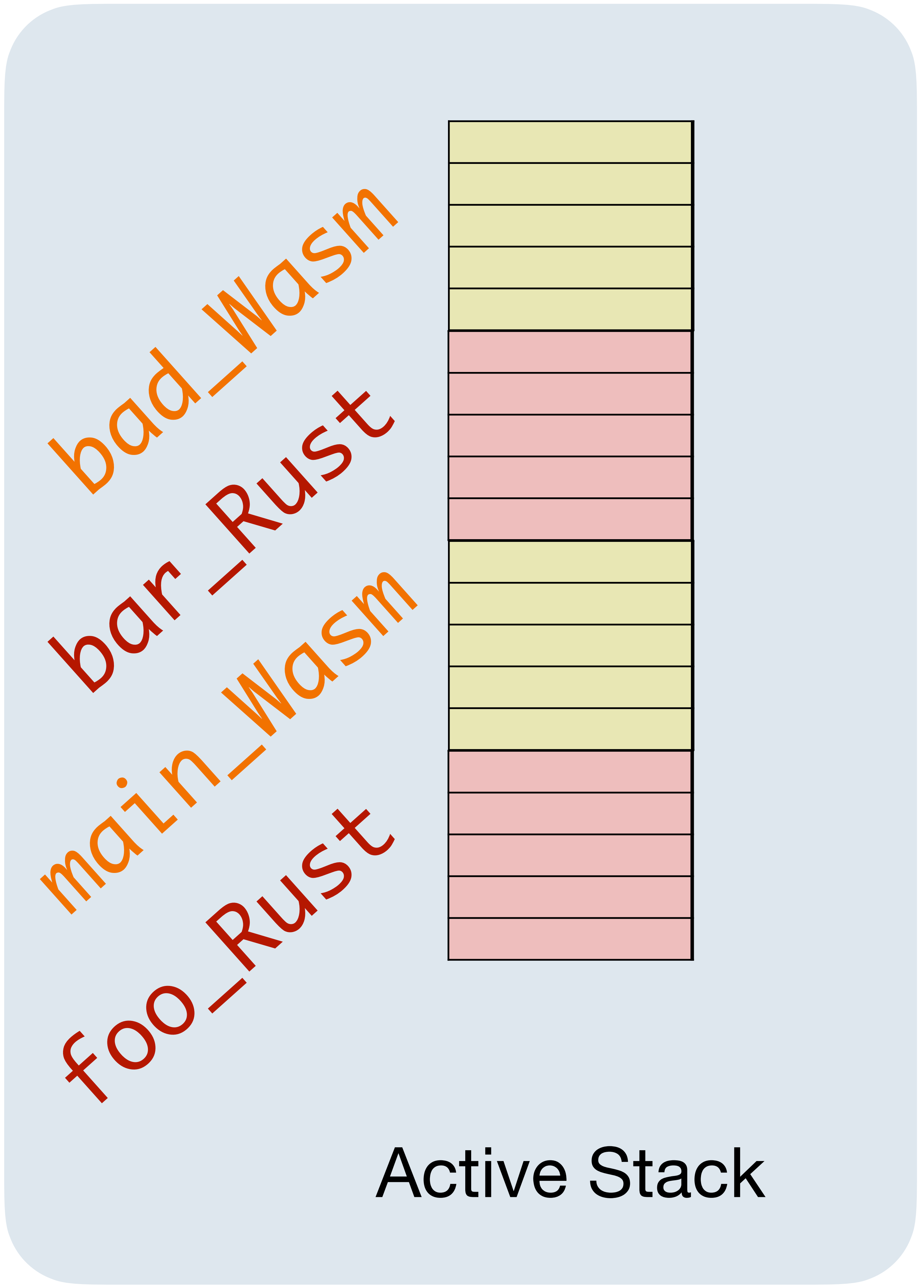
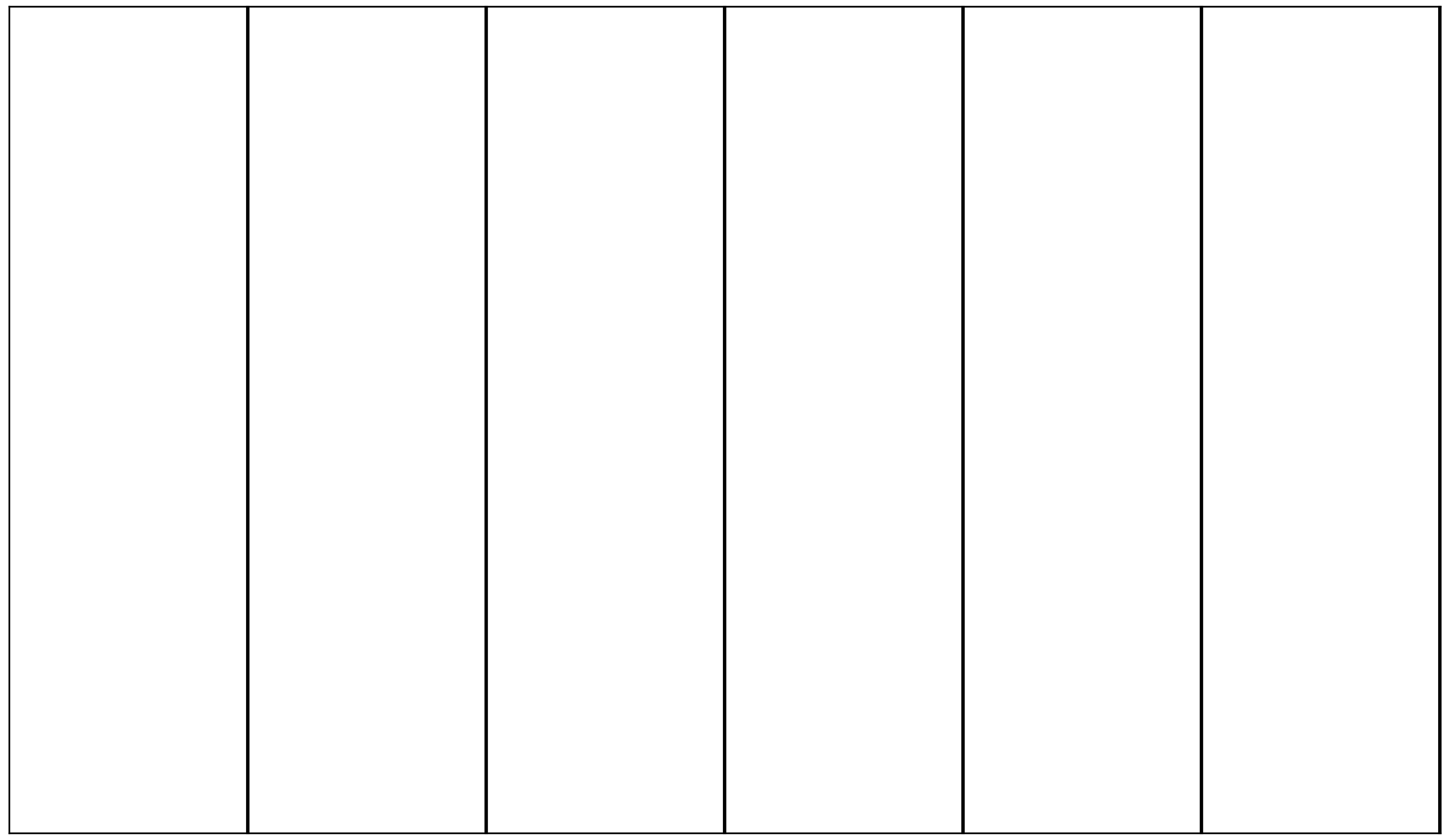
Almost… what about FFI?





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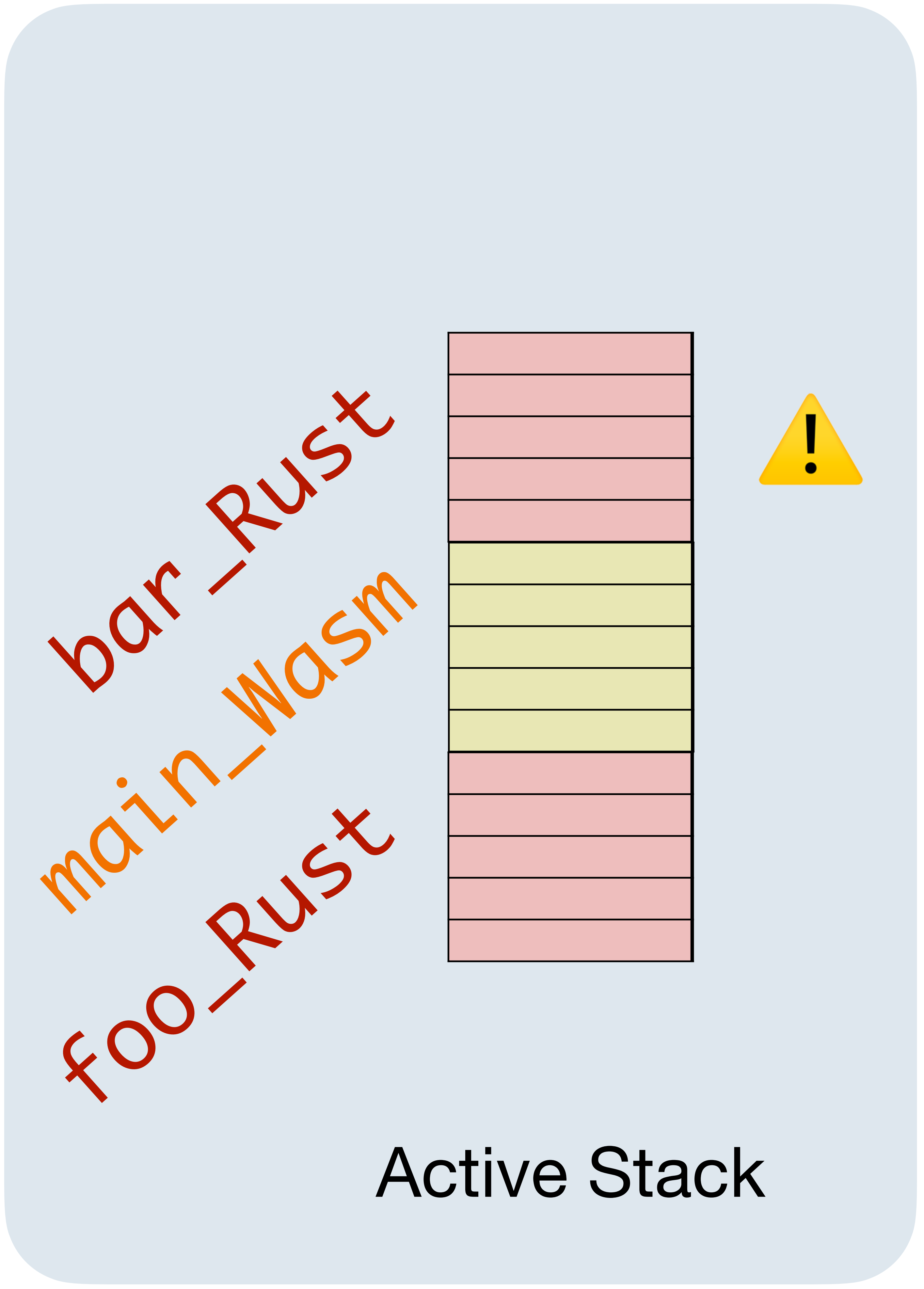
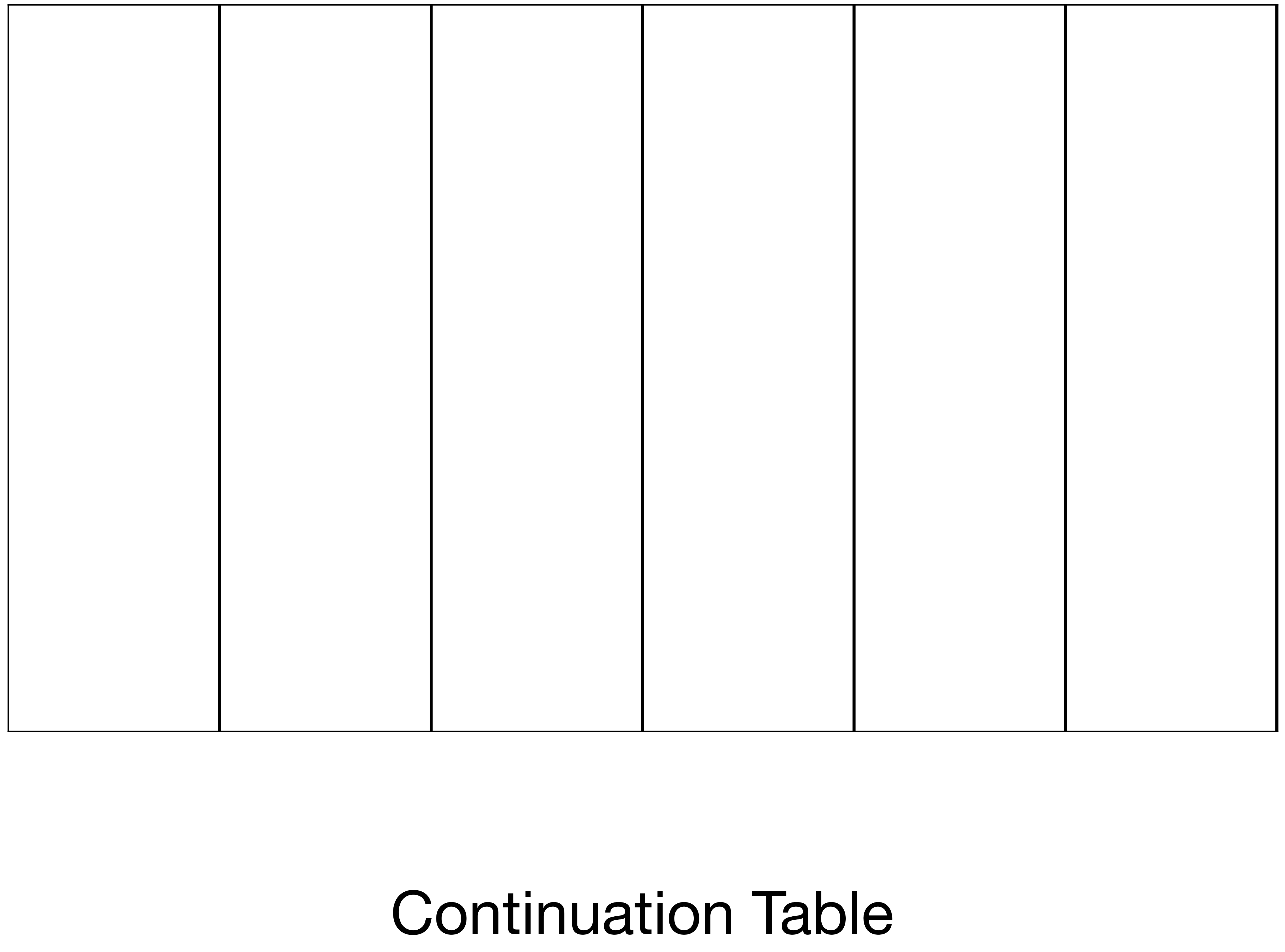
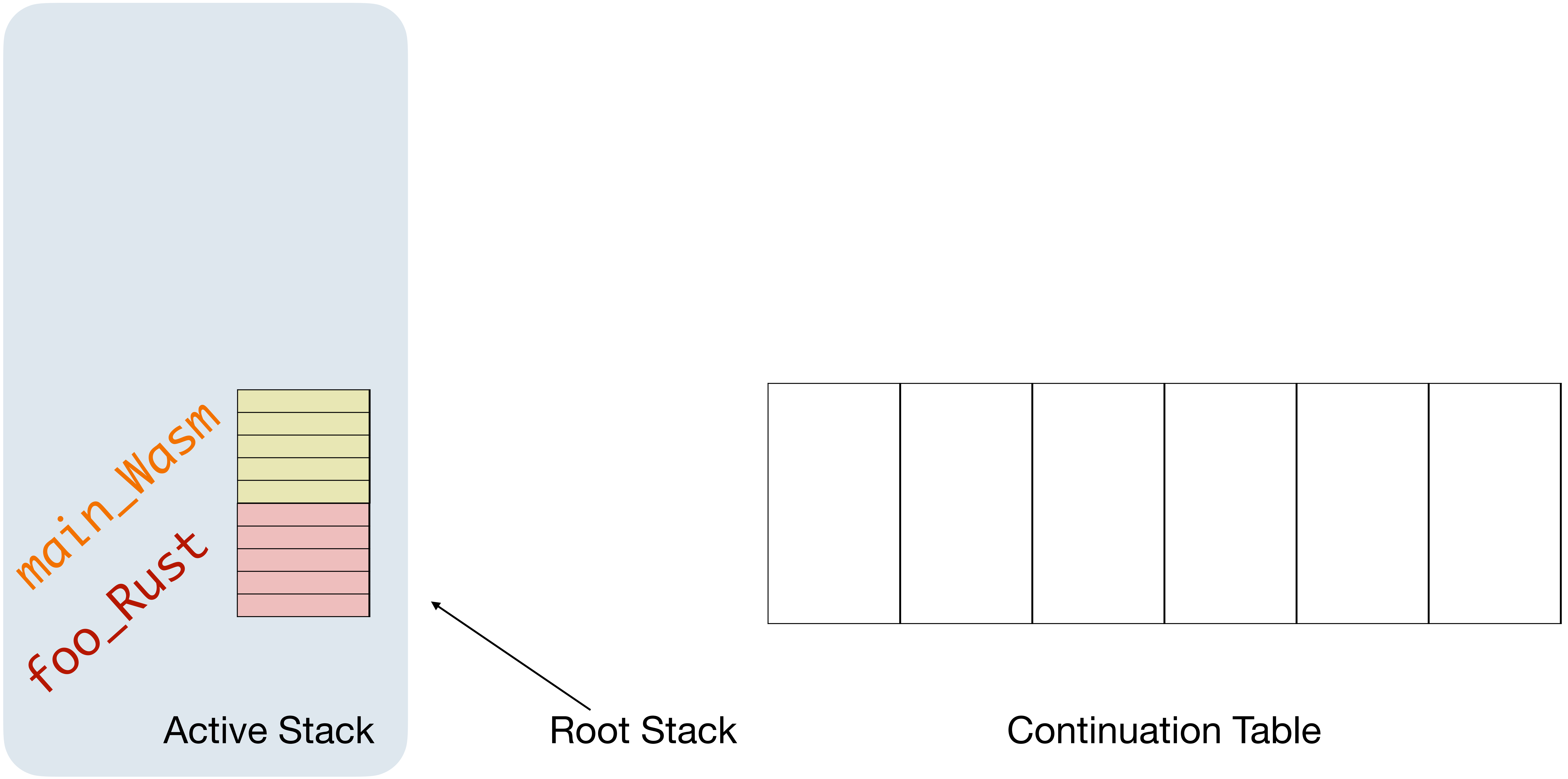
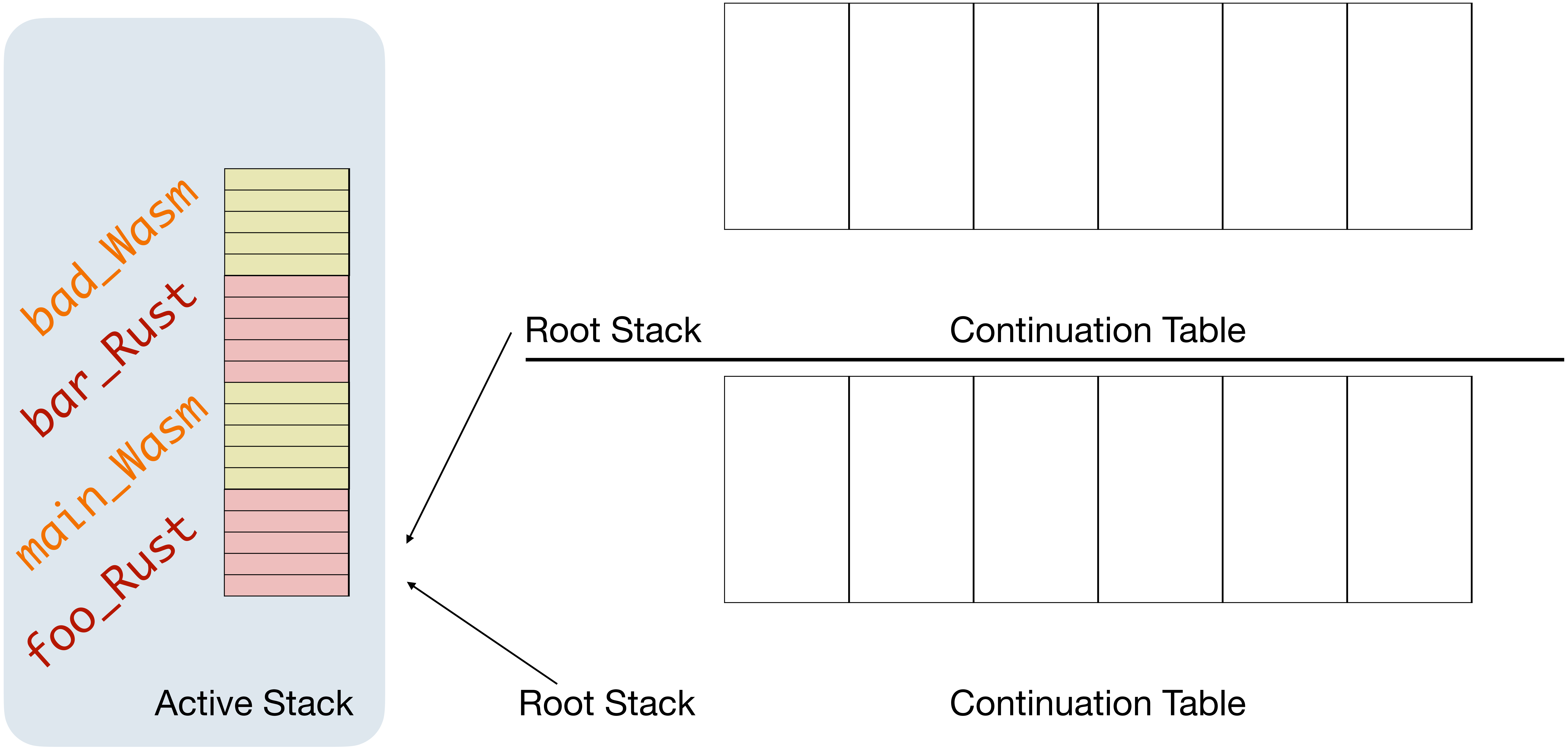




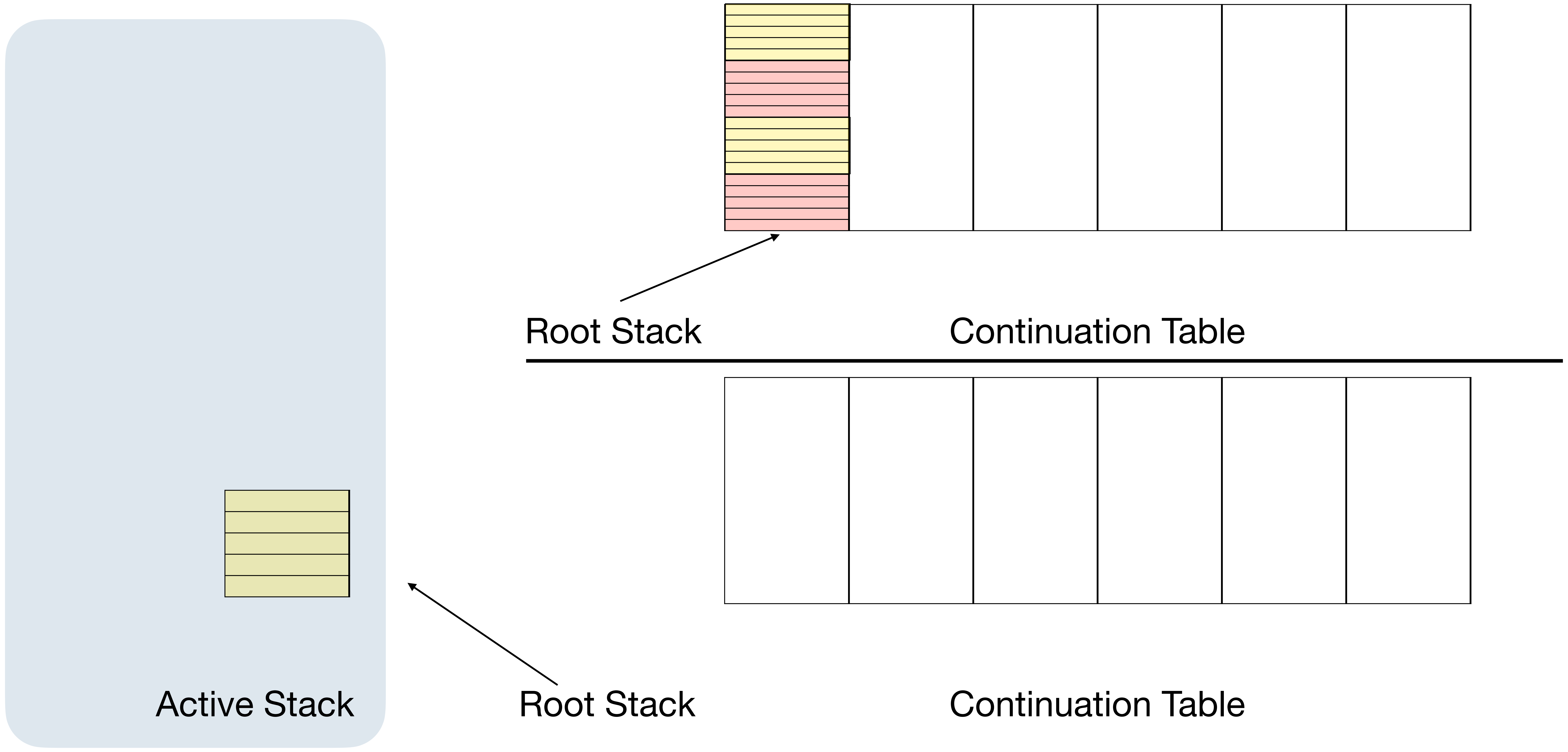
Solution: Delimit at FFI Boundaries



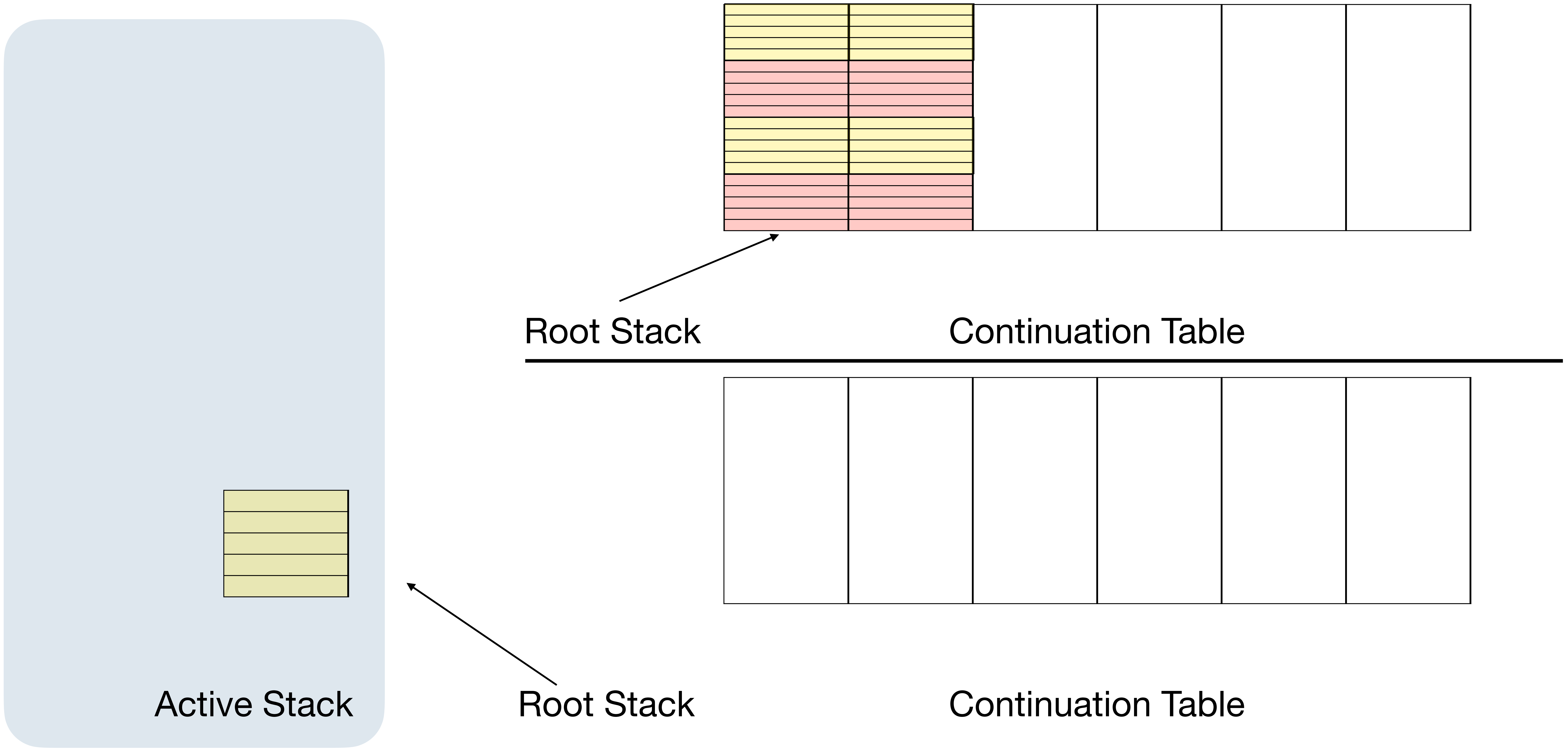
Solution: Delimit at FFI Boundaries



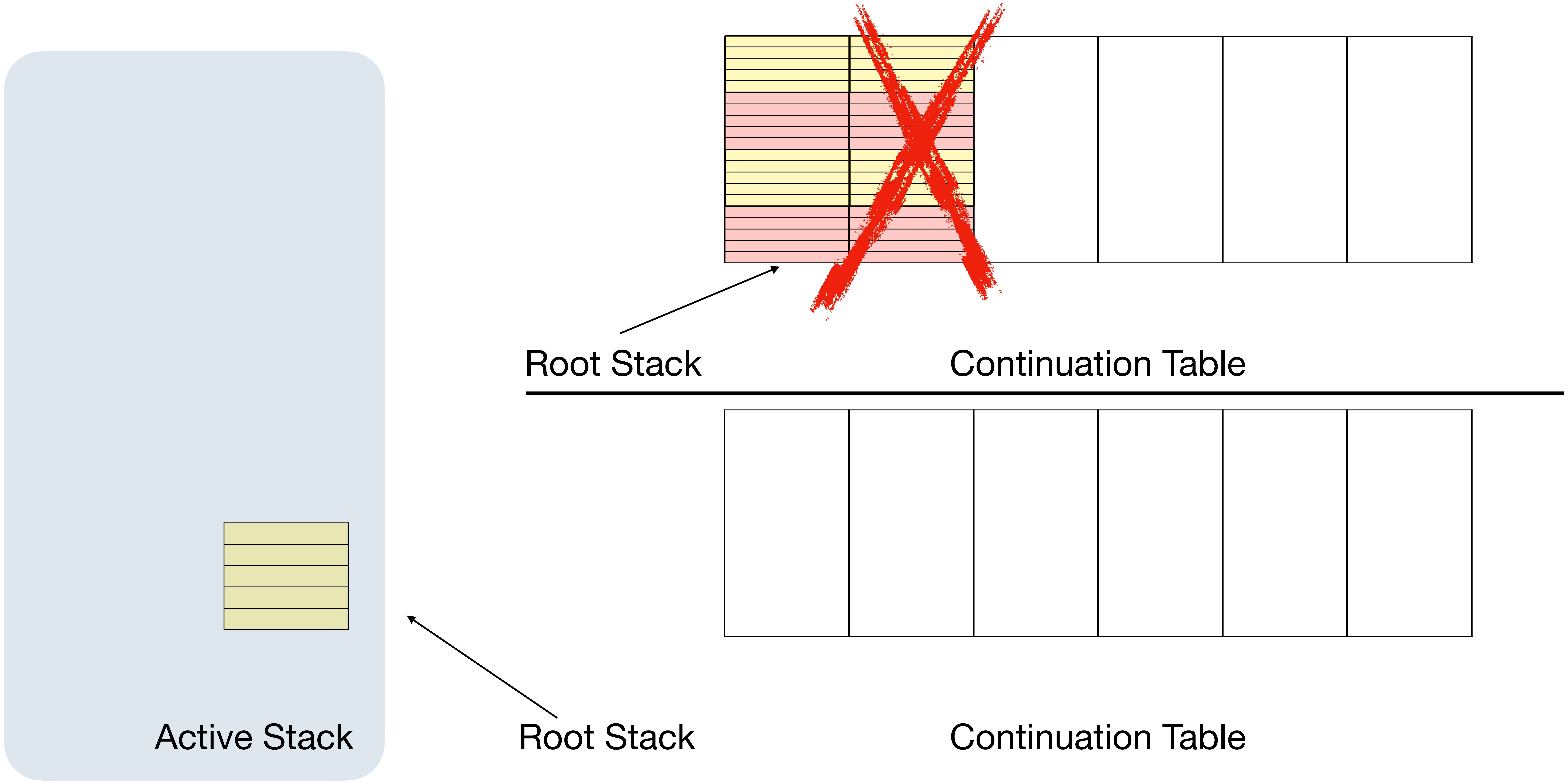
Solution: Delimit at FFI Boundaries



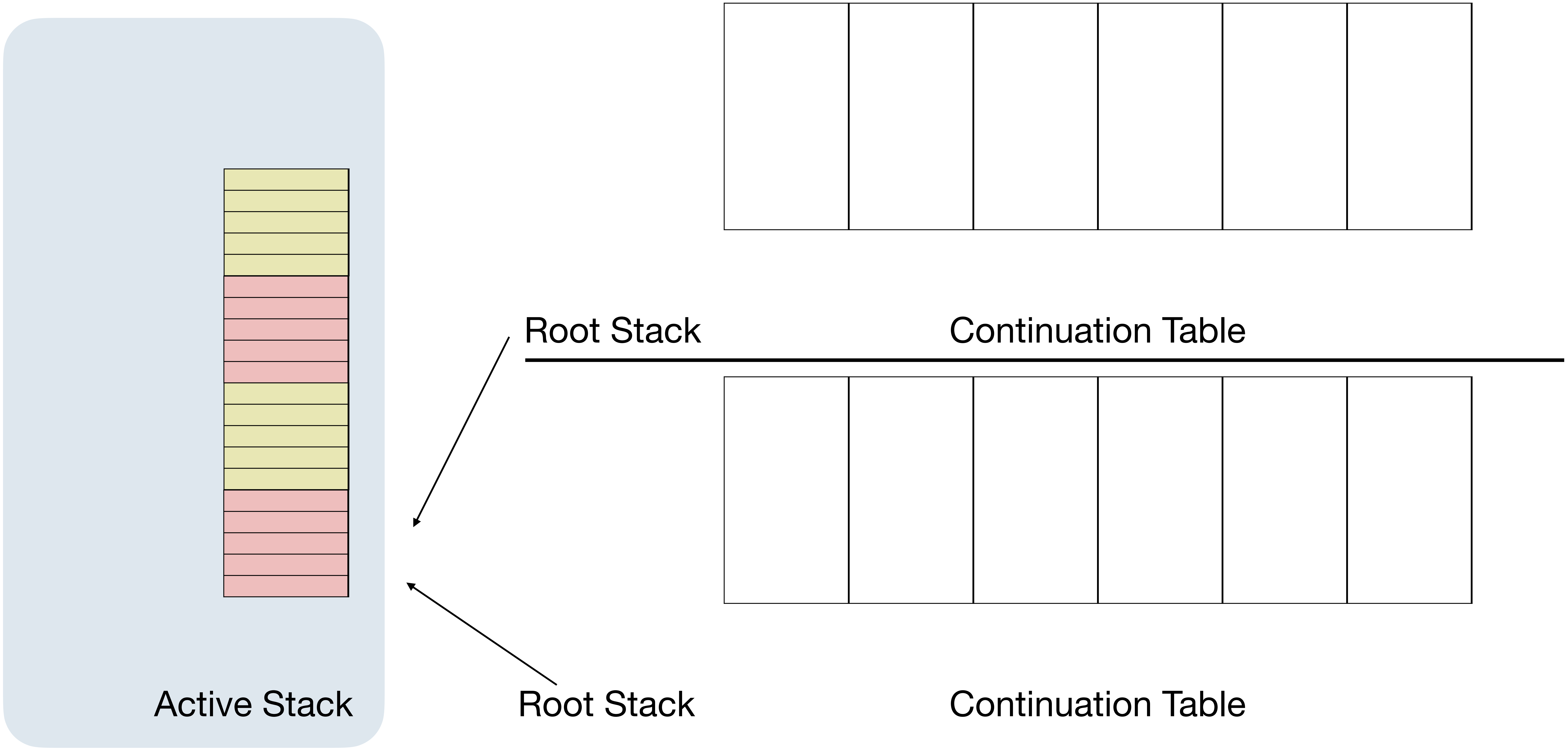
Solution: Delimit at FFI Boundaries



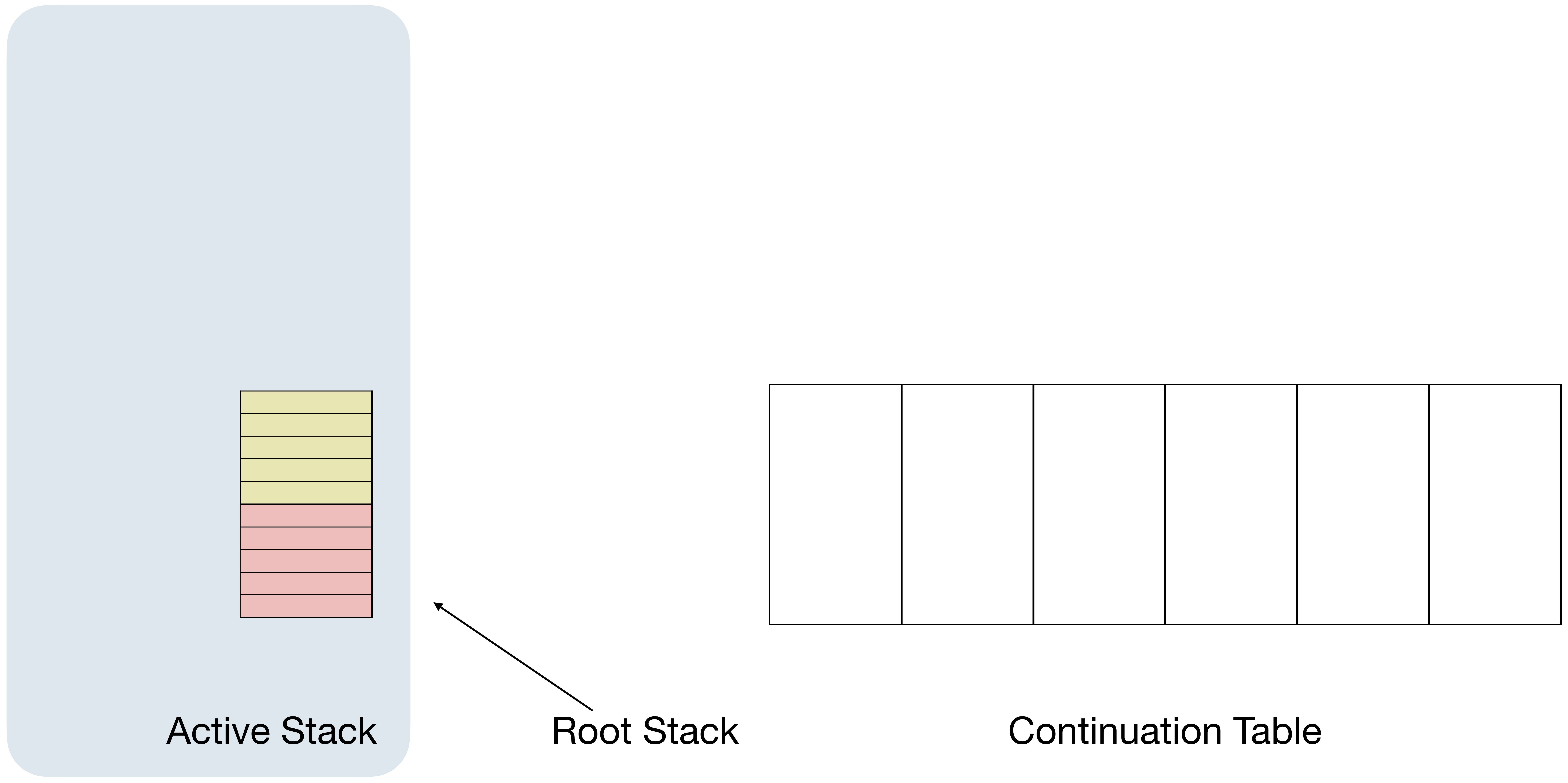
Solution: Delimit at FFI Boundaries



Solution: Delimit at FFI Boundaries



Solution: Delimit at FFI Boundaries



$$\boxed{s;\ v^*;\ e^* \rightsquigarrow_i s;\ v^*;\ e^*}$$

$$[\text{Cong}]\ \frac{s;\ v^*;\ e^* \hookrightarrow_i s';\ v'^*;\ e'^*}{s;\ v^*;\ L^k[e^*] \hookrightarrow_i s';\ v'^*;\ L^k[e'^*]} \qquad [\text{No-Ctrl}]\ \frac{s;\ v^*;\ e^* \hookrightarrow_i s';\ v'^*;\ e'^*}{s;\ v^*;\ e^* \rightsquigarrow_i s';\ v'^*;\ e'^*}$$

[Ctrl]	$s;\ v_l^*;\ L^{\max}[(\textbf{i64.const}\ v)\ (\textbf{control}\ h)] \rightsquigarrow_i s';\ \epsilon;\ (\textbf{i64.const}\ \kappa)\ (\textbf{i64.const}\ v)\ (\textbf{call}\ h)\ \textbf{trap}$	if $(s', \kappa) = \delta_{\text{ctrl}}(s, i, v_l^*, L^{\max})$
[Restore]	$s;\ v_l^*;\ L^{\max}[(\textbf{i64.const}\ \kappa)\ (\textbf{i64.const}\ v)\ \textbf{restore}] \rightsquigarrow_i s';\ v_l^{*\prime};\ L^{\max\prime}[(\textbf{i64.const}\ v)]$	if $(s', v_l^*, L^{\max\prime}) = \delta_{\text{rest}}(s, i, \kappa)$
[Restore-Err]	$s;\ v_l^*;\ L^{\max}[(\textbf{i64.const}\ \kappa)\ (\textbf{i64.const}\ v)\ \textbf{restore}] \rightsquigarrow_i s;\ v_l^*;\ \textbf{trap}$	otherwise
[Copy]	$s;\ (\textbf{i64.const}\ \kappa)\ \textbf{continuation\_copy} \hookrightarrow_i s';\ (\textbf{i64.const}\ \kappa')$	if $(s', \kappa') = \delta_{\text{copy}}(s, i, \kappa)$
[Copy-Err]	$s;\ (\textbf{i64.const}\ \kappa)\ \textbf{continuation\_copy} \hookrightarrow_i s;\ \textbf{trap}$	otherwise
[Delete]	$s;\ (\textbf{i64.const}\ \kappa)\ \textbf{continuation\_delete} \hookrightarrow_i s';\ \epsilon$	if $s' = \delta_{\text{delete}}(s, i, \kappa)$
[Delete-Err]	$s;\ (\textbf{i64.const}\ \kappa)\ \textbf{continuation\_delete} \hookrightarrow_i s;\ \textbf{trap}$	otherwise
[Prompt]	$s;\ \textbf{prompt}\ tf\ e^*\ \textbf{end} \hookrightarrow_i s';\ \textbf{block}\ tf\ e^*\ \textbf{end}\ \textbf{prompt\_end}$	if $s' = \delta_{\text{p}}(s, i)$
[Prompt-End]	$s;\ \textbf{prompt\_end} \hookrightarrow_i s';\ \epsilon$	if $s' = \delta_{\text{p-end}}(s, i)$

$$\delta_{\text{ctrl}}(s, i, v_l^*, L^{\max}) ::= \begin{cases} (\text{setCont}(\text{setRoot}(s, i, \kappa), i, \kappa, \{\text{locals} = v_l^*, \text{ctx} = L^{\max}, \text{inst} = i\}),\ \kappa) & \text{if getRoot}(s, i) = nil \\ (\text{setCont}(s, i, \kappa, \{\text{locals} = v_l^*, \text{ctx} = L^{\max}, \text{inst} = i\}),\ \kappa) & \text{if getRoot}(s, i) \neq nil \end{cases}$$

where κ is fresh, i.e., $\text{getCont}(s, i, \kappa) = nil$

$$\delta_{\text{rest}}(s, i, \kappa) ::= \begin{cases} (\text{setRoot}(\text{setCont}(s, i, \kappa, nil), i, nil),\ \text{getCont}(s, i, \kappa)_{\text{locals}},\ \text{getCont}(s, i, \kappa)_{\text{ctx}}) & \text{if getRoot}(s, i) = \kappa \\ (\text{setCont}(s, i, \kappa, nil),\ \text{getCont}(s, i, \kappa)_{\text{locals}},\ \text{getCont}(s, i, \kappa)_{\text{ctx}}) & \text{if } nil \neq \text{getRoot}(s, i) \neq \kappa \end{cases}$$

$$\delta_{\text{copy}}(s, i, \kappa) ::= (\text{setCont}(s, i, \kappa', \text{getCont}(s, i, \kappa)),\ \kappa') \qquad \text{if getRoot}(s, i) \neq \kappa \wedge \text{getCont}(s, i, \kappa) \neq nil$$

where κ' is fresh, i.e., $\text{getCont}(s, i, \kappa') = nil$

$$\delta_{\text{delete}}(s, i, \kappa) ::= \text{setCont}(s, i, \kappa, nil) \qquad \text{if getRoot}(s, i) \neq \kappa \wedge \text{getCont}(s, i, \kappa) \neq nil$$

$$\delta_{\text{p}}(s, i) ::= s' \text{ where } s' = s \text{ except } s'_{\text{inst}}(i)_{\text{pstack}} \mapsto \text{push}(s_{\text{inst}}(i)_{\text{pstack}}, \{\text{ctable} = nil^*, \text{root} = nil, \text{inst} = i\})$$

$$\delta_{\text{p-end}}(s, i) ::= s' \text{ where } s' = s \text{ except } s'_{\text{inst}}(i)_{\text{pstack}} \mapsto \text{pop}(s_{\text{inst}}(i)_{\text{pstack}}) \qquad \text{if getRoot}(s, i) = nil$$

$$\text{getRoot}(s, i) ::= \text{top}(s_{\text{inst}}(i)_{\text{pstack}})_{\text{root}}$$

$$\text{getCont}(s, i, \kappa) ::= \text{top}(s_{\text{inst}}(i)_{\text{pstack}})_{\text{ctable}}(\kappa)$$

$$\text{setRoot}(s, i, \kappa_R^?) ::= s' \text{ where } s' = s \text{ except top}(s'_{\text{inst}}(i)_{\text{pstack}})_{\text{root}} \mapsto \kappa_R^?$$

$$\text{setCont}(s, i, \kappa, \gamma^?) ::= s' \text{ where } s' = s \text{ except top}(s'_{\text{inst}}(i)_{\text{pstack}})_{\text{ctable}}(\kappa) \mapsto \gamma^?$$

$$C ::= \{\ldots, \text{label}\ ((t^*)^*)^*, \text{pstack}\{\text{ctable}(t^* \mid nil)^*, \text{root}(\kappa_R \mid nil)\}^*\}$$

$$\frac{C_{\text{func}}(h) = \text{i64 i64} \to \epsilon}{C \vdash (\textbf{control}\ h) : \text{i64} \to \text{i64}}$$

$$\frac{}{C \vdash \textbf{restore} : t_1^*\ \text{i64 i64} \to t_2^*}$$

$$\frac{}{C \vdash \textbf{continuation\_copy} : \text{i64} \to \text{i64}}$$

$$\frac{}{C \vdash \textbf{continuation\_delete} : \text{i64} \to \epsilon}$$

$$\frac{tf = t_1^n \to t_2^m \qquad C\{\text{label} = C_{\text{label}}; ((t_2^m)),\ \text{return} = \epsilon\} \vdash e^* : tf}{C \vdash \textbf{prompt}\ tf\ e^*\ \textbf{end} : tf}$$

Implementation

- How to compile C/k → Wasm/k?
  - Mostly easy: Can be done locally… using C macros + regex find / replace on Emscripten output
  - But, need to also capture / restore the C shadow stack in linear memory
- Implementation of Wasm/k
  - Implemented in a fork of Wasmtime, targeting x86
  - Each instruction (e.g. `control`) calls handwritten x86 assembly to save registers and the stack. Similar to `setjmp` / `longjmp`
  - One-shot continuations means only `continuation_copy` needs to perform a `memcpy`

Thank you!

Full proofs and implementation at:

https://wasmk.github.io

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