Racket's Intermediate Language for Control

based on talks at VMIL'20 and PLDI'20

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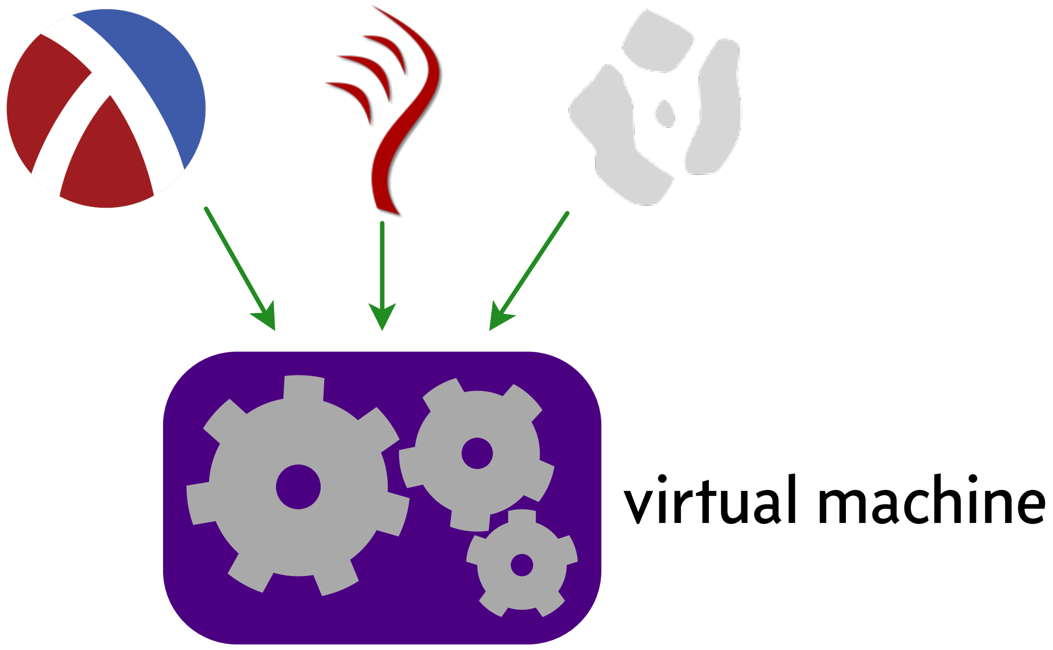
University of Utah

including work with R. Kent Dybvig, John Clements, Gang Yu, Robby Findler, and Matthias Felleisen

Language Building Blocks



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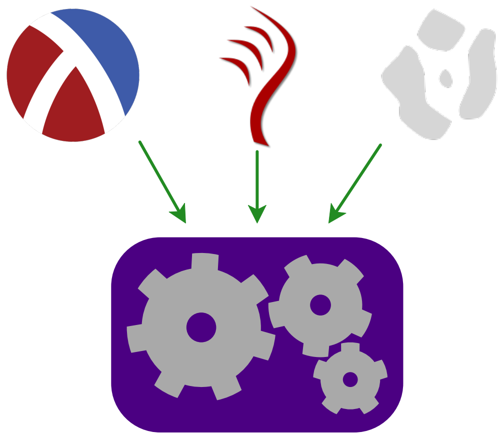

functions

```
(λ (x) e₁)
```

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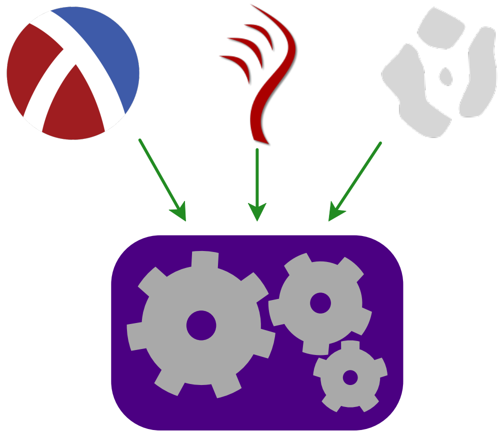
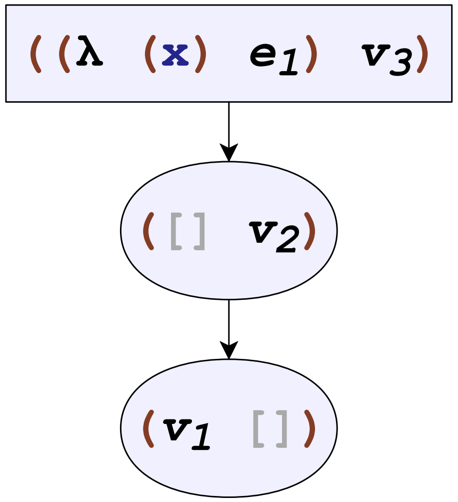


functions

call and return



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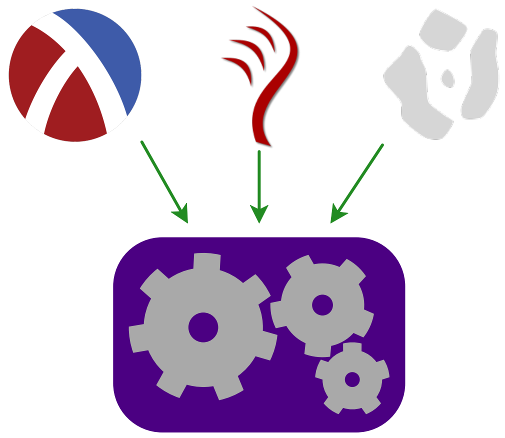
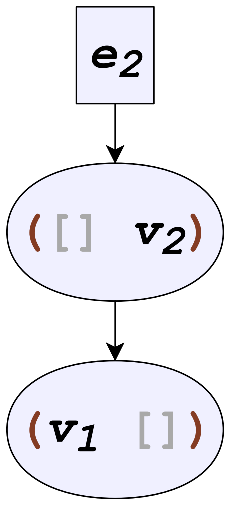


functions

call and return

tail calls



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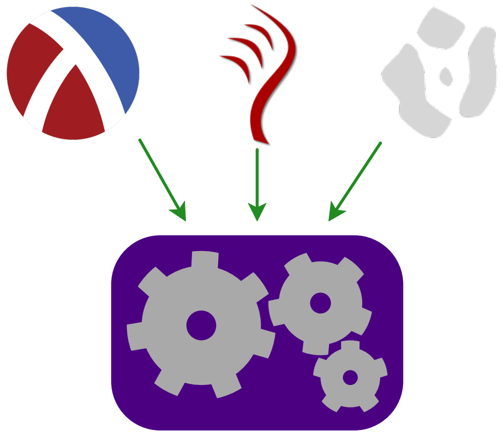
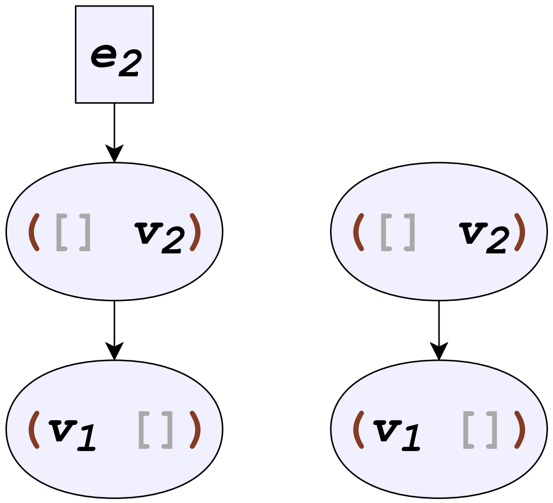


functions

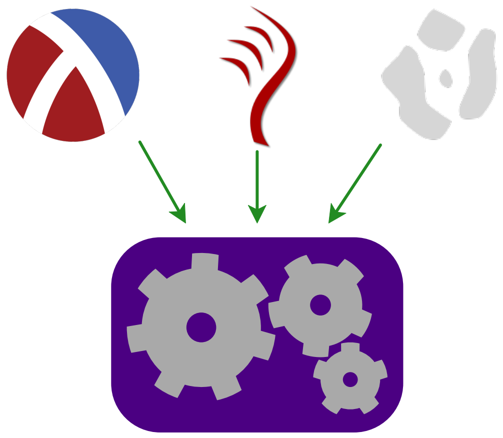
call and return

tail calls

continuations



Language Building Blocks



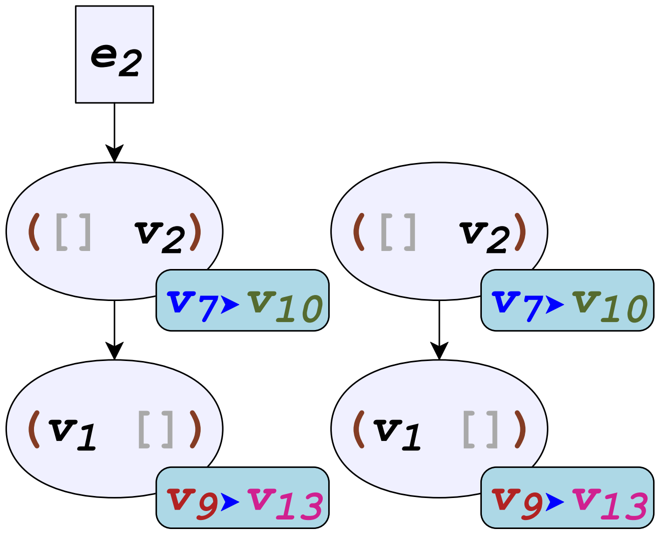
functions

call and return

tail calls

continuations

continuation marks



e_2
$([]\ v_2)$
$v_7 \blacktriangleright v_{10}$
$(v_1\ [])$
$v_9 \blacktriangleright v_{13}$
$([]\ v_2)$
$v_7 \blacktriangleright v_{10}$
$(v_1\ [])$
$v_9 \blacktriangleright v_{13}$

Language Building Blocks

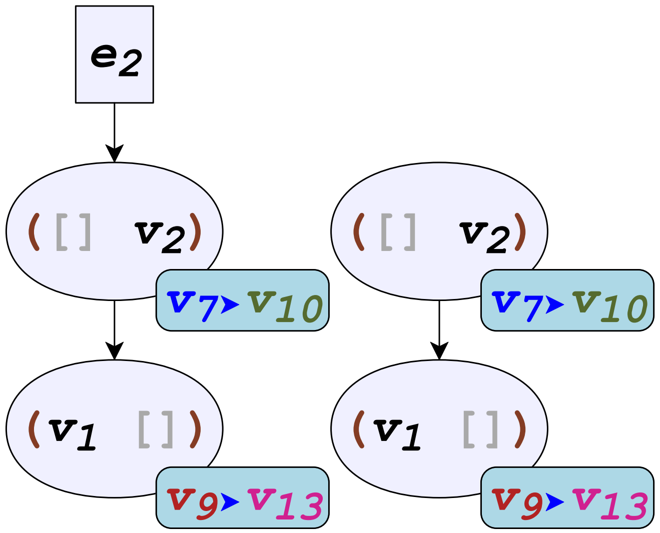
functions

call and return

tail calls

continuations

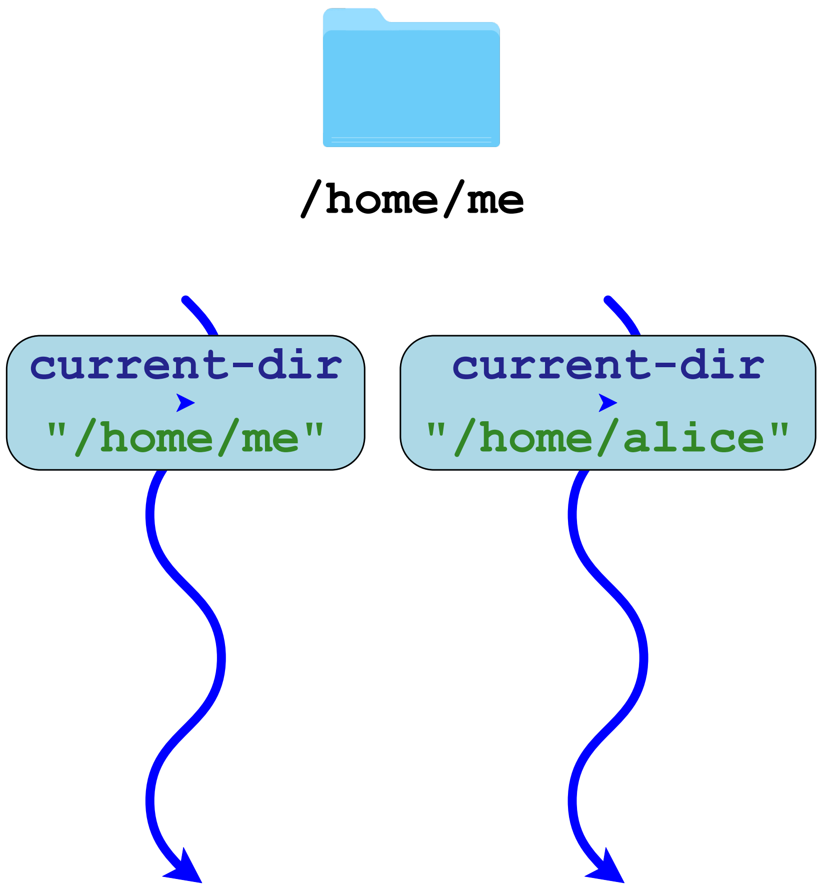
continuation marks



Continuations and Marks

`/home/me`

Continuations and Marks



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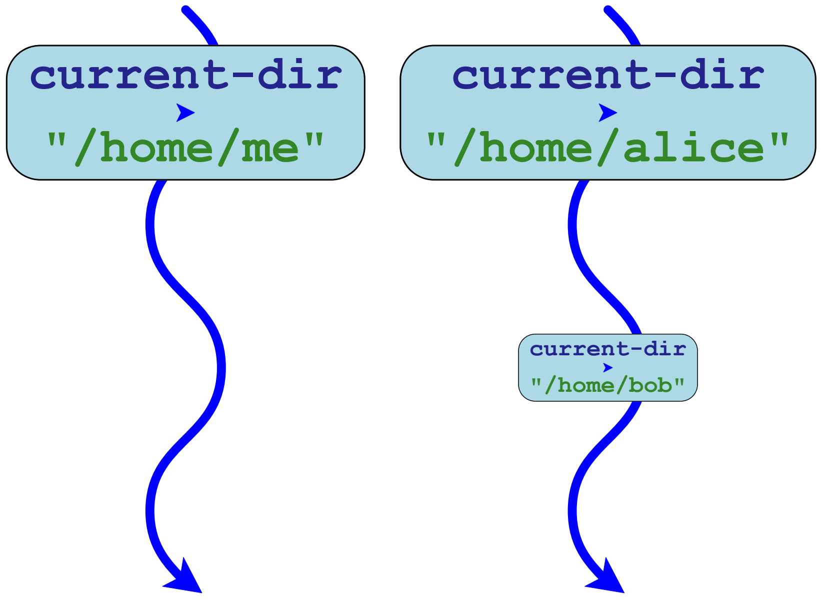

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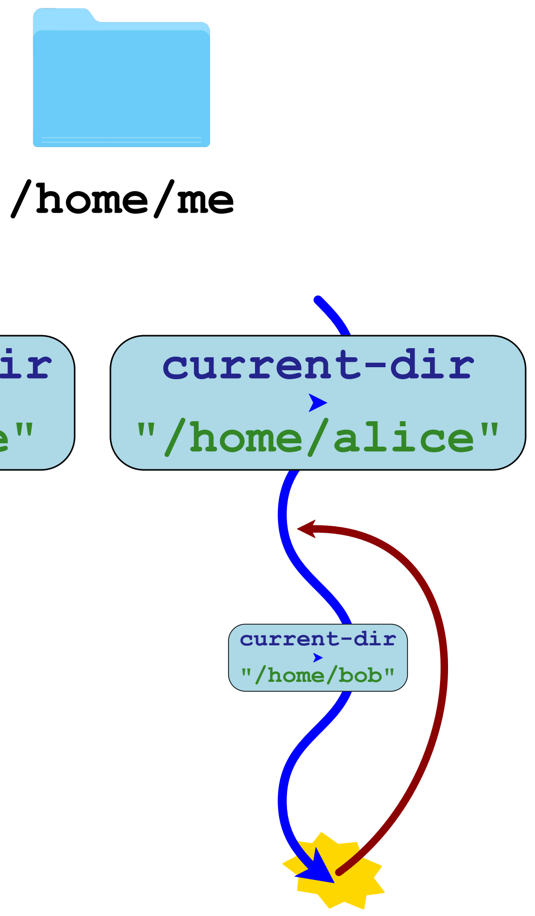
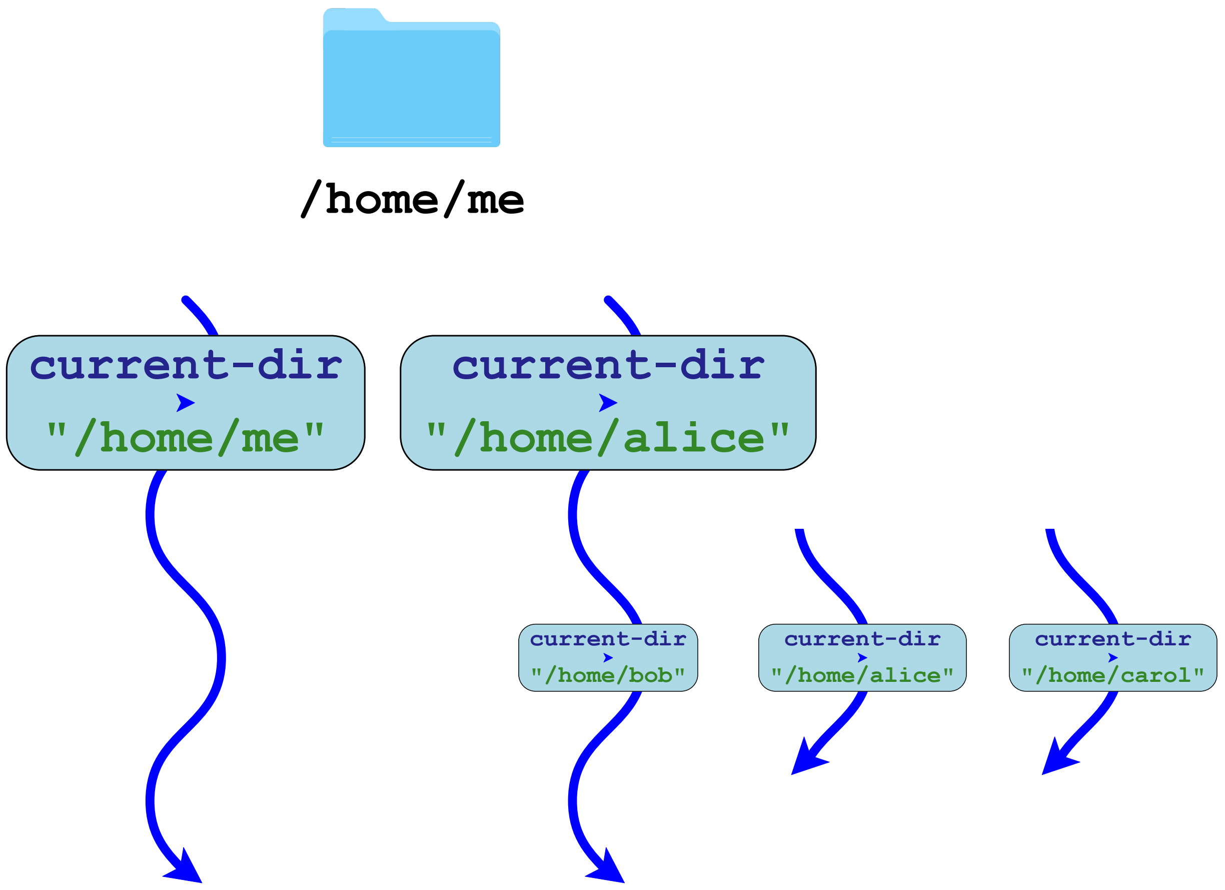


Continuations and Marks



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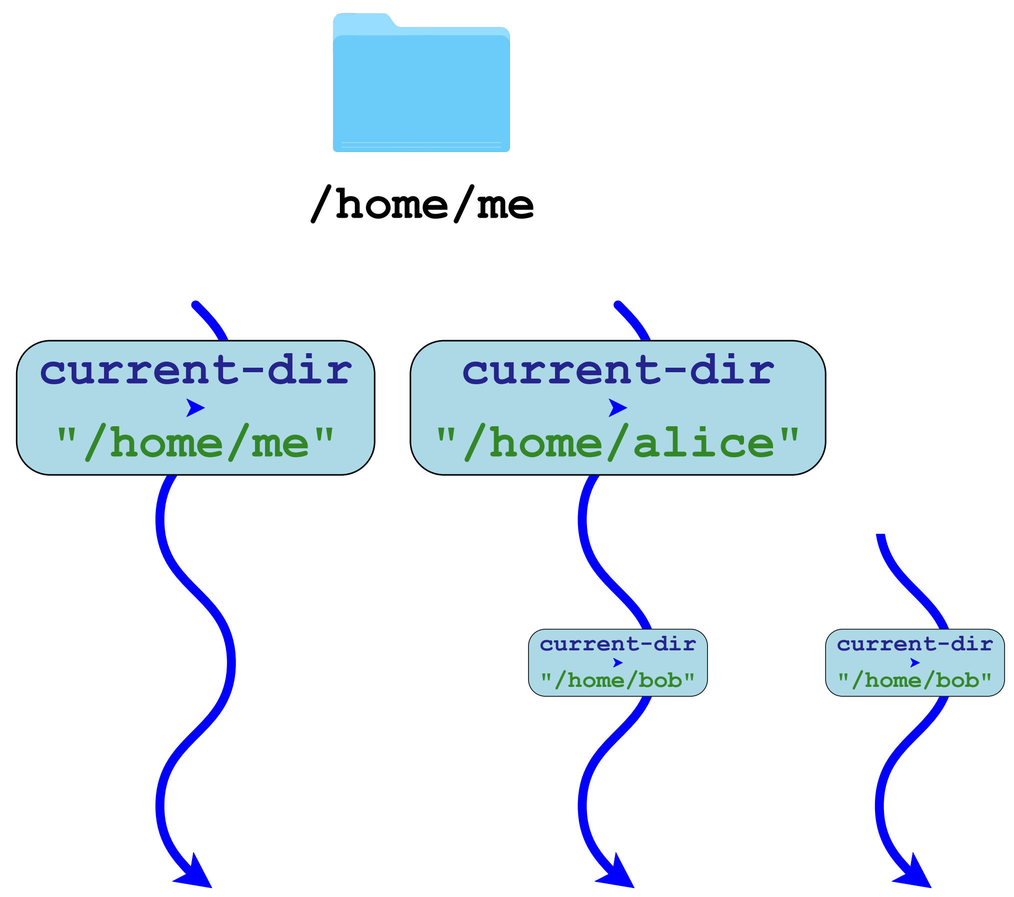

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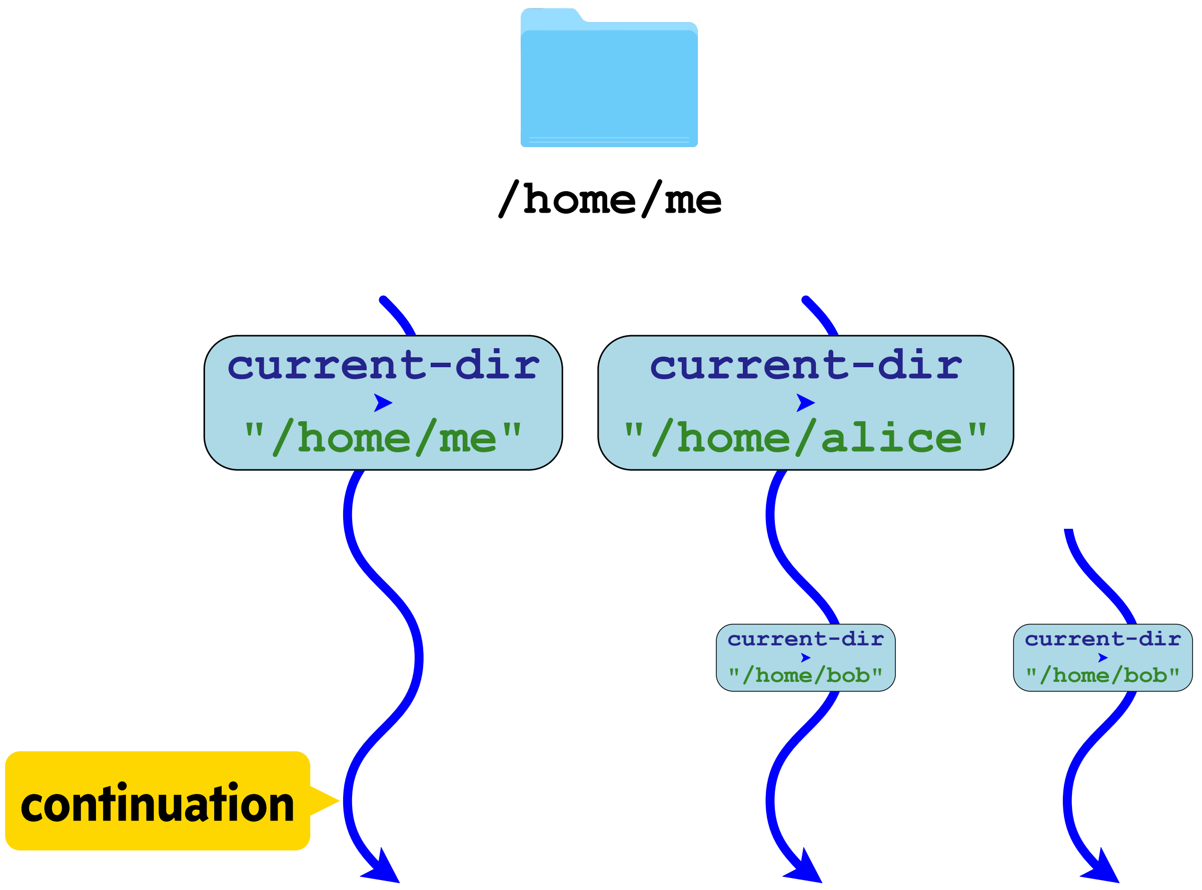

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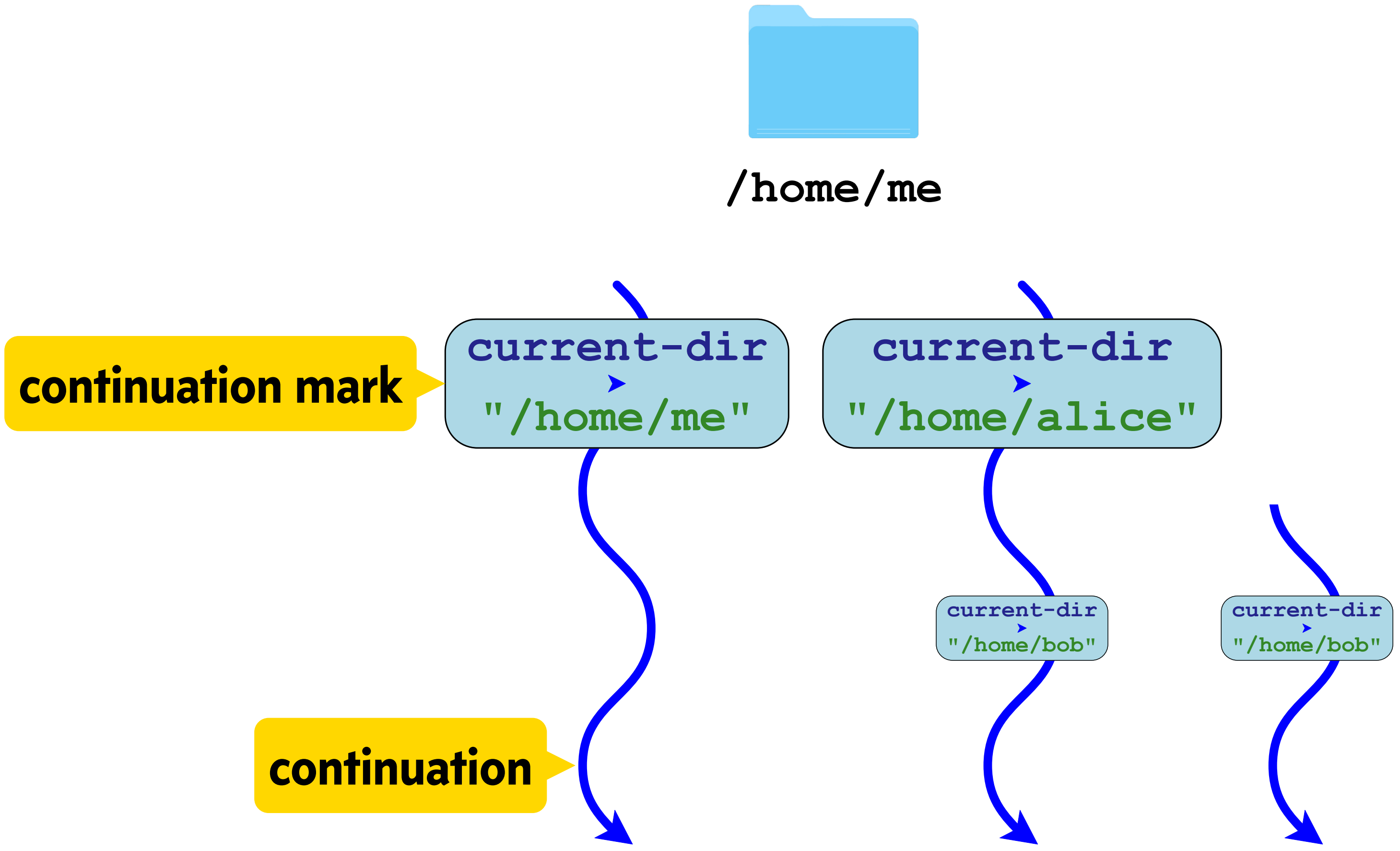

Some Papers on Control

Felleisen ’88
Danvy and Filinski ’90
Hieb and Dybvig ’90
Sitaram and Felleisen ’90
Queinnec and Serpette ’91
Reppy ’91
Sitaram ’93
Queinnec ’93
Moreau and Queinnec ’94
Wadler ’94
deGroote ’94
Rehof and Sørensen ’94
Gunter et al. ’95
Gunter et al. ’95
Thielecke ’97
Flatt et al. ’99
Feeley ’01
Rehof ’01
Clements et al. ’01
Gasbichler and Sperber ’02
Gasbichler and Sperber ’03
Kameyama and Hasegawa ’03
Ariola et al. ’04
Shan ’04
Queinnec ’04
Saurin ’05
Kiselyov et al. ’06
Dybvig et al. ’06
Biernacki et al. ’06
Flatt et al. ’07
Ariola et al. ’09
Plotkin and Pretnar ’09
Garcia et al. ’10
James and Sabry ’11
Kiselyov ’12
Kiselyov et al. ’13
Plotkin and Pretnar ’13
Downen and Ariola ’14
Dolan et al. ’15
Hillerström and Lindley ’16
Philips et al. ’16
Hillerström and Lindley ’18
Flatt and Dybvig ’19
Brachthauser and Leijen ’19
Biernacki ’19

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Thielecke '97	Flatt et al. '07	Biernacki '19

Racket Control API

Continuations
function [tail] calls
`call/cc`
`call-with-composable-continuation`
continuation application
`call-in-continuation`

Prompts
`call-with-continuation-prompt`
`abort-current-continuation`
`continuation-prompt-available?`
`make-continuation-prompt-tag`
`default-continuation-prompt-tag`

Winding
`dynamic-wind`
`call-with-continuation-barrier`

Exceptions
`raise`
`call-with-exception-handler`

Continuation Marks
`with-continuation-mark`
`continuation-marks`
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`continuation-mark-set->iterator`
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Dynamic Binding
`parameterize`
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Threads (Green)
`thread`
`kill-thread`
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Custodians
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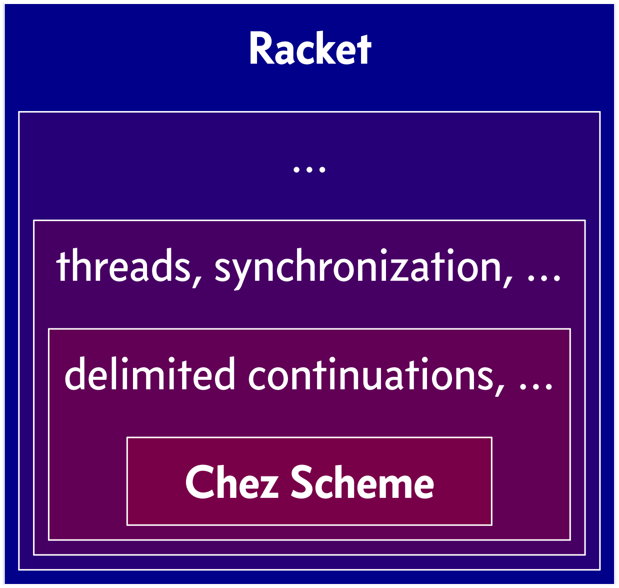
Futures
`future`
`touch`

Racket Implementation



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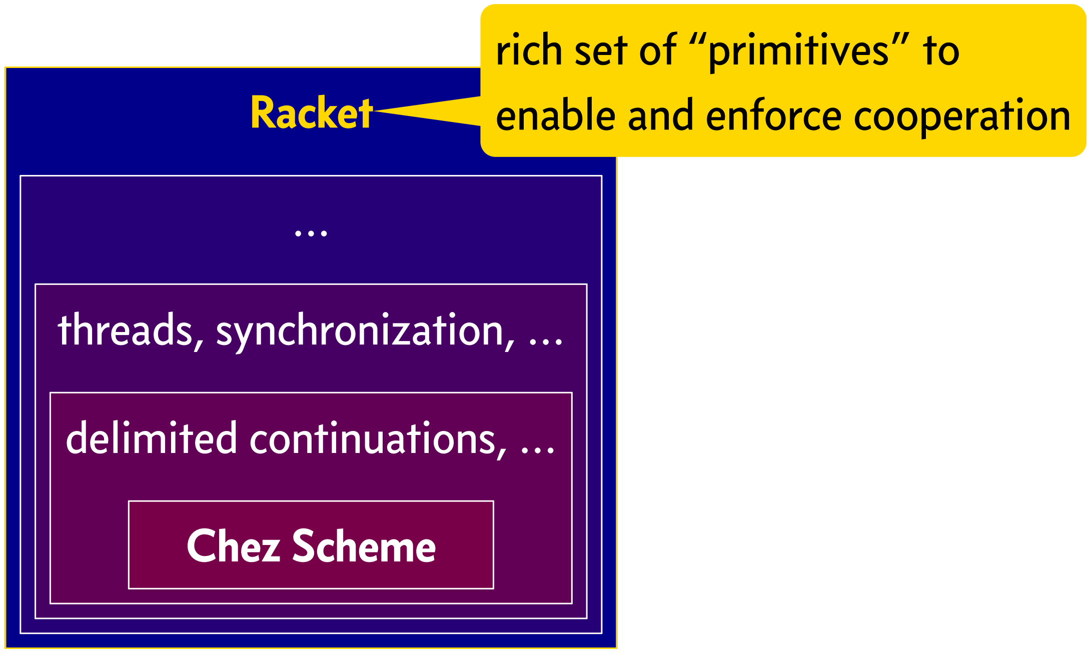
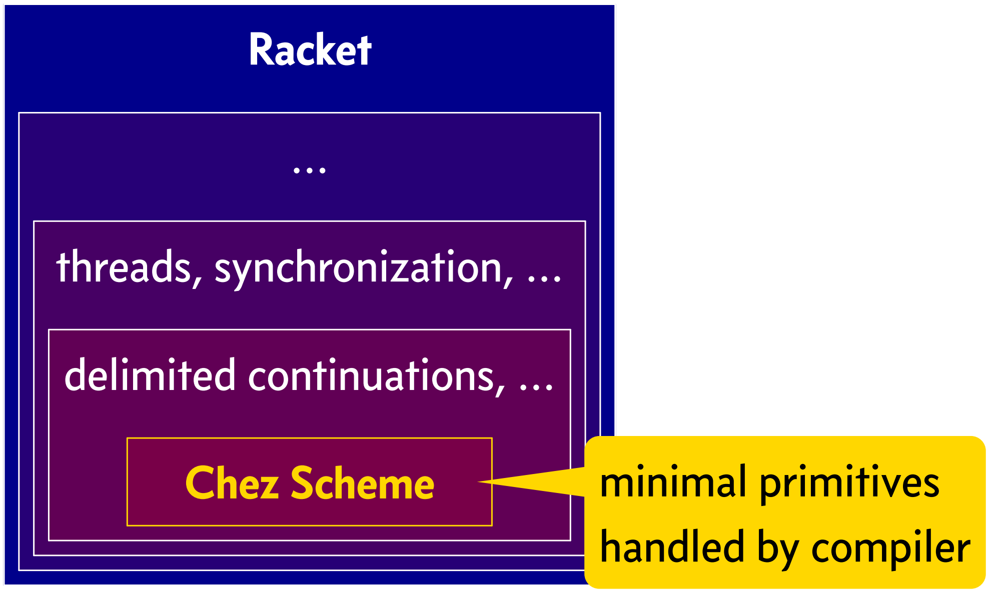
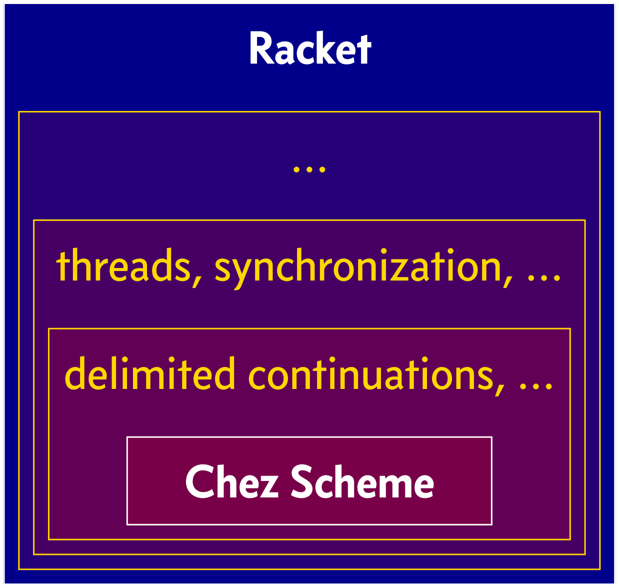

Racket
rich set of “primitives” to enable and enforce cooperation
...
threads, synchronization, ...
delimited continuations, ...
Chez Scheme

Racket Implementation


Racket
...
threads, synchronization, ...
delimited continuations, ...
Chez Scheme
minimal primitives handled by compiler

Racket Implementation



Chez Scheme Control API

as used to implement Racket

Continuations

function [tail] calls

`call/cc`

`call-in-continuation`

`null-continuation`

Continuation Marks

`current-continuation-attachments`

`continuation-next-attachments`

`call-getting-continuation-attachment`

`call-setting-continuation-attachment`

`call-consuming-continuation-attachment`

Exceptions

`raise`

`base-exception-handler`

Signals

`start-timer`

`timer-interrupt-handler`

Chez Scheme Control API

as used to implement Racket

globally connect to primitive exceptions

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timer signal to implement (green) thread preemption

Chez Scheme Control API

as used to implement Racket

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Control Layers

Racket

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Part 1 of 2

Language for Control

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Notation

```
(+ 1 (* (- 7 3) 2))
```

Notation

```
(+ 1 (* (- 7 3) 2))
```

Notation

```
(- 7 3)
```

```
(+ 1 (* (- 7 3) 2))
```

Notation

```
(- 7 3)
```

```
(+ 1 (* (- 7 3) 2))
```

Notation

```
                          (- 7 3)

(+ 1 (* (- 7 3) 2))       (* [] 2)
```

Notation

```
(- 7 3)
```

```
(+ 1 (* (- 7 3) 2))
```

```
(* [] 2)
```

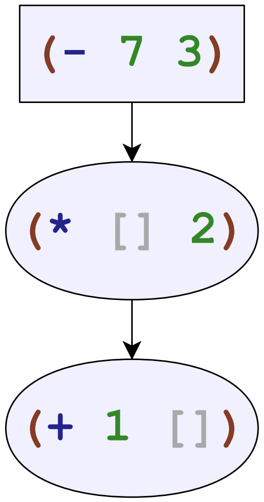
Notation

```
(+ 1 (* (- 7 3) 2))
```

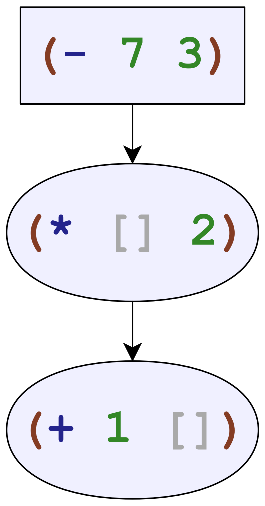
```
(- 7 3)

(* [] 2)

(+ 1 [])
```

Notation

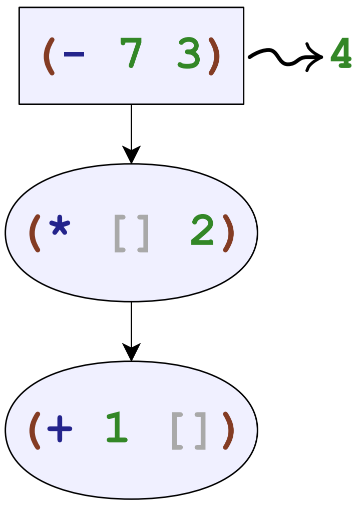
`(+ 1 (* (- 7 3) 2)) =`



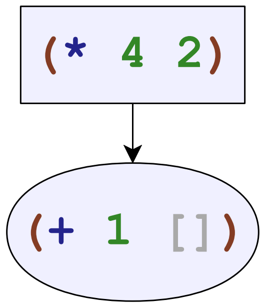
Reductions



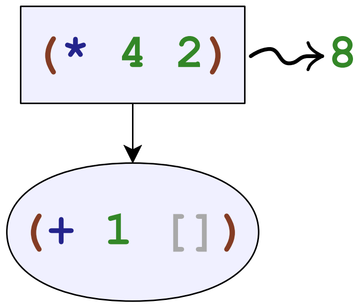
Reductions



Reductions



Reductions



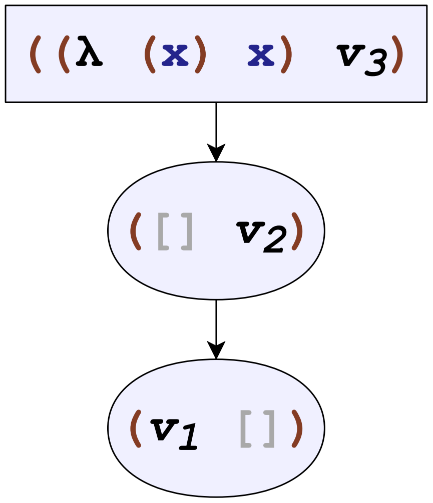
Reductions

```
(+ 1 8)
```

Notation

```
(v₁ (((λ (x) x) v₃) v₂))
```

Reductions



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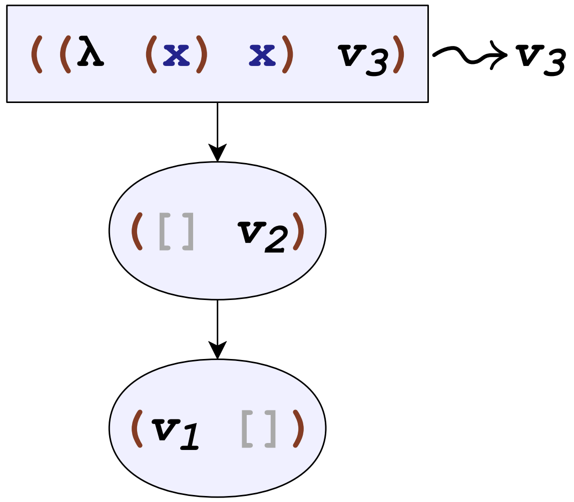

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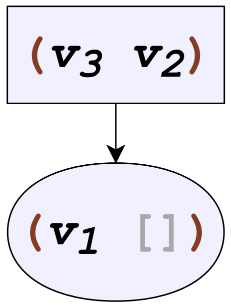
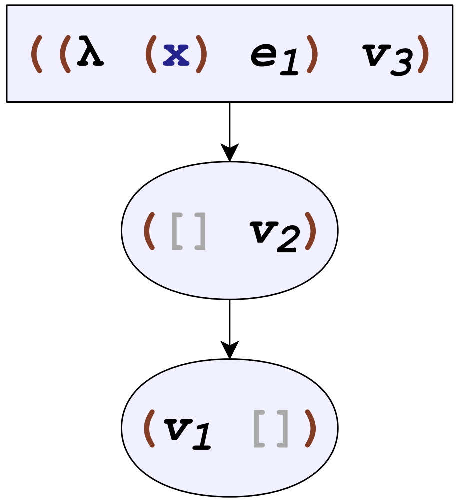


Reductions

$$\begin{tikzcd}
\boxed{\texttt{((}\lambda\ \texttt{(x) x)}\ v_3\texttt{)}} \arrow[d] \\
\texttt{([]}\ v_2\texttt{)} \arrow[d] \\
\texttt{(}v_1\ \texttt{[])}
\end{tikzcd}$$

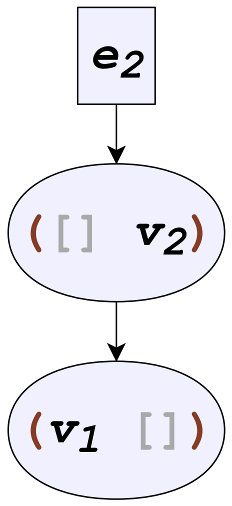
Tail Evaluation



Tail Evaluation

$$\begin{tikzcd} \boxed{((\lambda\ (x)\ e_1)\ v_3)} \arrow[d] \arrow[r, rightsquigarrow] & e_2 \;=\; e_1[x \leftarrow v_3] \\ ([\,]\ \ v_2) \arrow[d] & \\ (v_1\ \ [\,]) & \end{tikzcd}$$

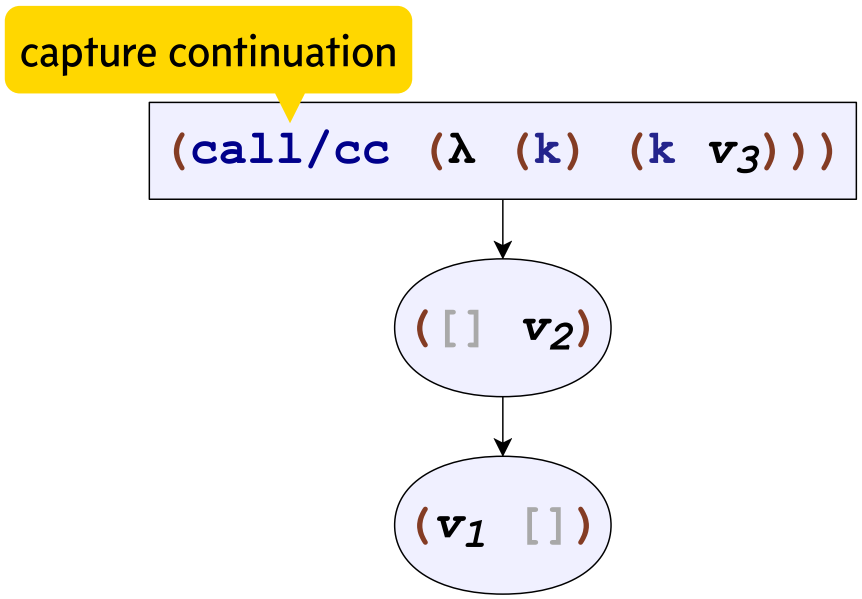
Tail Evaluation



Continuations

$$\begin{tikzcd}
\boxed{\texttt{(call/cc (}\lambda\texttt{ (k) (k }v_3\texttt{)))}} \arrow[d] \\
\texttt{([] }v_2\texttt{)} \arrow[d] \\
\texttt{(}v_1\texttt{ [])}
\end{tikzcd}$$

Continuations



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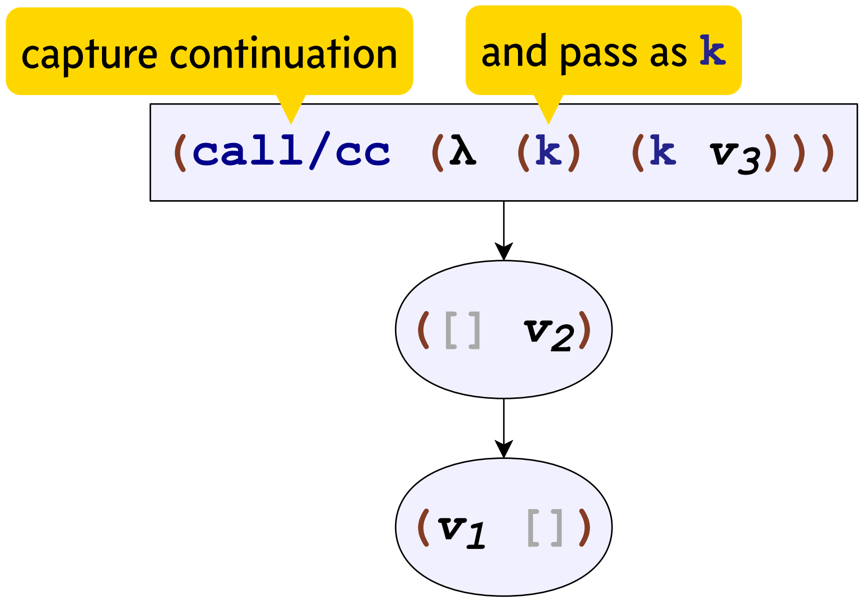

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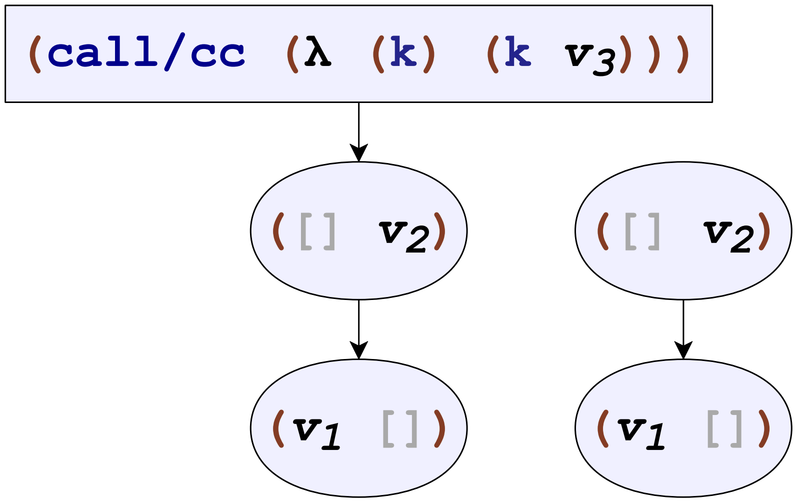

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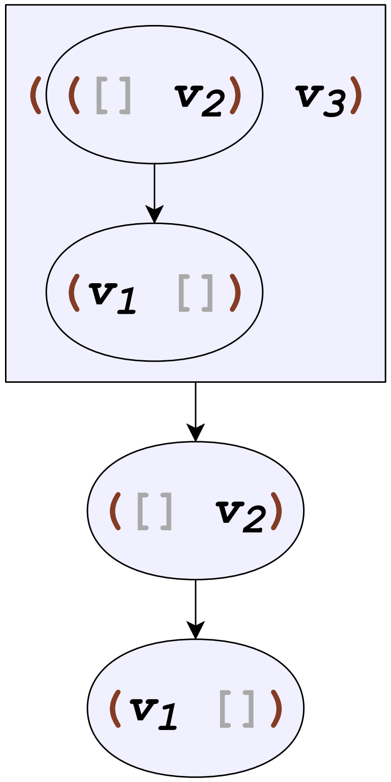

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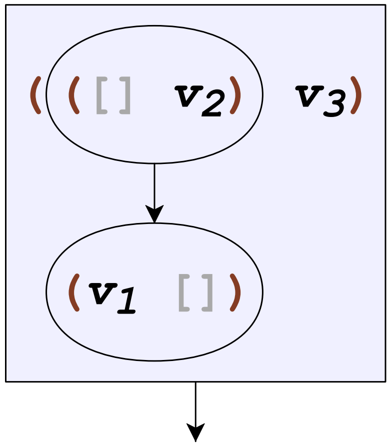

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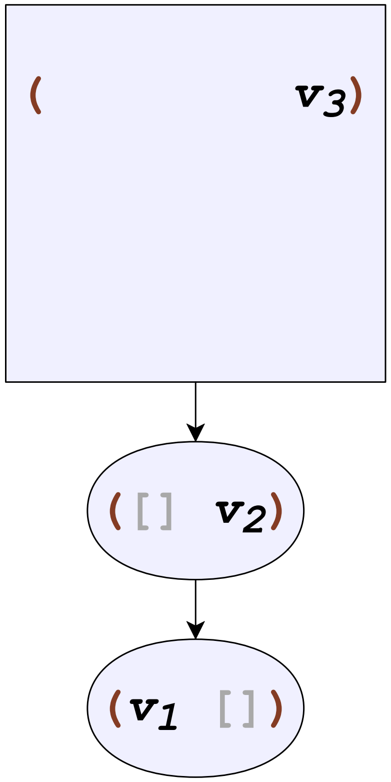

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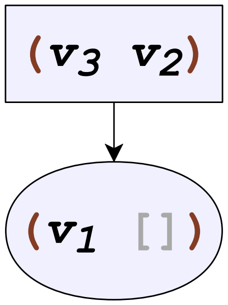
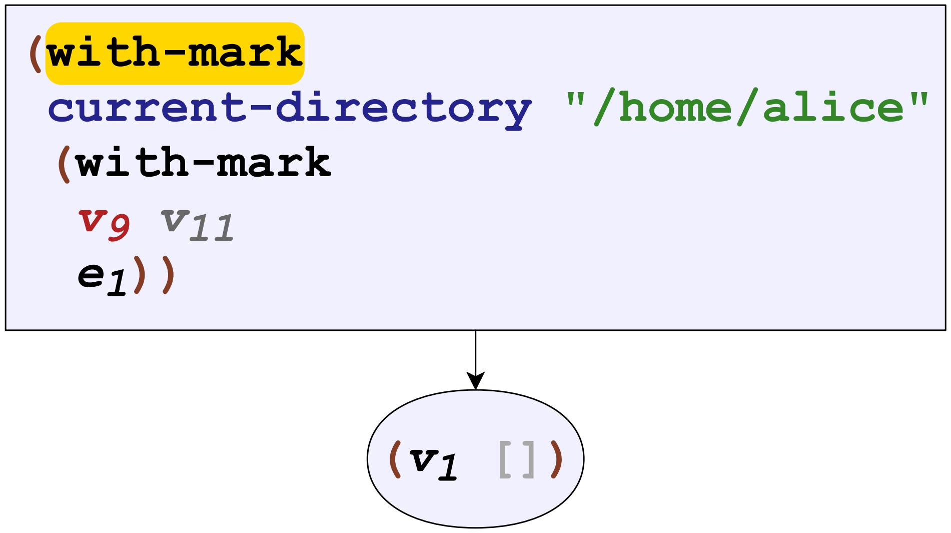


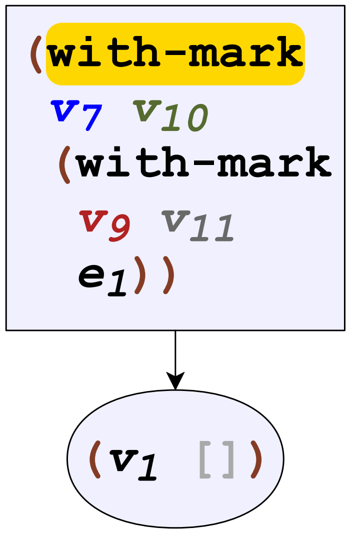
Continuation Marks



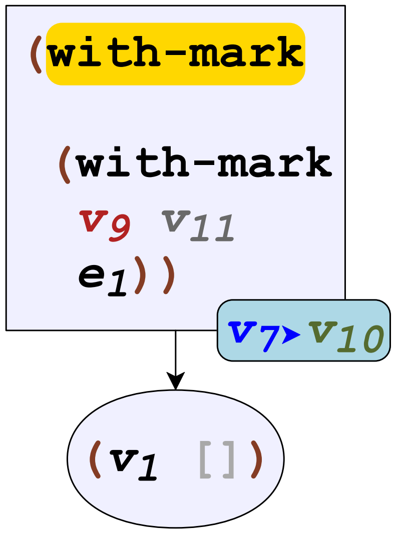
```
(with-mark
 current-directory "/home/alice"
 (with-mark
  v9 v11
  e1))
```

```
(v1 [])
```

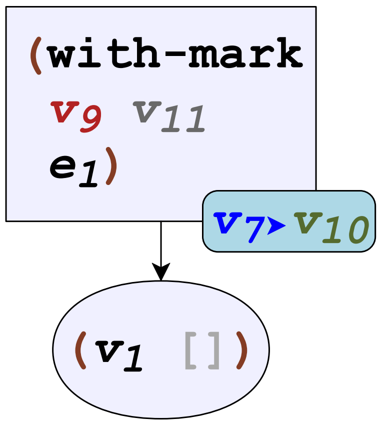
Continuation Marks



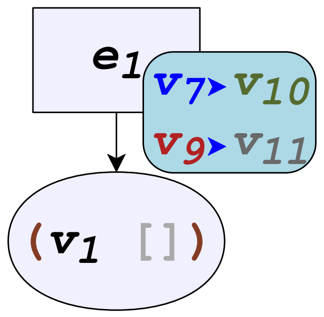
Continuation Marks



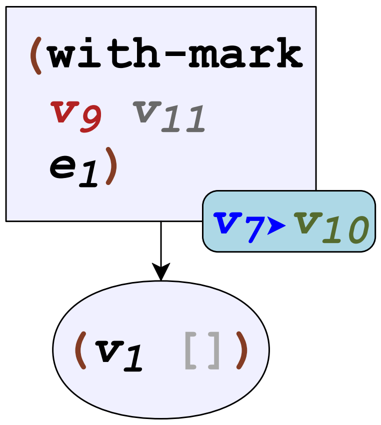
Continuation Marks



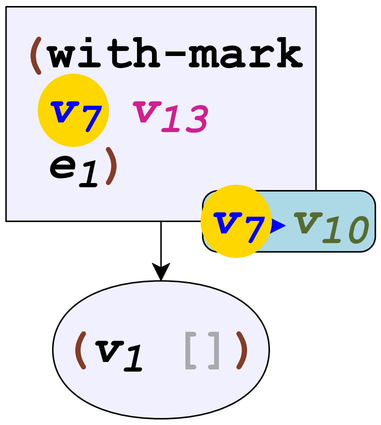
Continuation Marks


e_1
$v_7 \blacktriangleright v_{10}$
$v_9 \blacktriangleright v_{11}$
$(v_1\ [\,])$

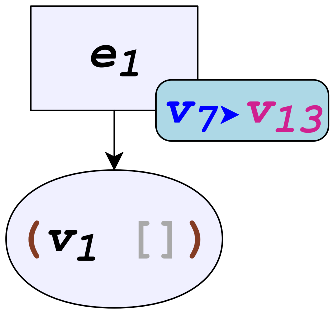
Continuation Marks



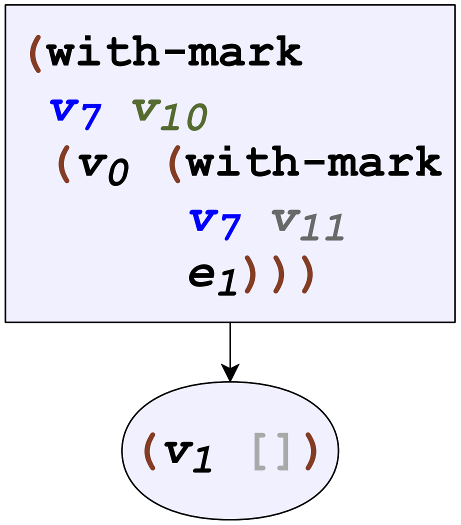
Continuation Marks



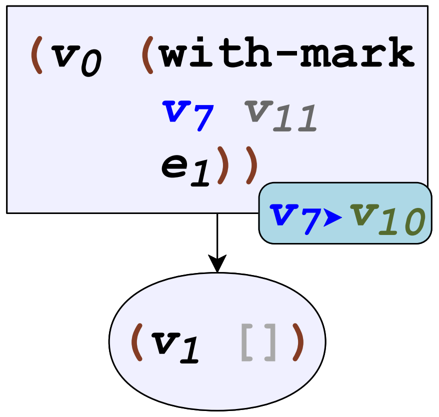
Continuation Marks



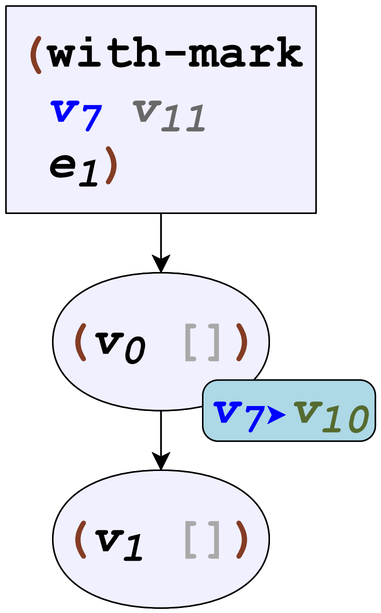
Continuation Marks



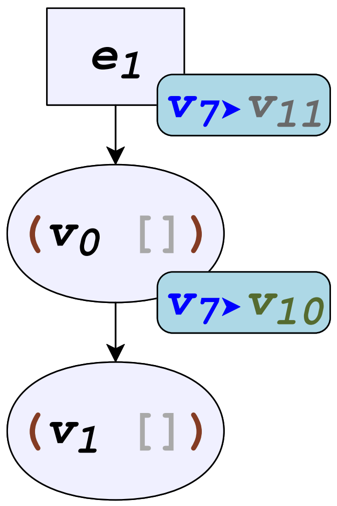
Continuation Marks



Continuation Marks

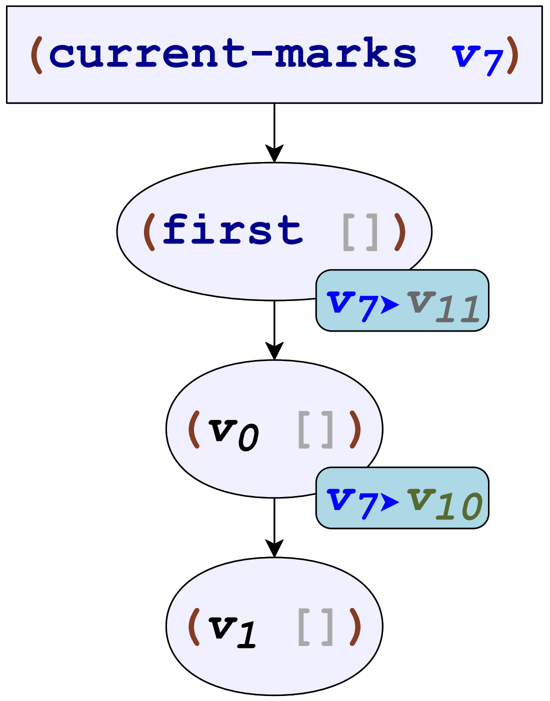


Continuation Marks

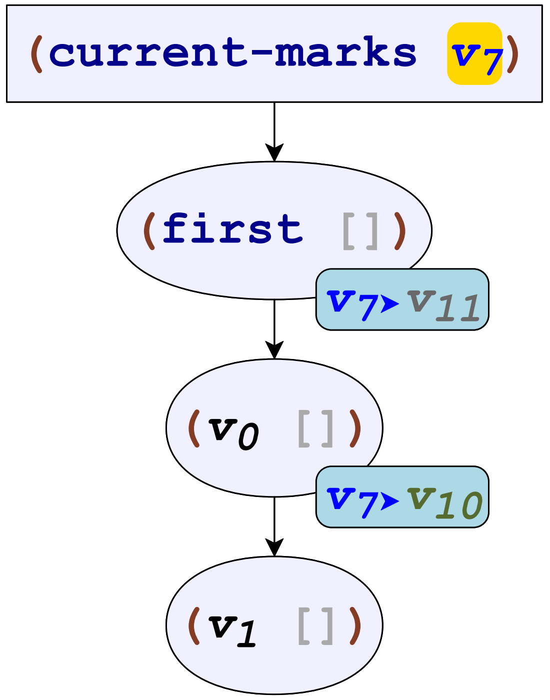


e_1
$v_7 \blacktriangleright v_{11}$
$(v_0\ [\,])$
$v_7 \blacktriangleright v_{10}$
$(v_1\ [\,])$

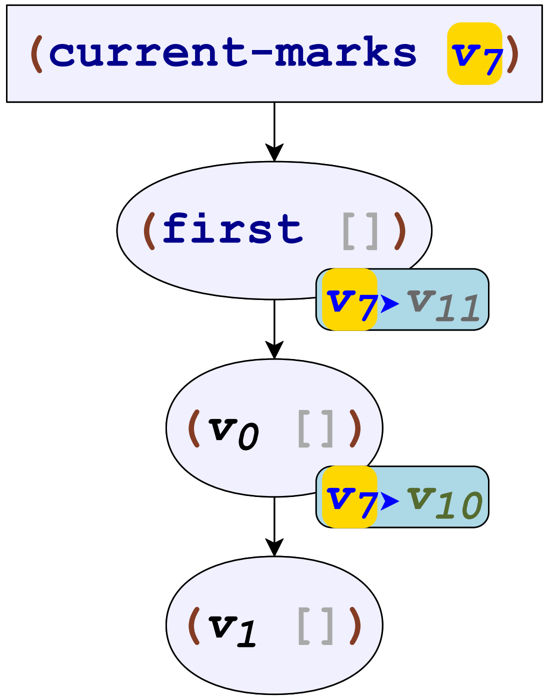
Continuation Marks



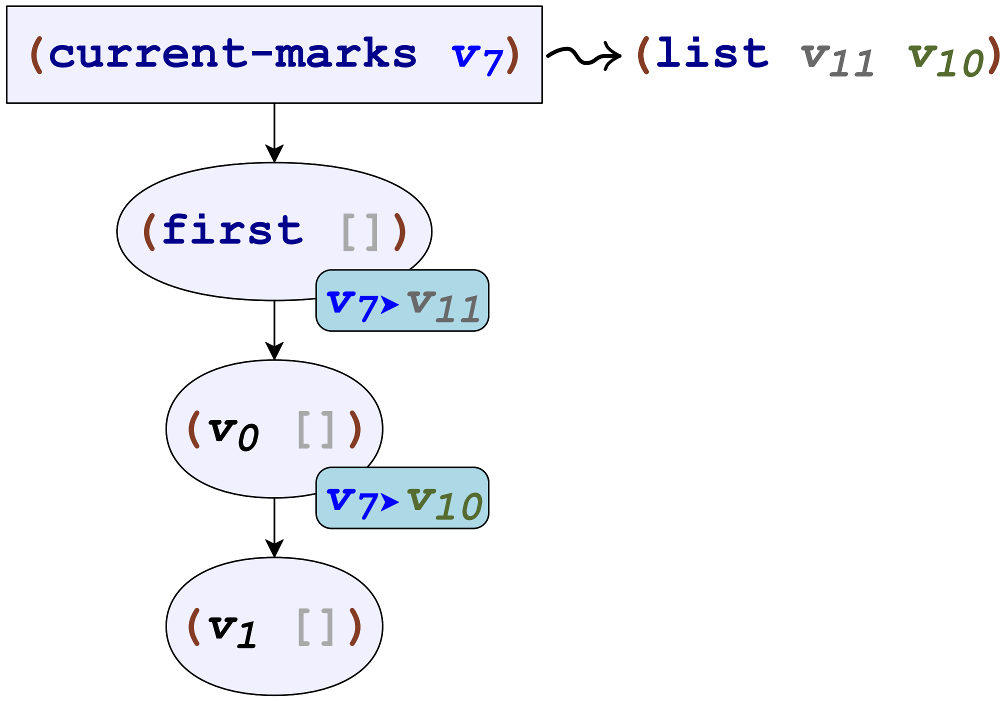
Continuation Marks



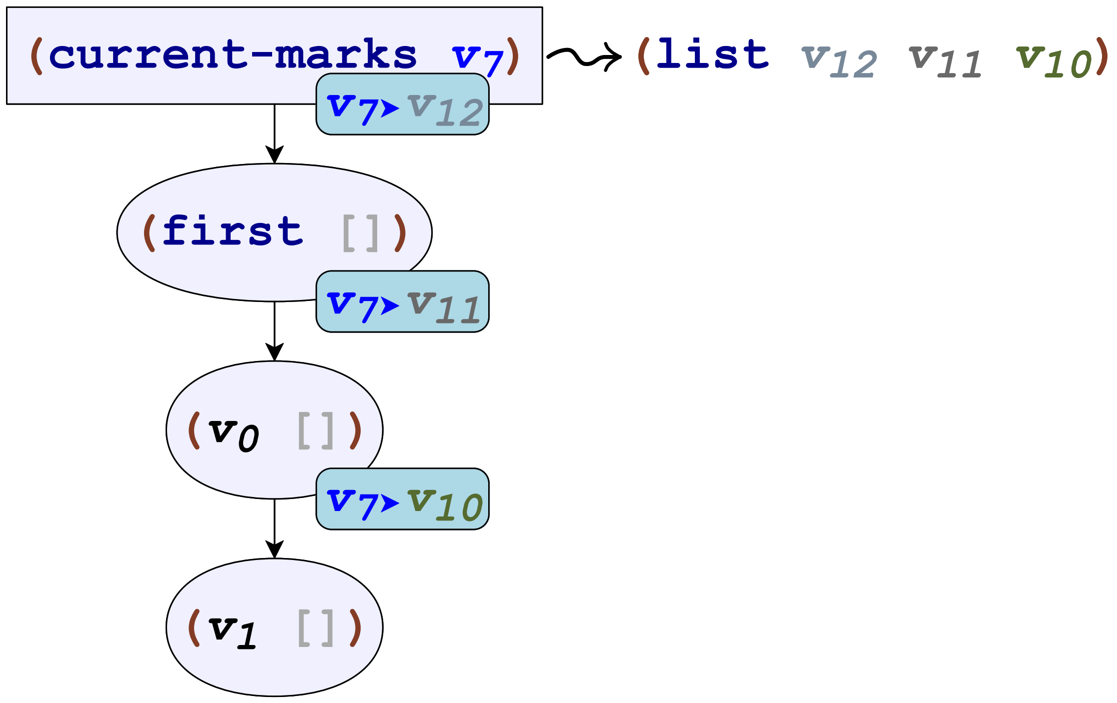
Continuation Marks



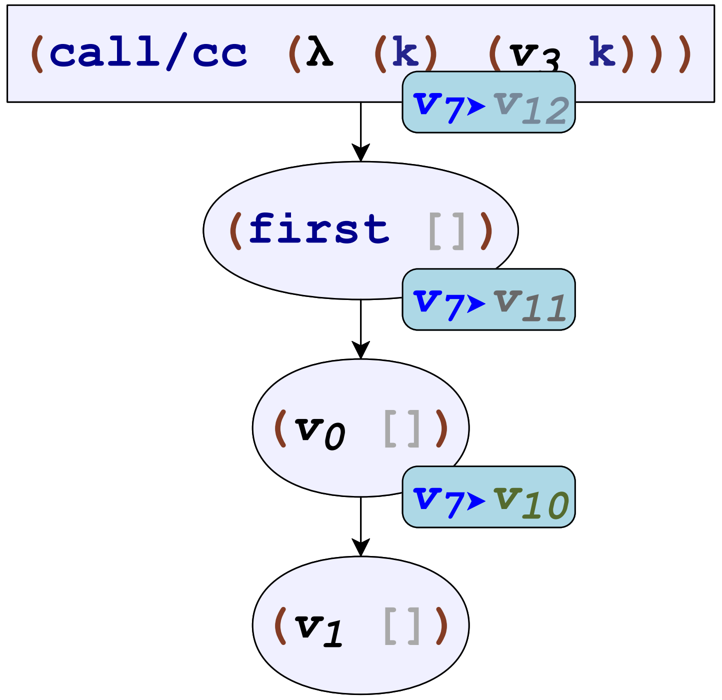
Continuation Marks



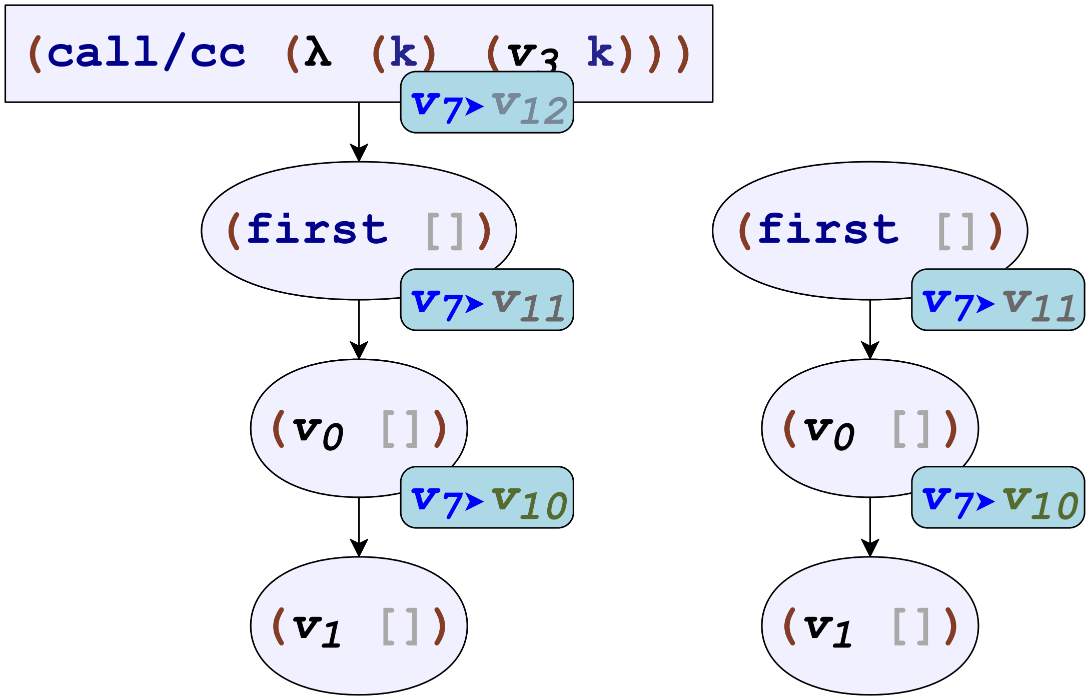
Continuation Marks



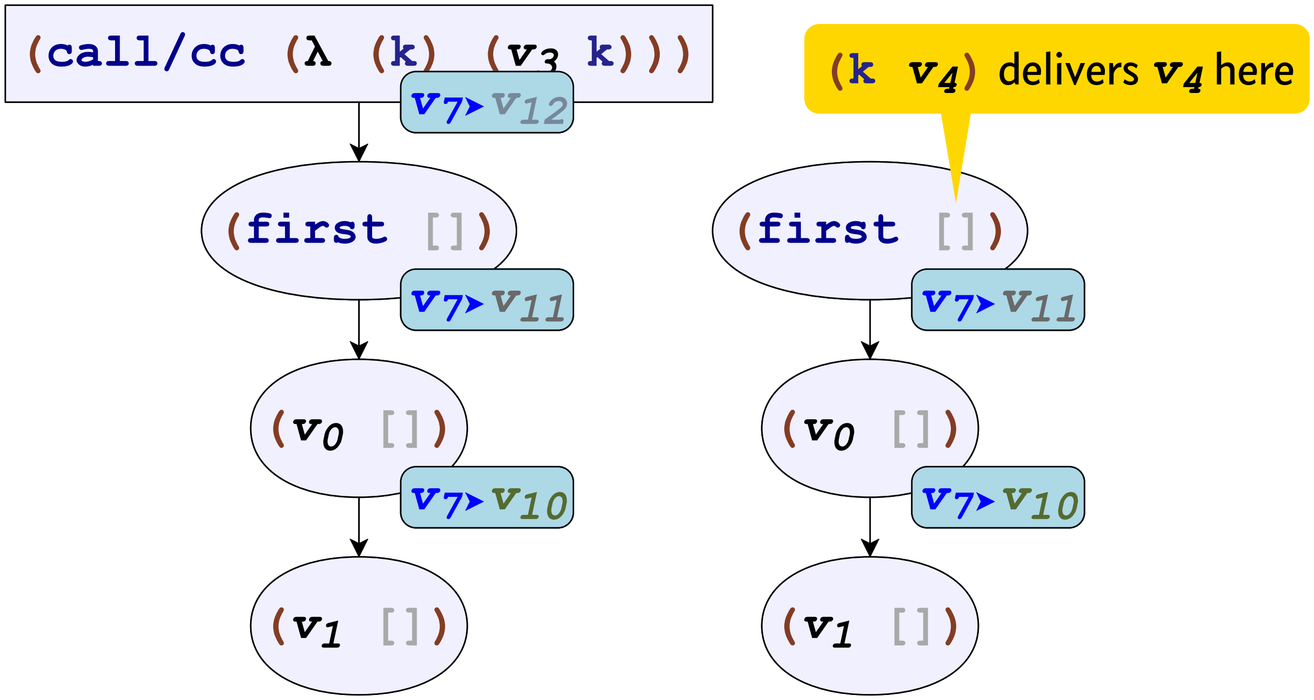
Capturing Marks



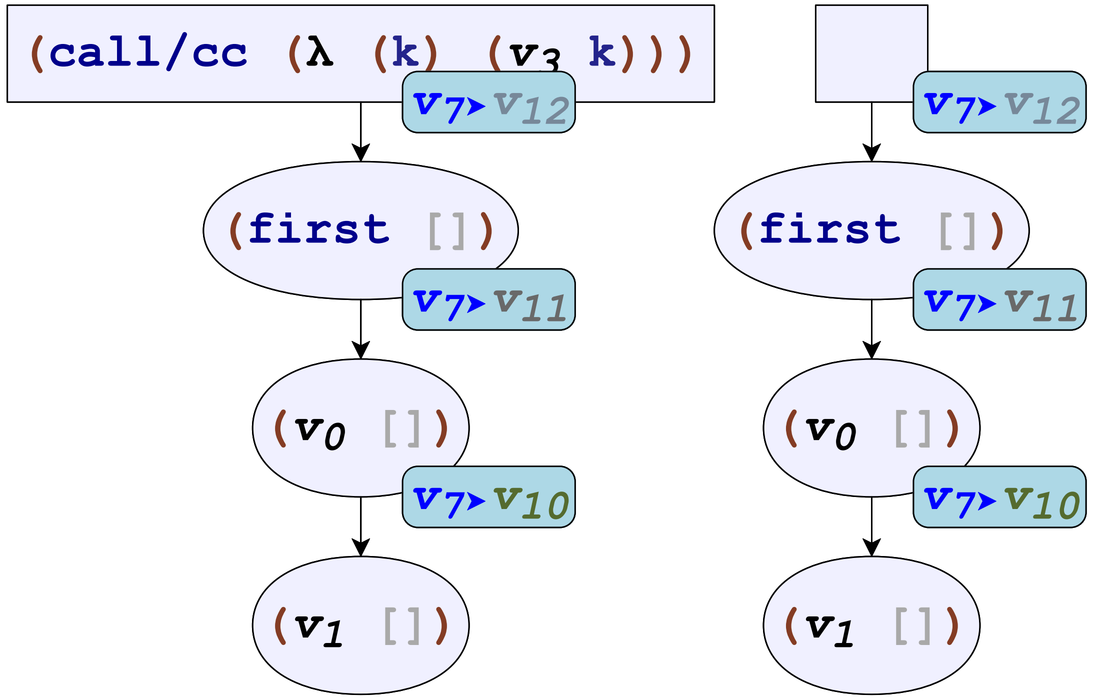
Capturing Marks



Capturing Marks

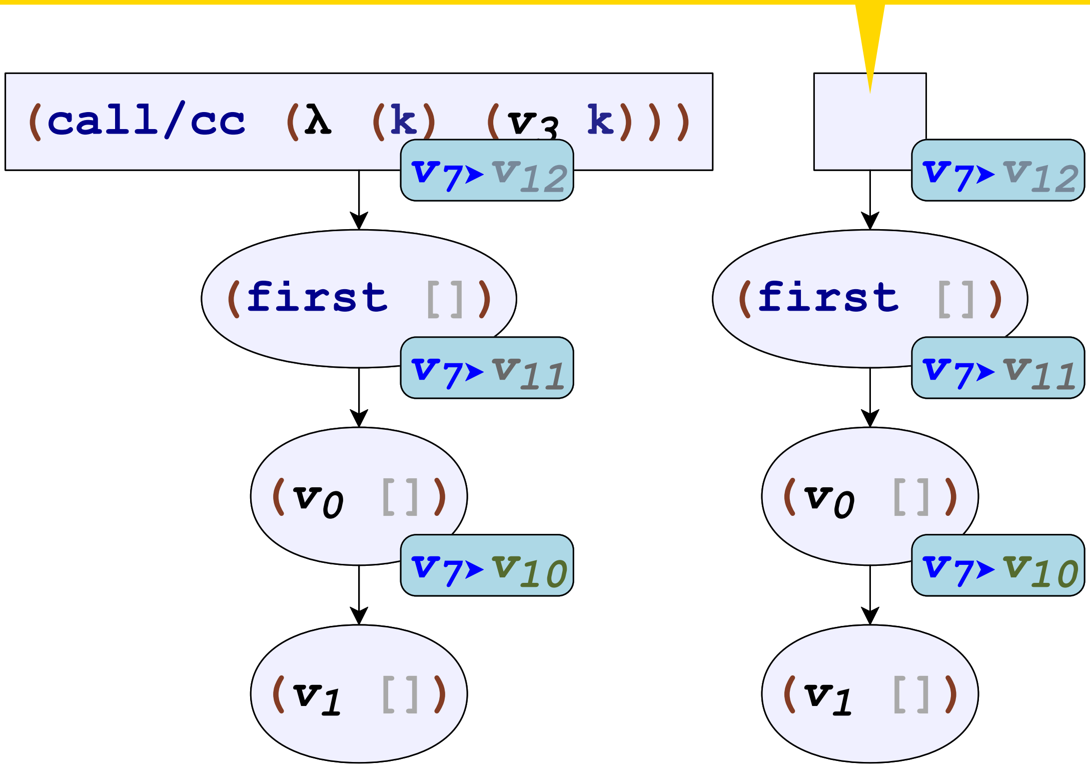


Capturing Marks

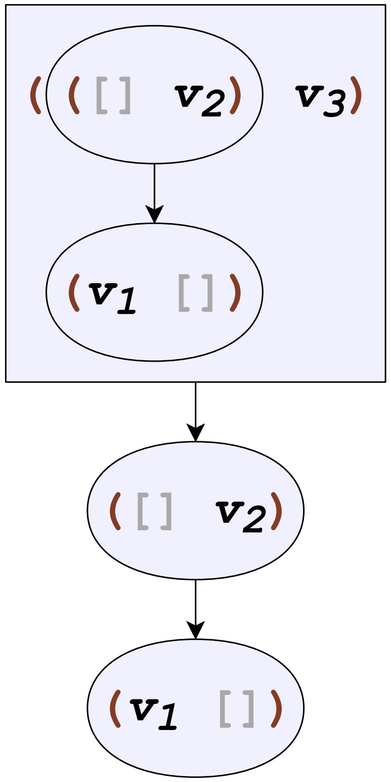


Capturing Marks

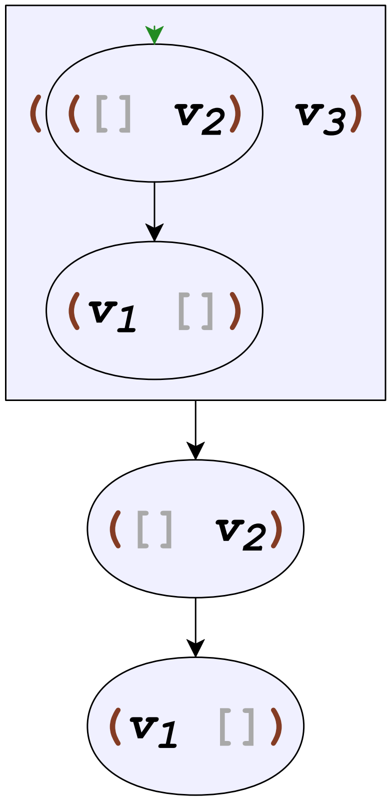
`(call-in-continuation k (λ () e₅))` delivers e_5 here



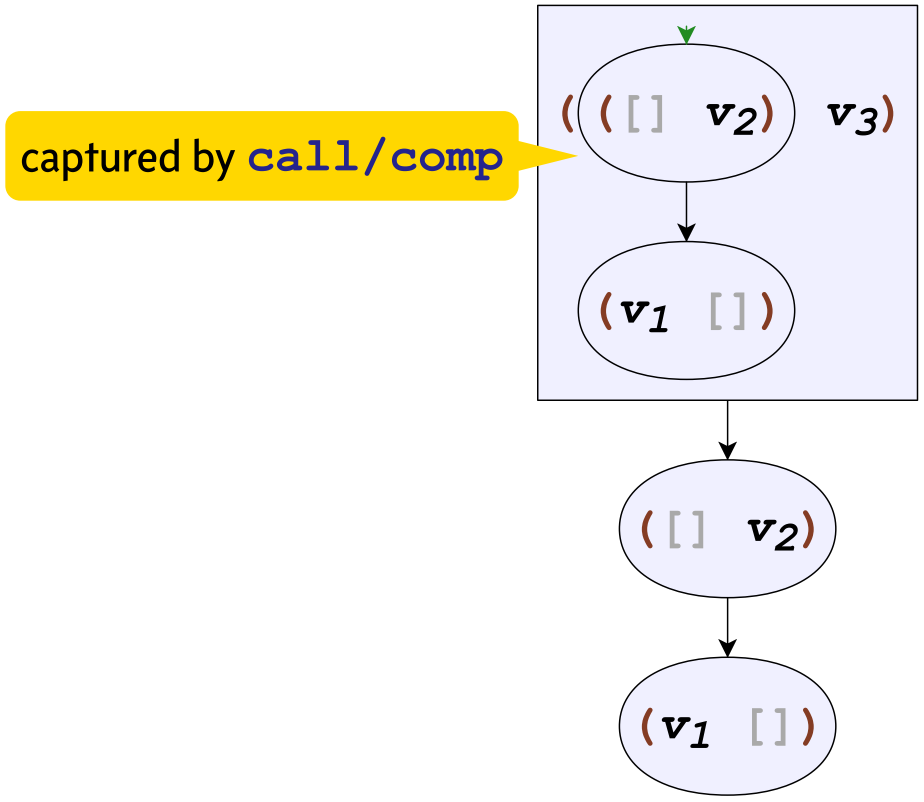
Continuations



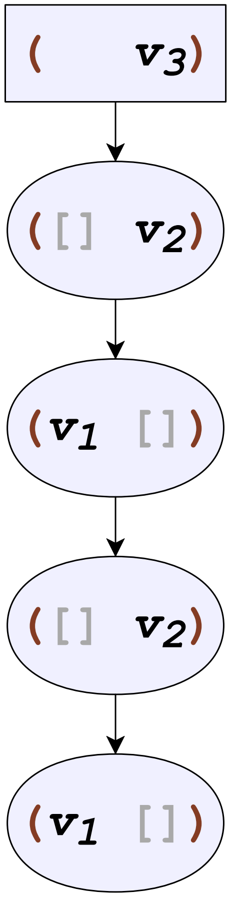
Composable Continuations



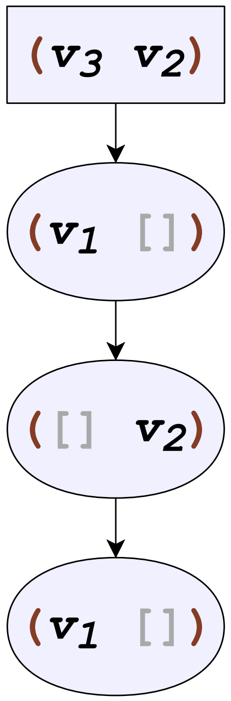
Composable Continuations



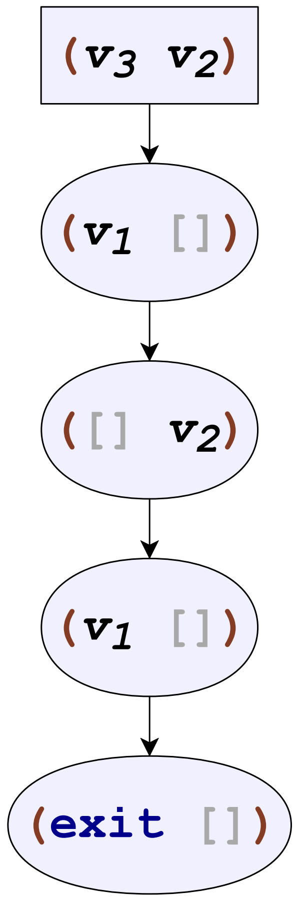
Composable Continuations



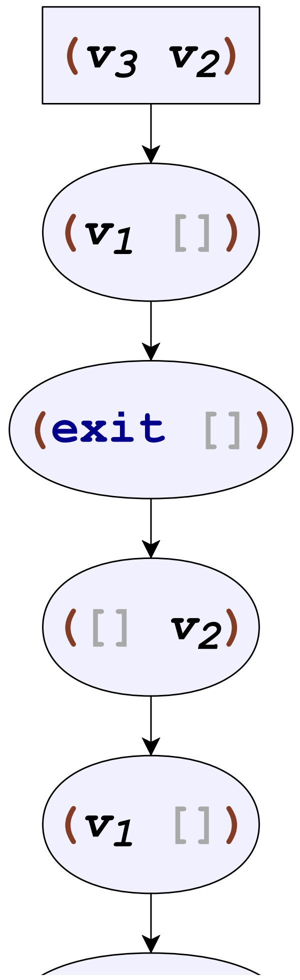
Composable Continuations



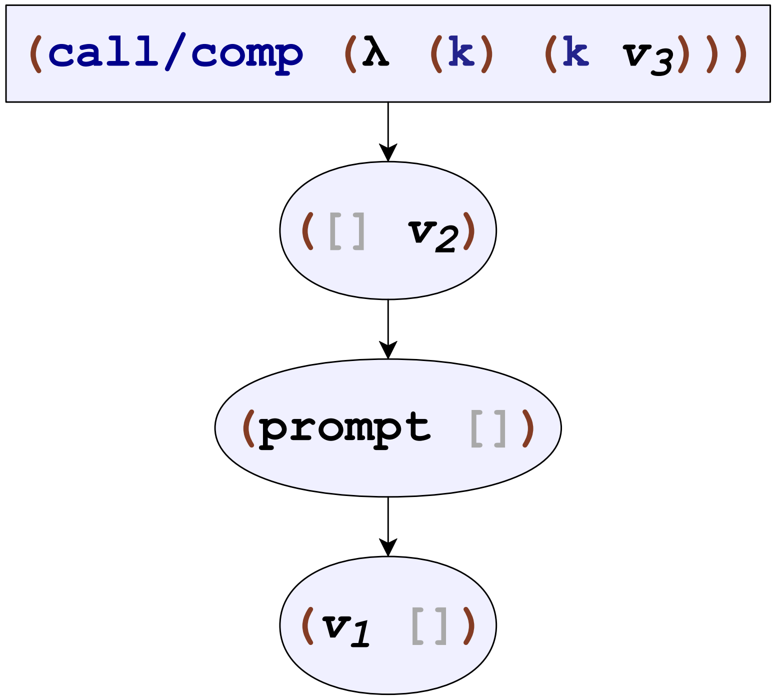
Composable Continuations



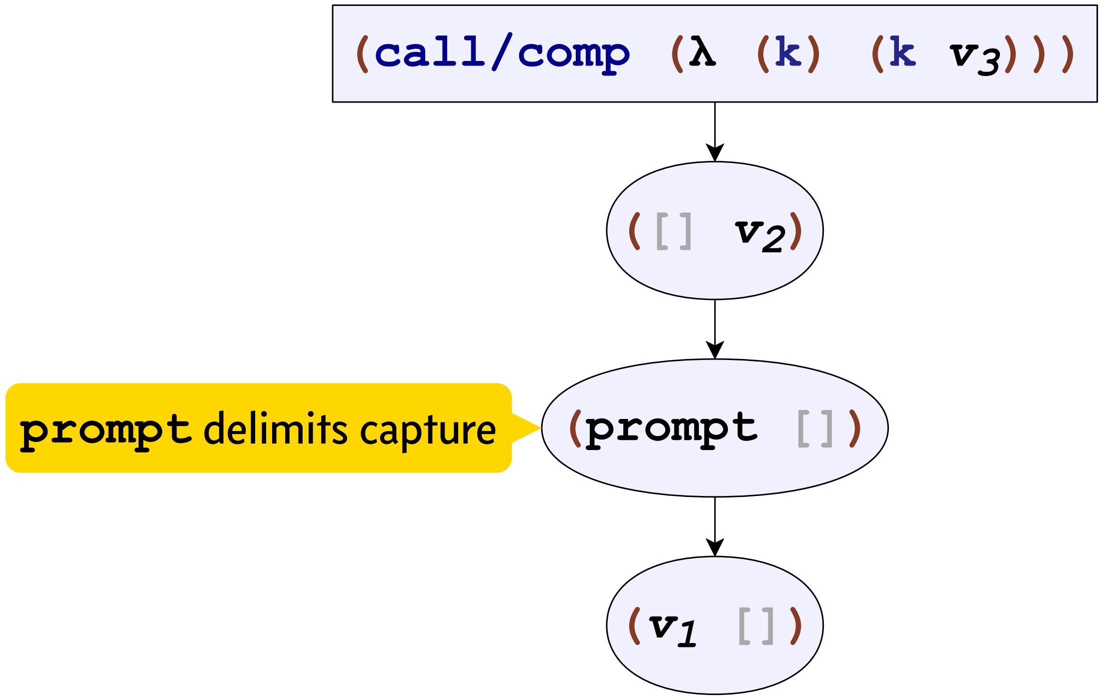
Composable Continuations



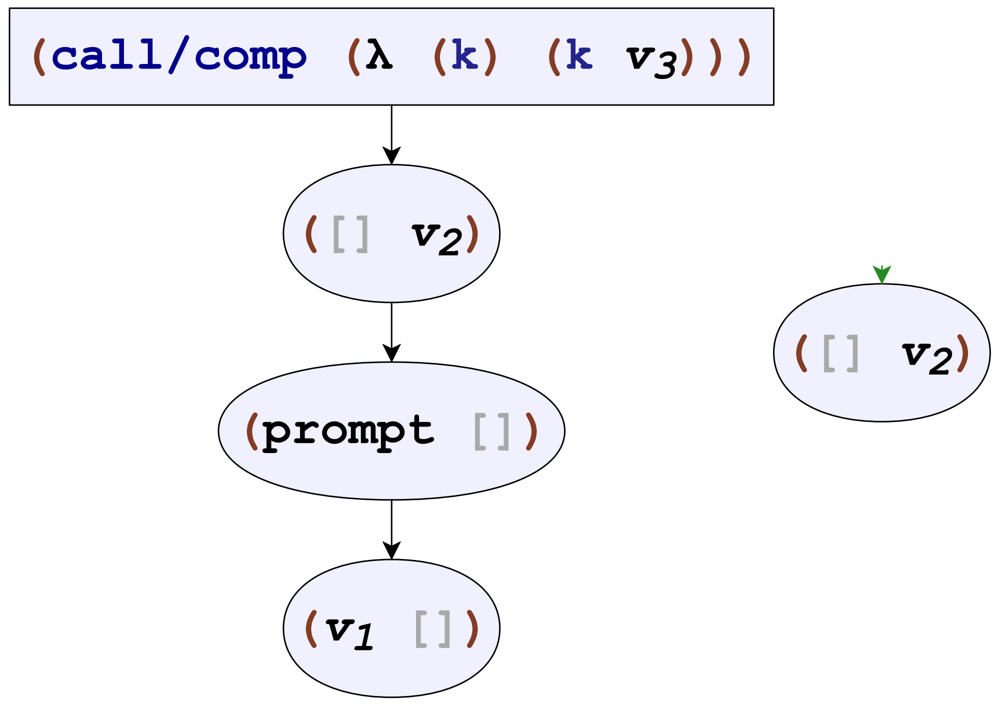
Delimited Capture



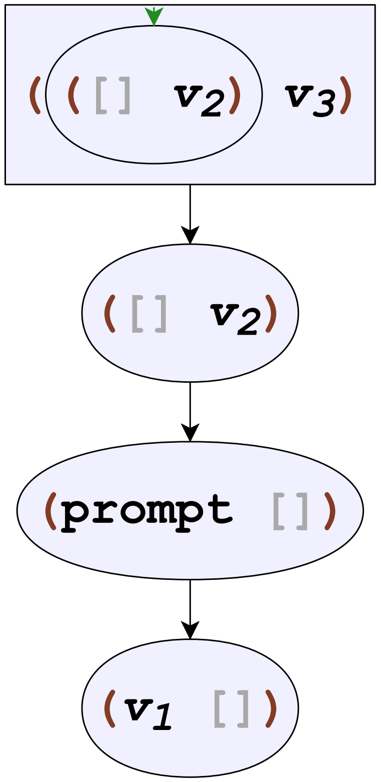
Delimited Capture



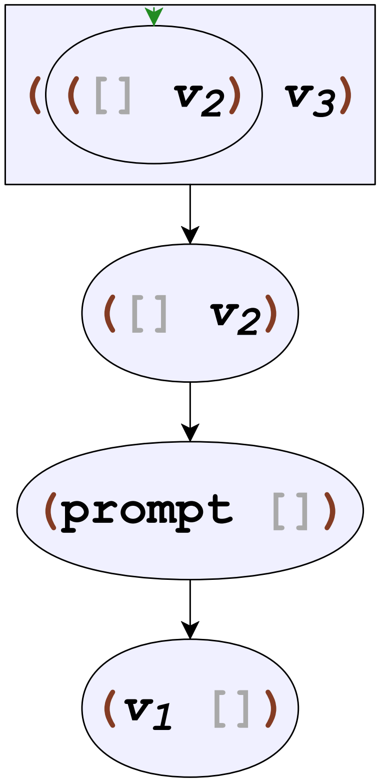
Delimited Capture



Delimited Capture

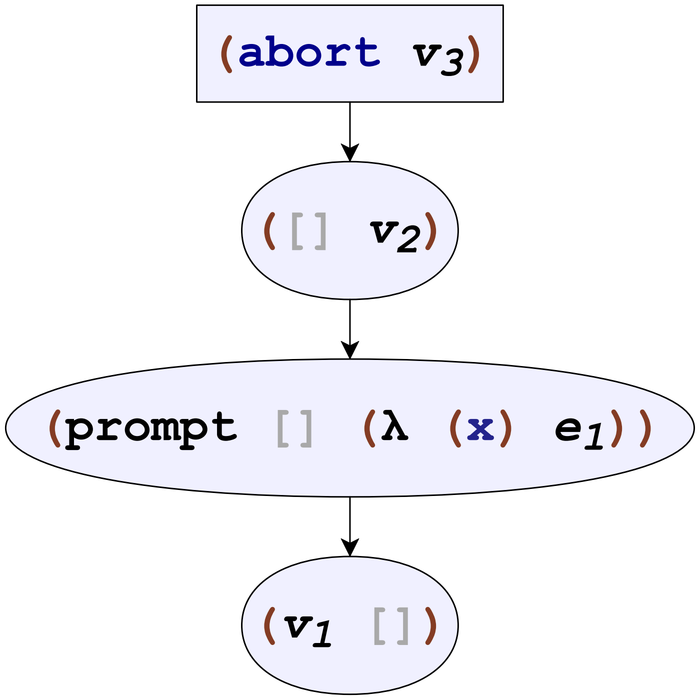


Delimited Capture



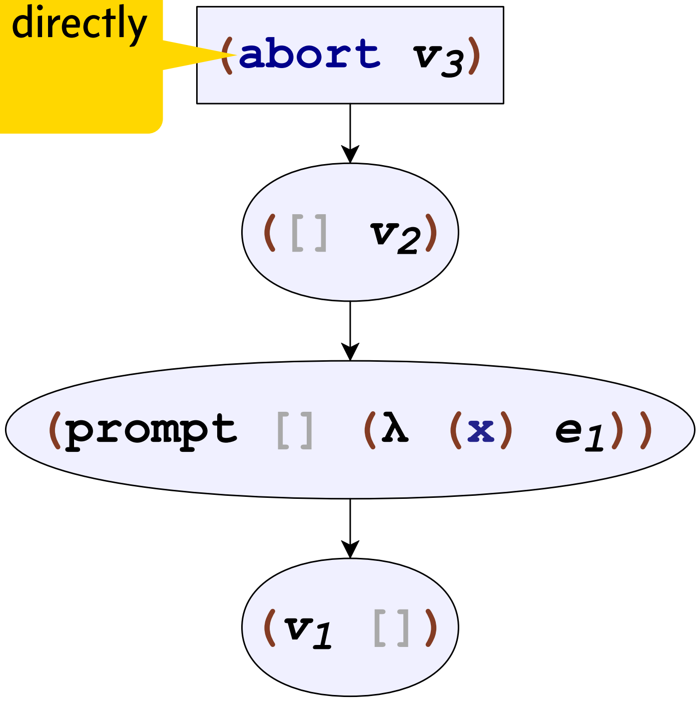
Practically all uses of continuations are better as **delimited**

Abort and Prompt Handlers

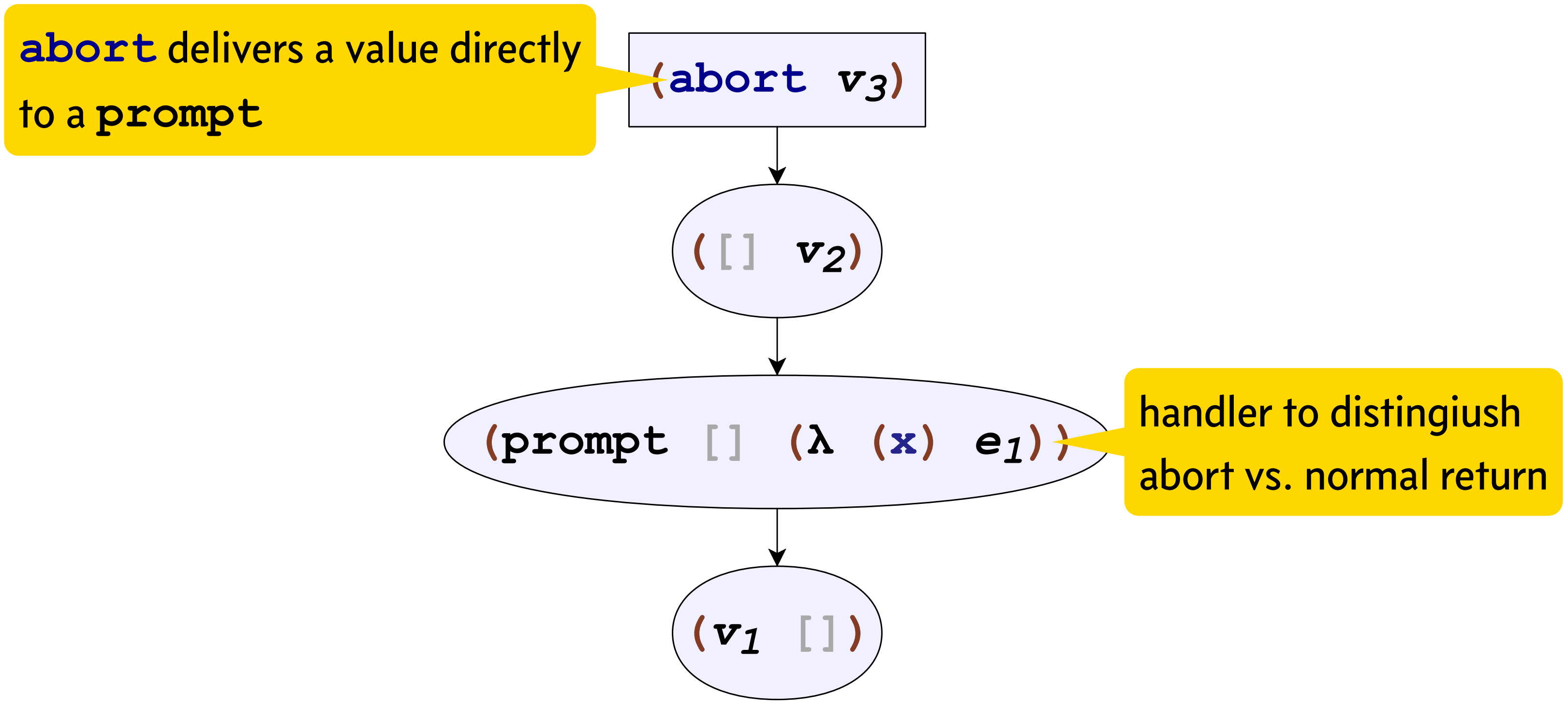


Abort and Prompt Handlers

abort delivers a value directly to a **prompt**



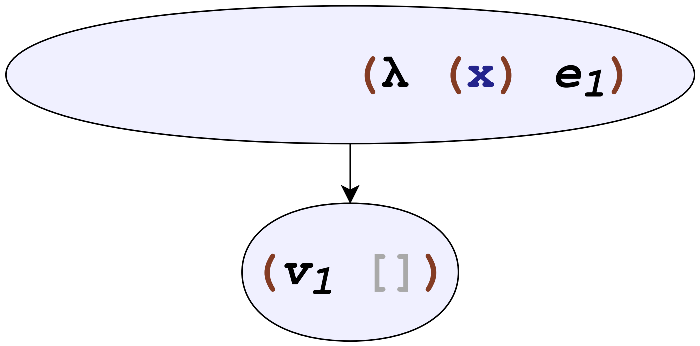
Abort and Prompt Handlers



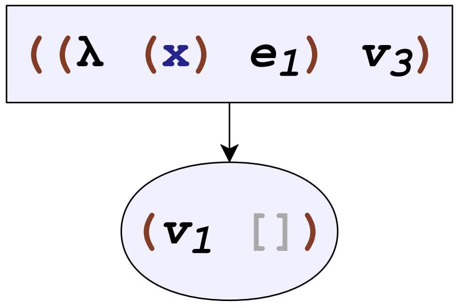
abort delivers a value directly to a prompt
(abort v3)
([] v2)
(prompt [] (λ (x) e1))
handler to distingiush abort vs. normal return
(v1 [])

Abort and Prompt Handlers

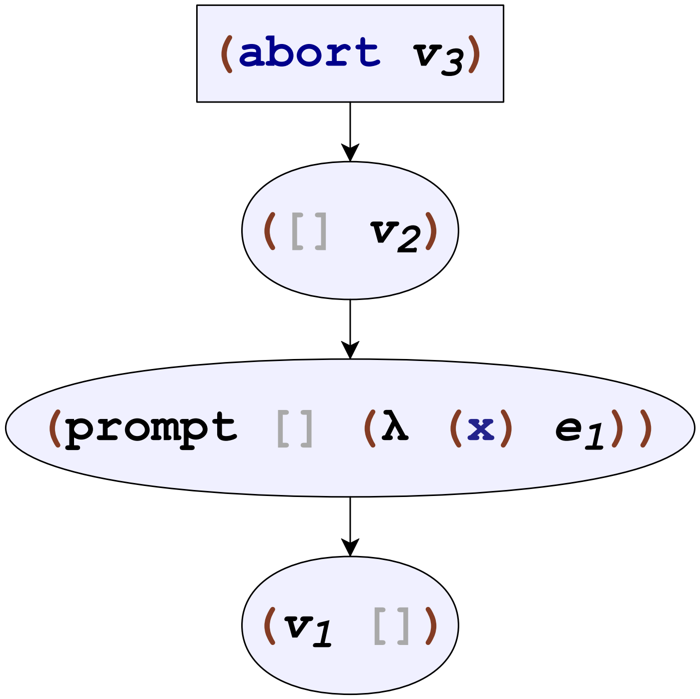
`v3`



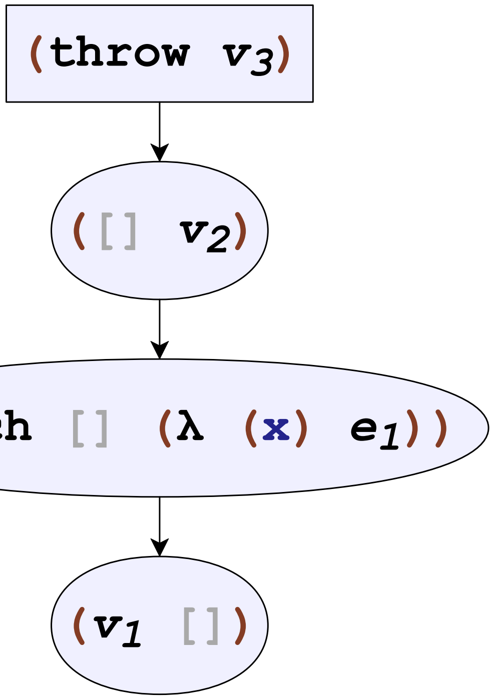
Abort and Prompt Handlers



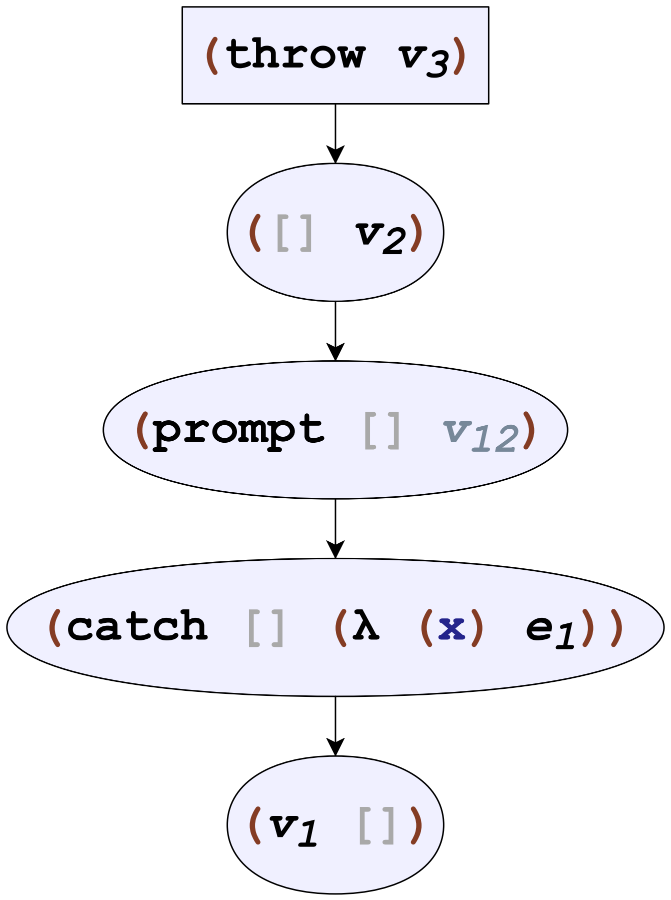
Abort and Prompt Handlers



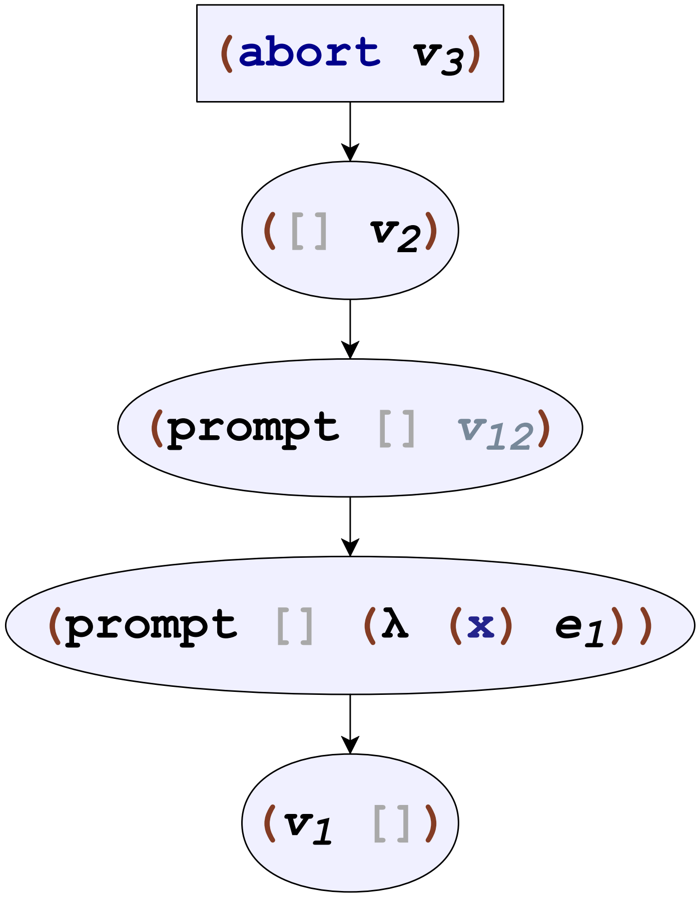
Implementing Catch and Throw



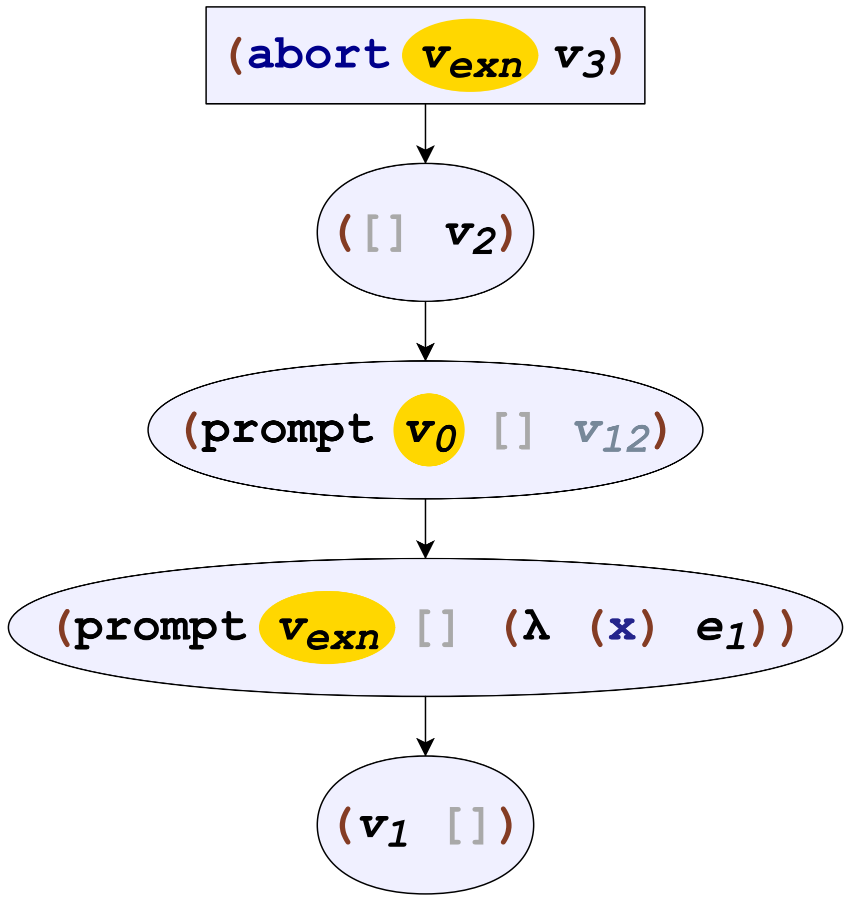
Implementing Catch and Throw



Implementing Catch and Throw

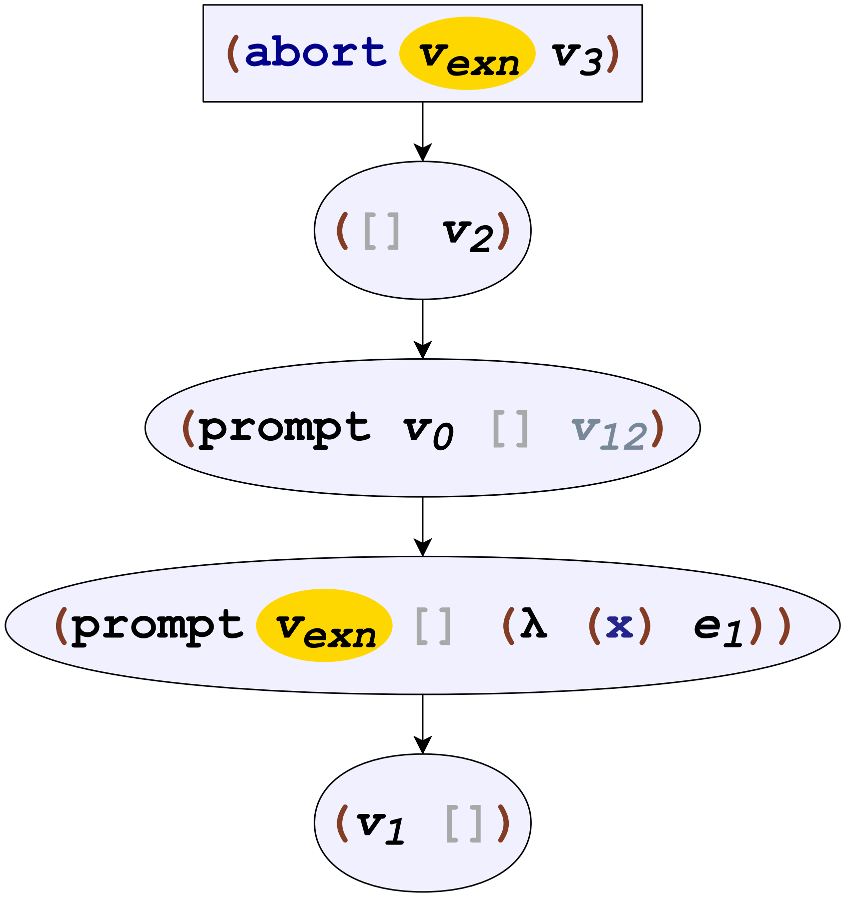


Implementing Catch and Throw

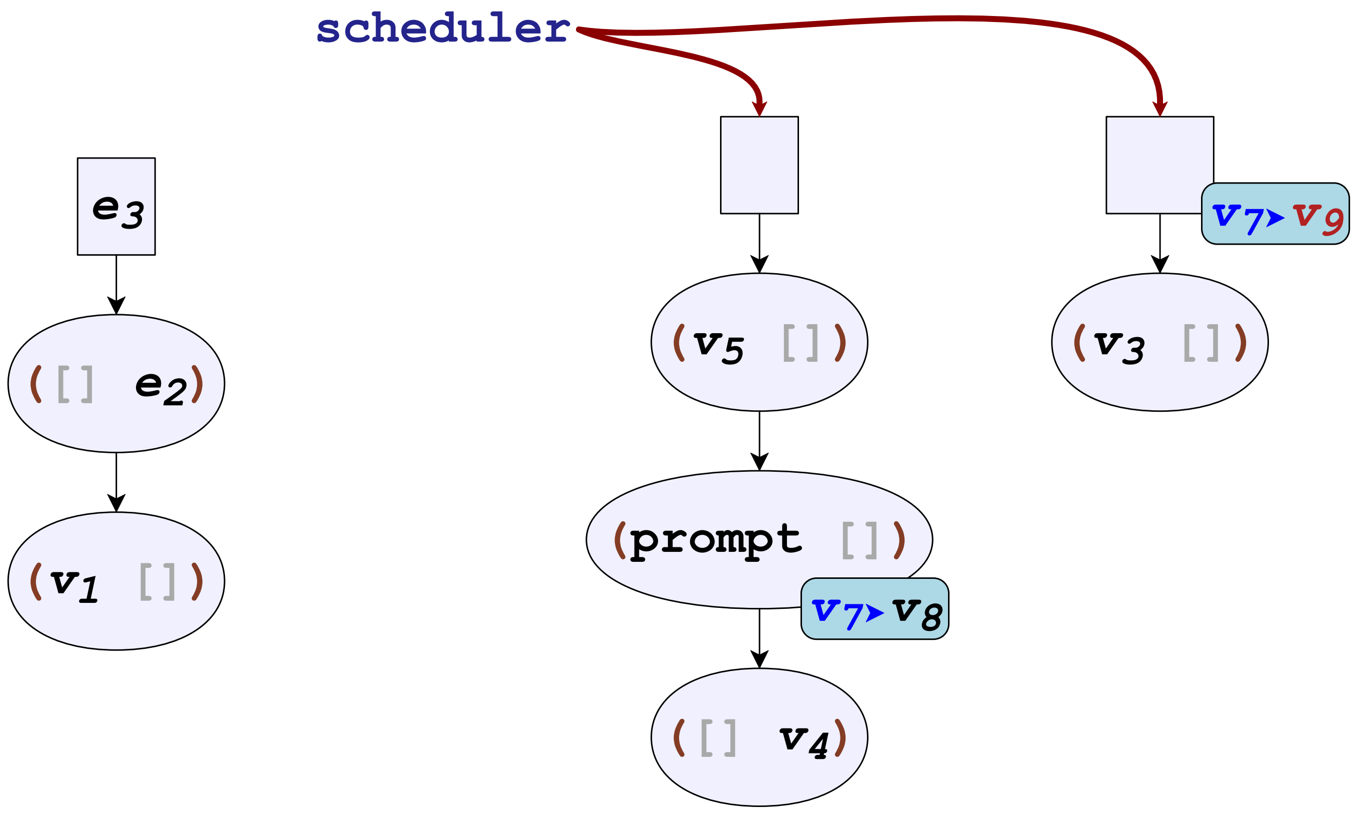

(abort v_{exn} v_3)
([] v_2)
(prompt v_0 [] v_{12})
(prompt v_{exn} [] (λ (x) e_1))
(v_1 [])

prompt **tags**
distinguish uses

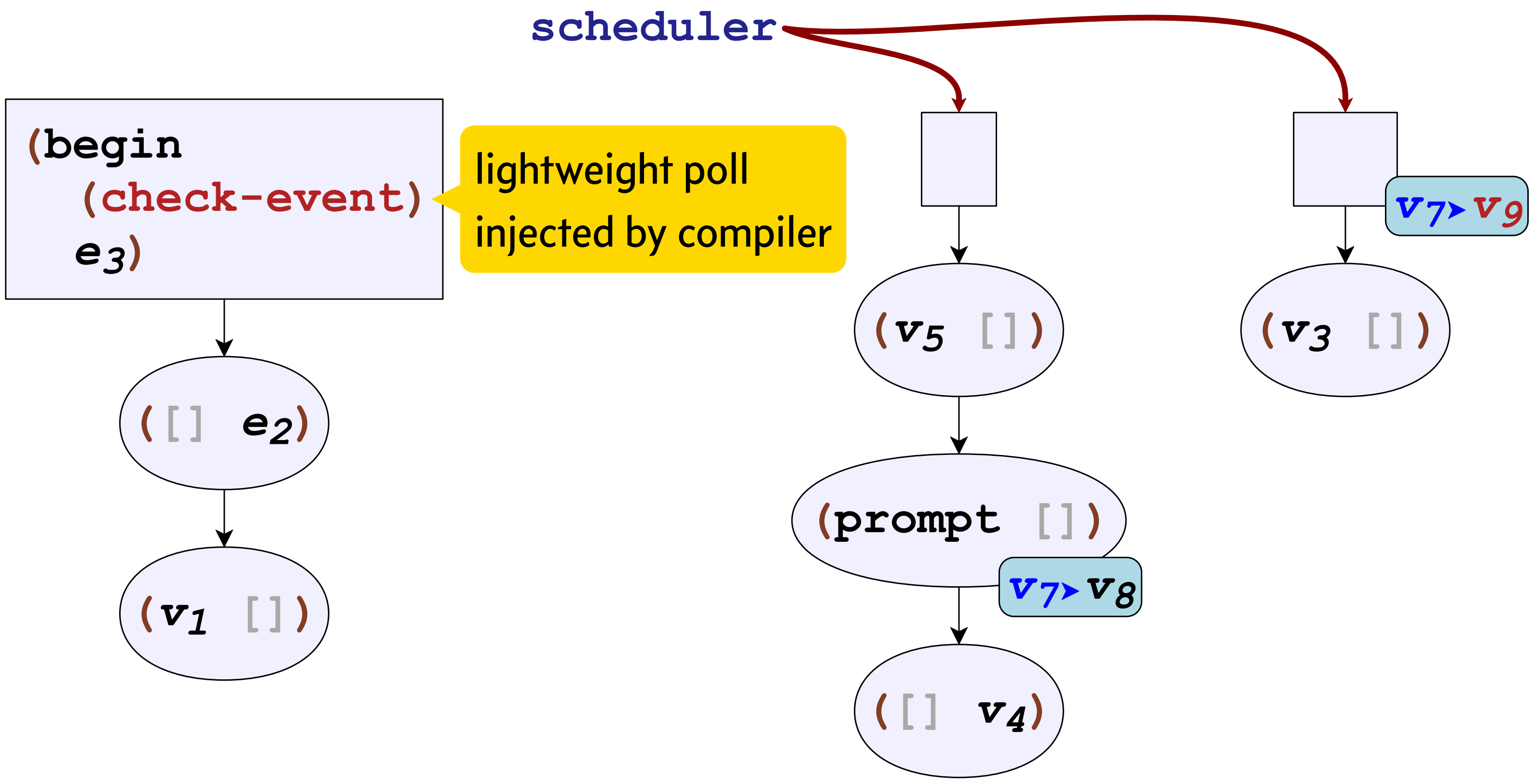
Implementing Catch and Throw


(abort v_{exn} v_3)
([] v_2)
(prompt v_0 [] v_{12})
(prompt v_{exn} [] (λ (x) e_1))
(v_1 [])

Threads



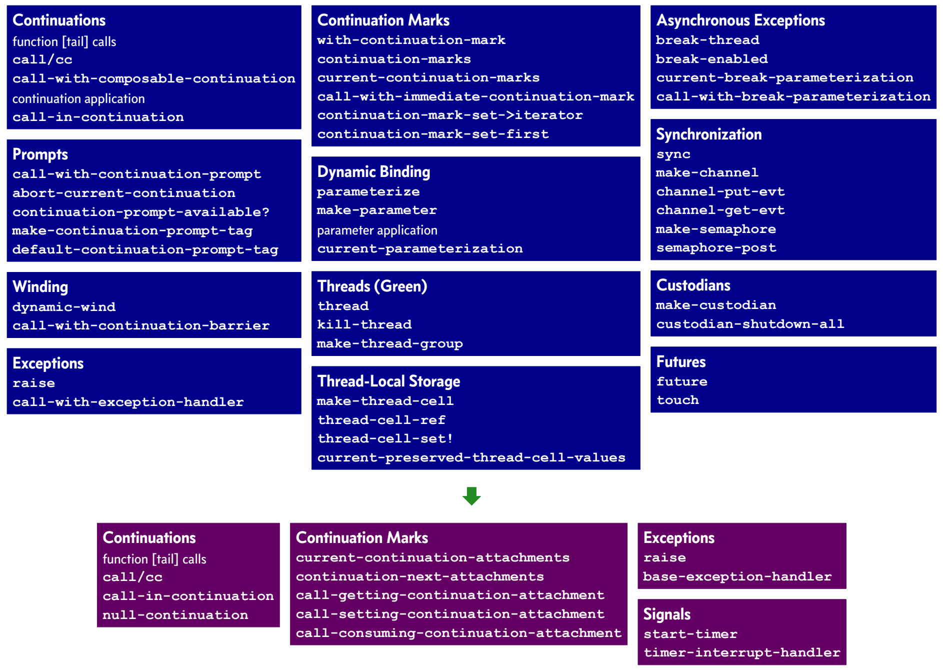
Threads



scheduler
(begin
(check-event)
e3)
lightweight poll
injected by compiler
([] e2)
(v1 [])
(v5 [])
(prompt [])
v7➤v8
([] v4)
v7➤v9
(v3 [])

Part 2 of 2

Implementation



Continuations
function [tail] calls
`call/cc`
`call-with-composable-continuation`
continuation application
`call-in-continuation`

Prompts
`call-with-continuation-prompt`
`abort-current-continuation`
`continuation-prompt-available?`
`make-continuation-prompt-tag`
`default-continuation-prompt-tag`

Winding
`dynamic-wind`
`call-with-continuation-barrier`

Exceptions
`raise`
`call-with-exception-handler`

Continuation Marks
`with-continuation-mark`
`continuation-marks`
`current-continuation-marks`
`call-with-immediate-continuation-mark`
`continuation-mark-set->iterator`
`continuation-mark-set-first`

Dynamic Binding
`parameterize`
`make-parameter`
parameter application
`current-parameterization`

Threads (Green)
`thread`
`kill-thread`
`make-thread-group`

Thread-Local Storage
`make-thread-cell`
`thread-cell-ref`
`thread-cell-set!`
`current-preserved-thread-cell-values`

Asynchronous Exceptions
`break-thread`
`break-enabled`
`current-break-parameterization`
`call-with-break-parameterization`

Synchronization
`sync`
`make-channel`
`channel-put-evt`
`channel-get-evt`
`make-semaphore`
`semaphore-post`

Custodians
`make-custodian`
`custodian-shutdown-all`

Futures
`future`
`touch`

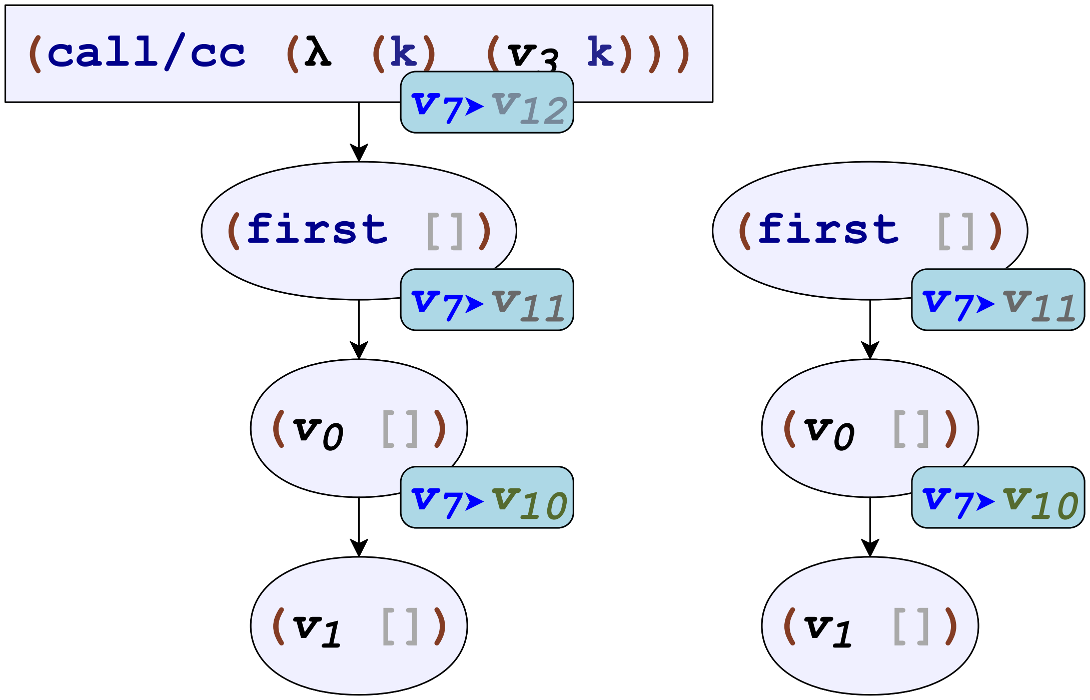
Continuations
function [tail] calls
`call/cc`
`call-in-continuation`
`null-continuation`

Continuation Marks
`current-continuation-attachments`
`continuation-next-attachments`
`call-getting-continuation-attachment`
`call-setting-continuation-attachment`
`call-consuming-continuation-attachment`

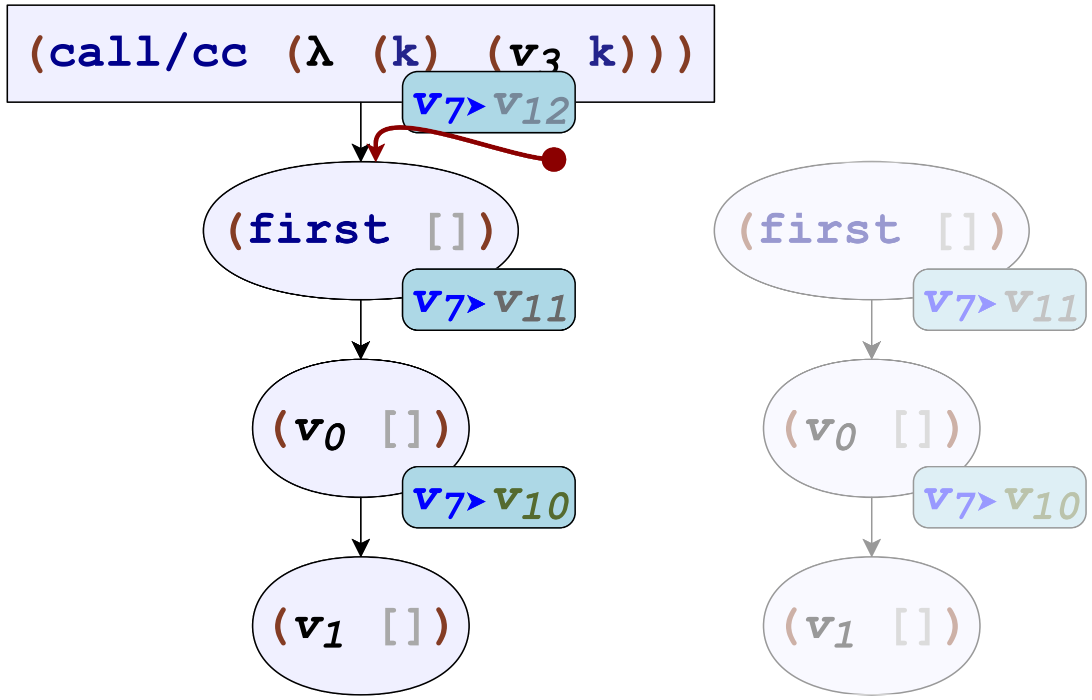
Exceptions
`raise`
`base-exception-handler`

Signals
`start-timer`
`timer-interrupt-handler`

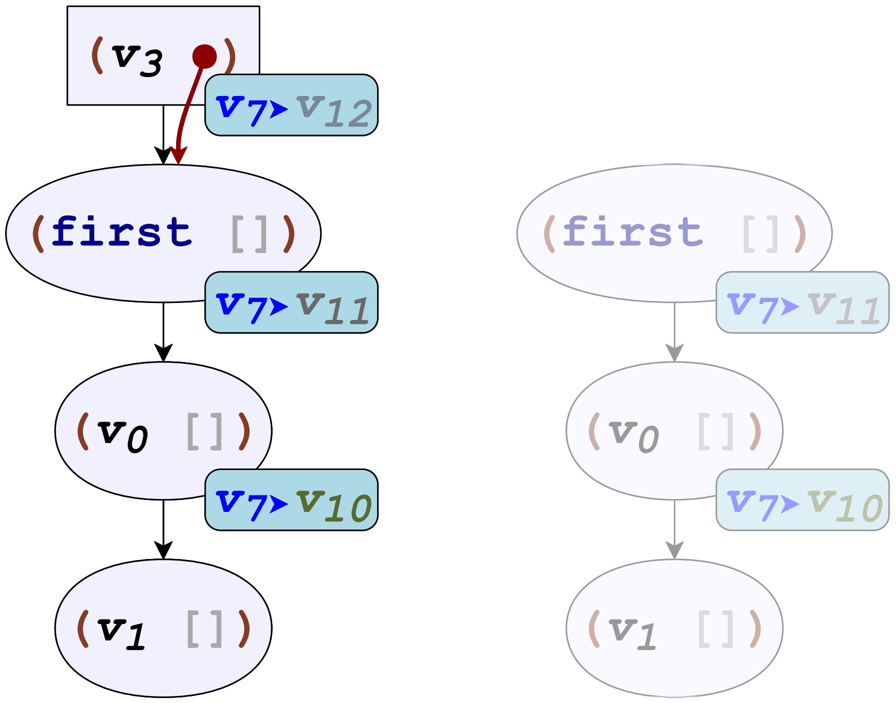
Heap-Allocated Frames



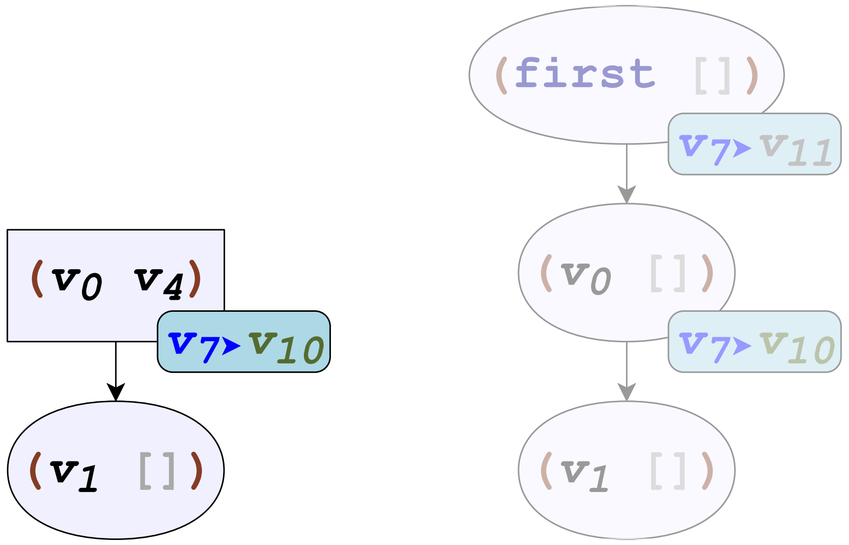
Heap-Allocated Frames



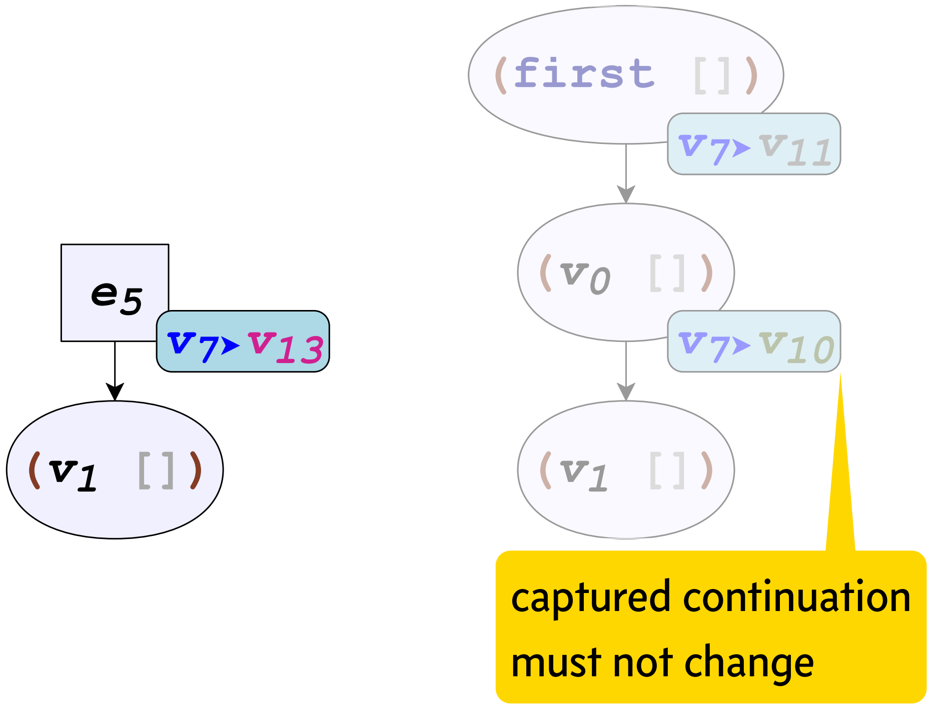
Heap-Allocated Frames



Heap-Allocated Frames

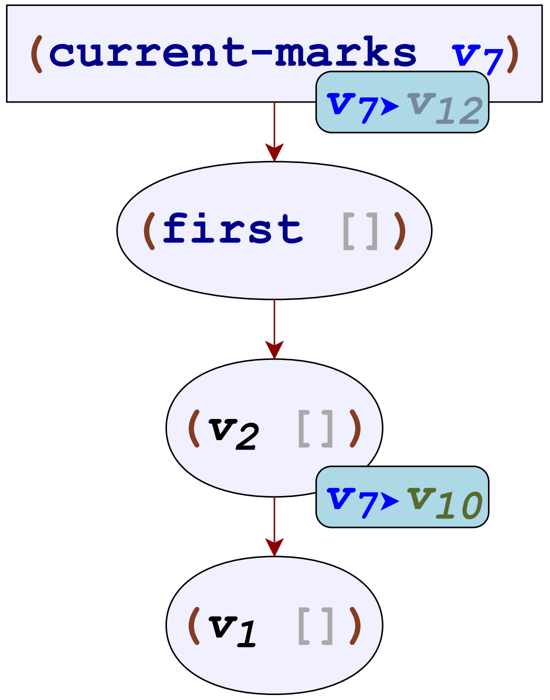


Heap-Allocated Frames

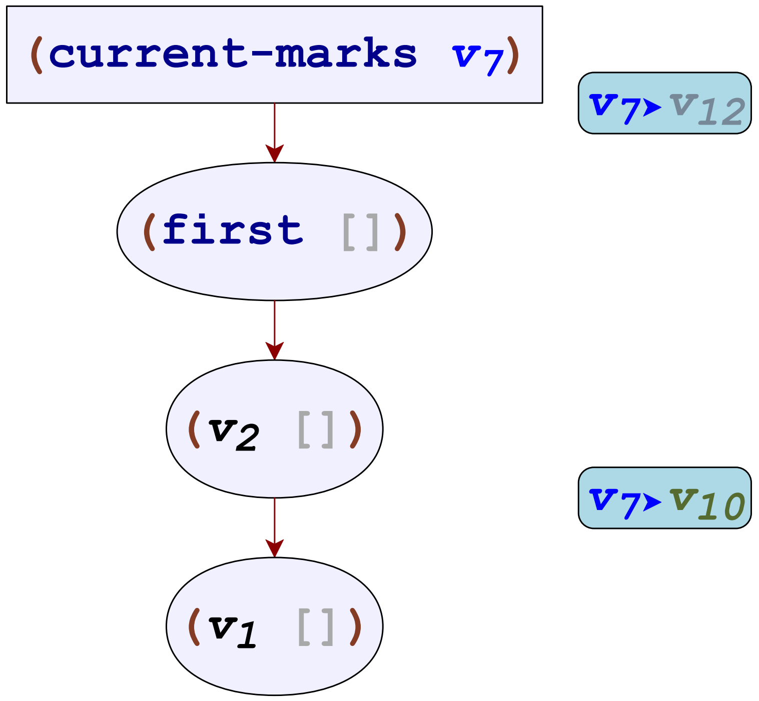


e_5
$v_7 \blacktriangleright v_{13}$
(v1 [])
(first [])
$v_7 \blacktriangleright v_{11}$
(v0 [])
$v_7 \blacktriangleright v_{10}$
(v1 [])
captured continuation must not change

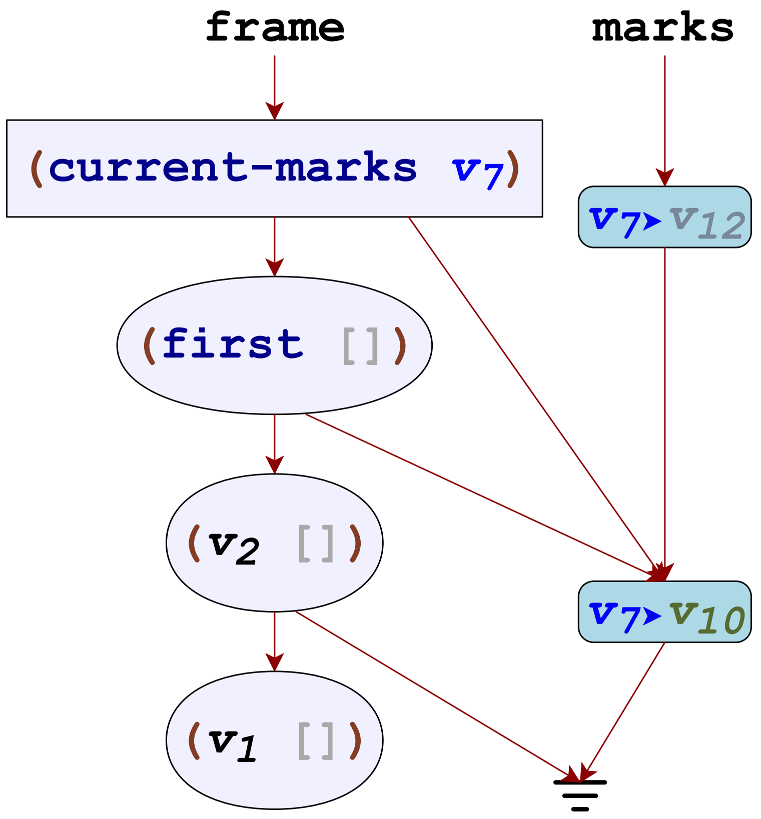
Functional Heap-Allocated Frames



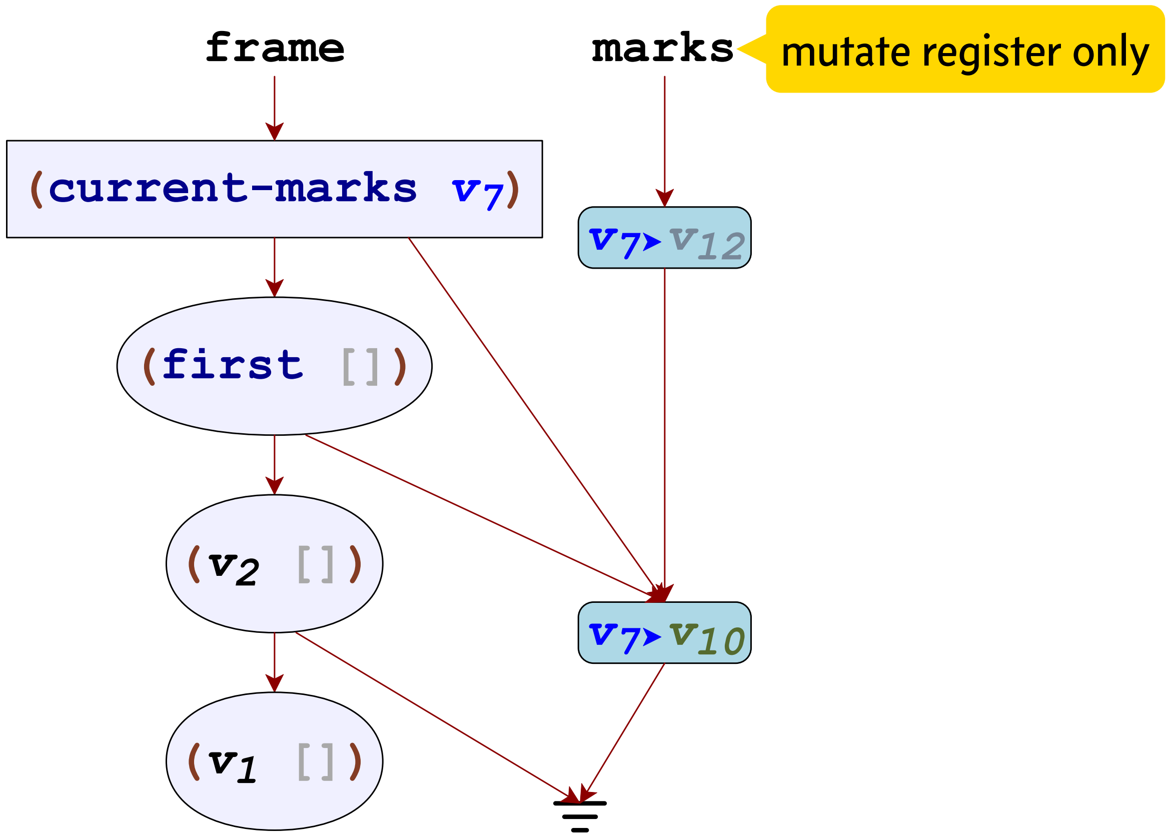
Functional Heap-Allocated Frames



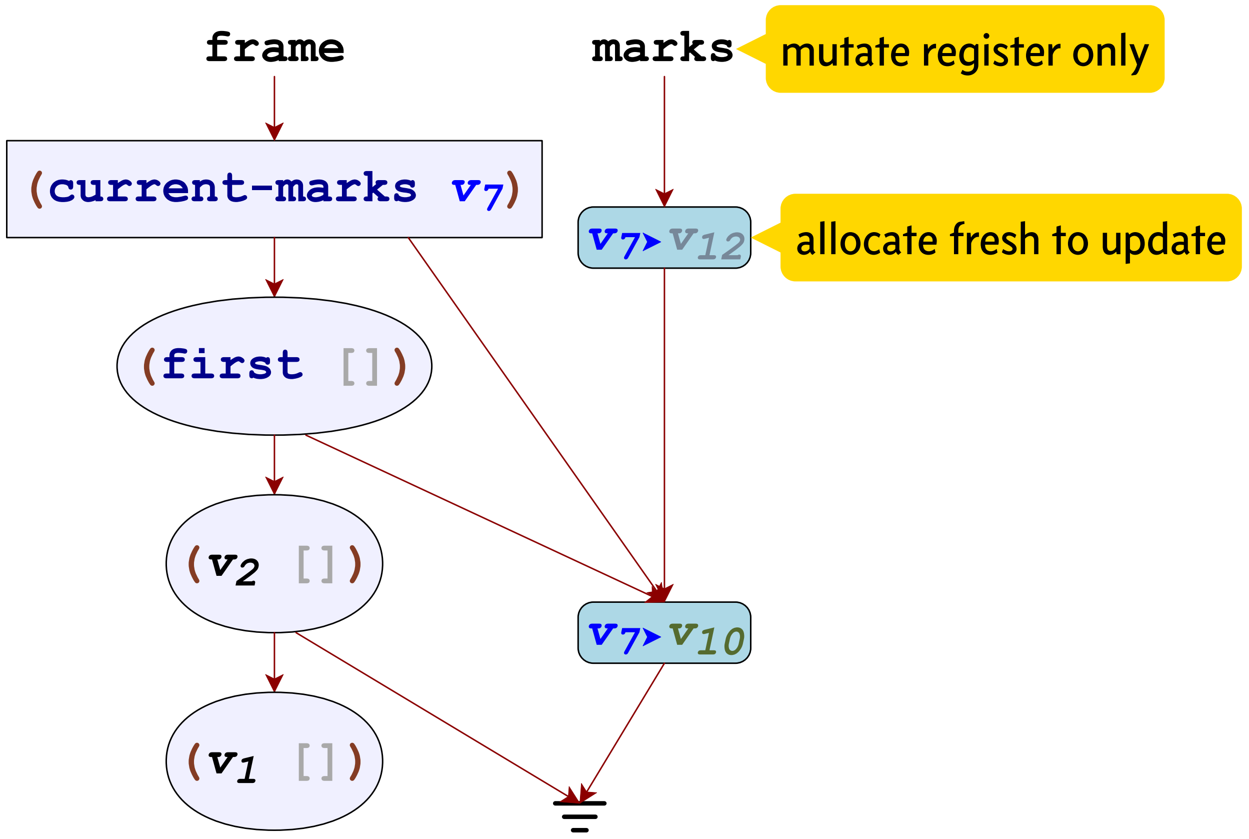
Functional Heap-Allocated Frames



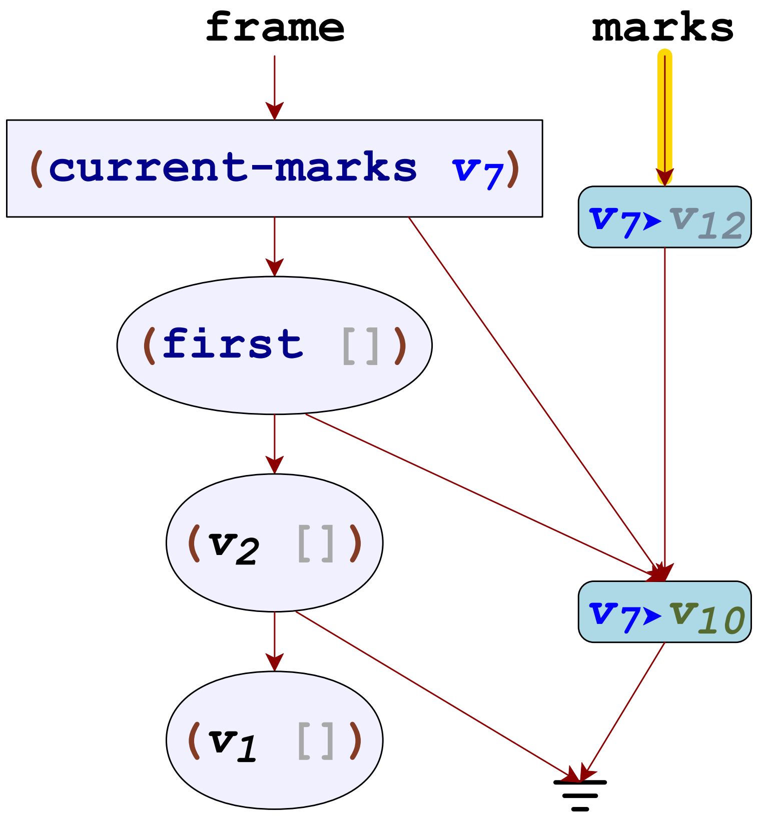
Functional Heap-Allocated Frames



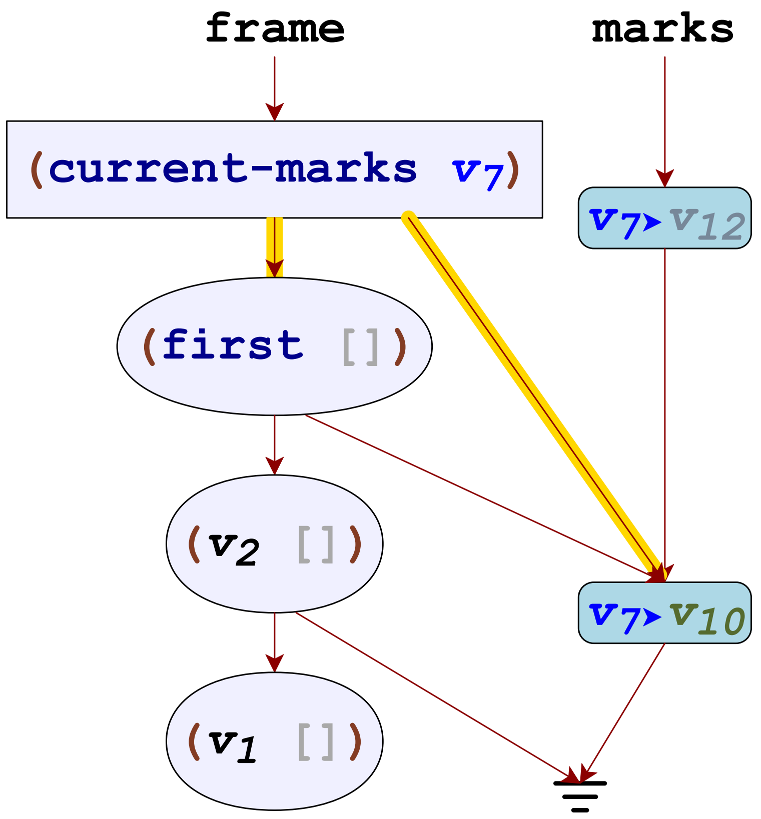
Functional Heap-Allocated Frames



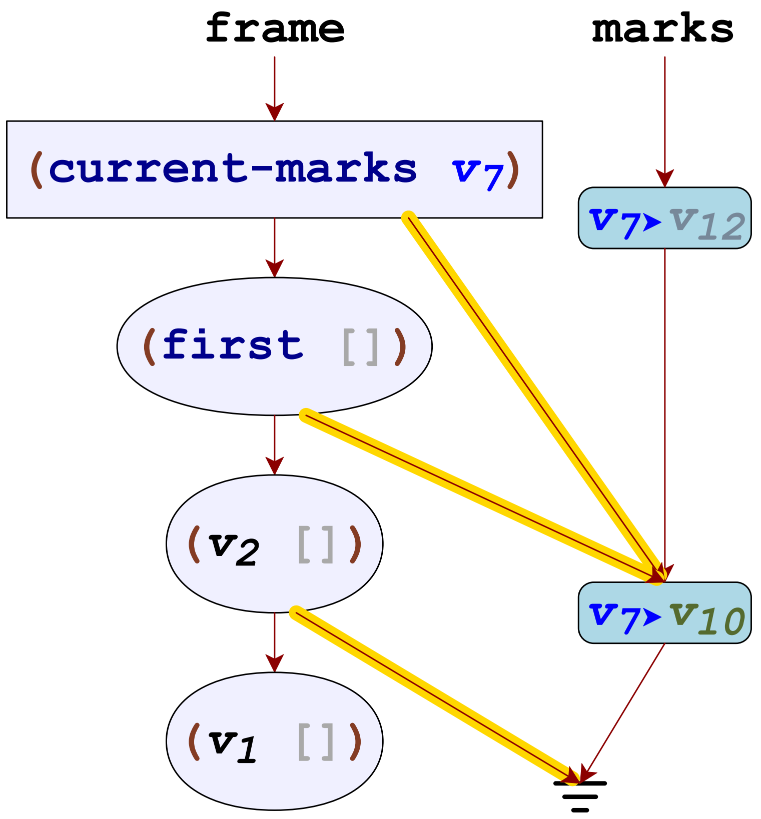
Functional Heap-Allocated Frames



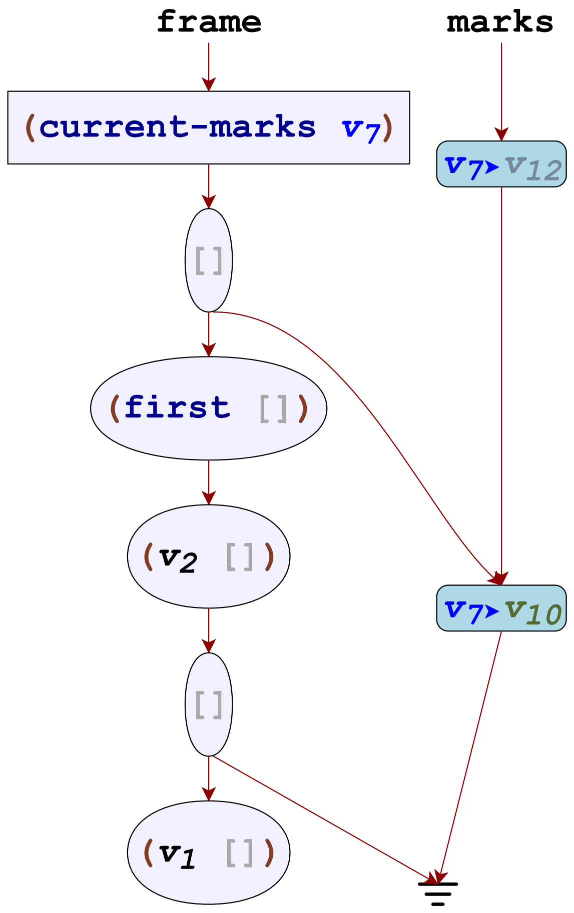
Functional Heap-Allocated Frames



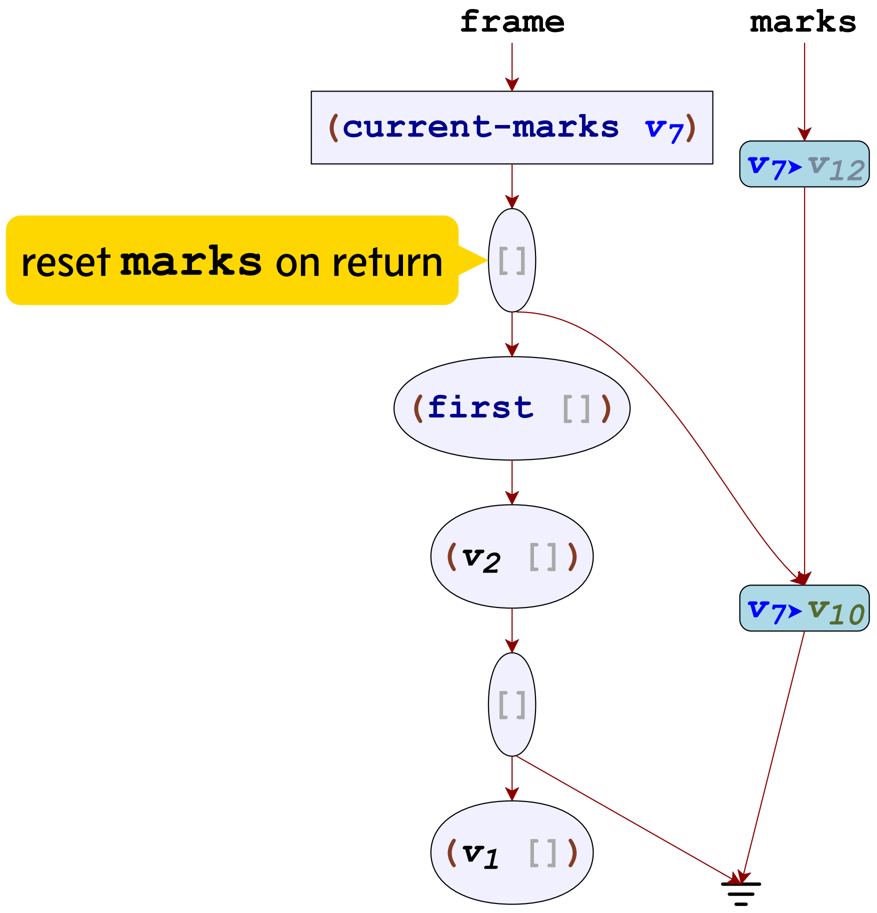
Functional Heap-Allocated Frames



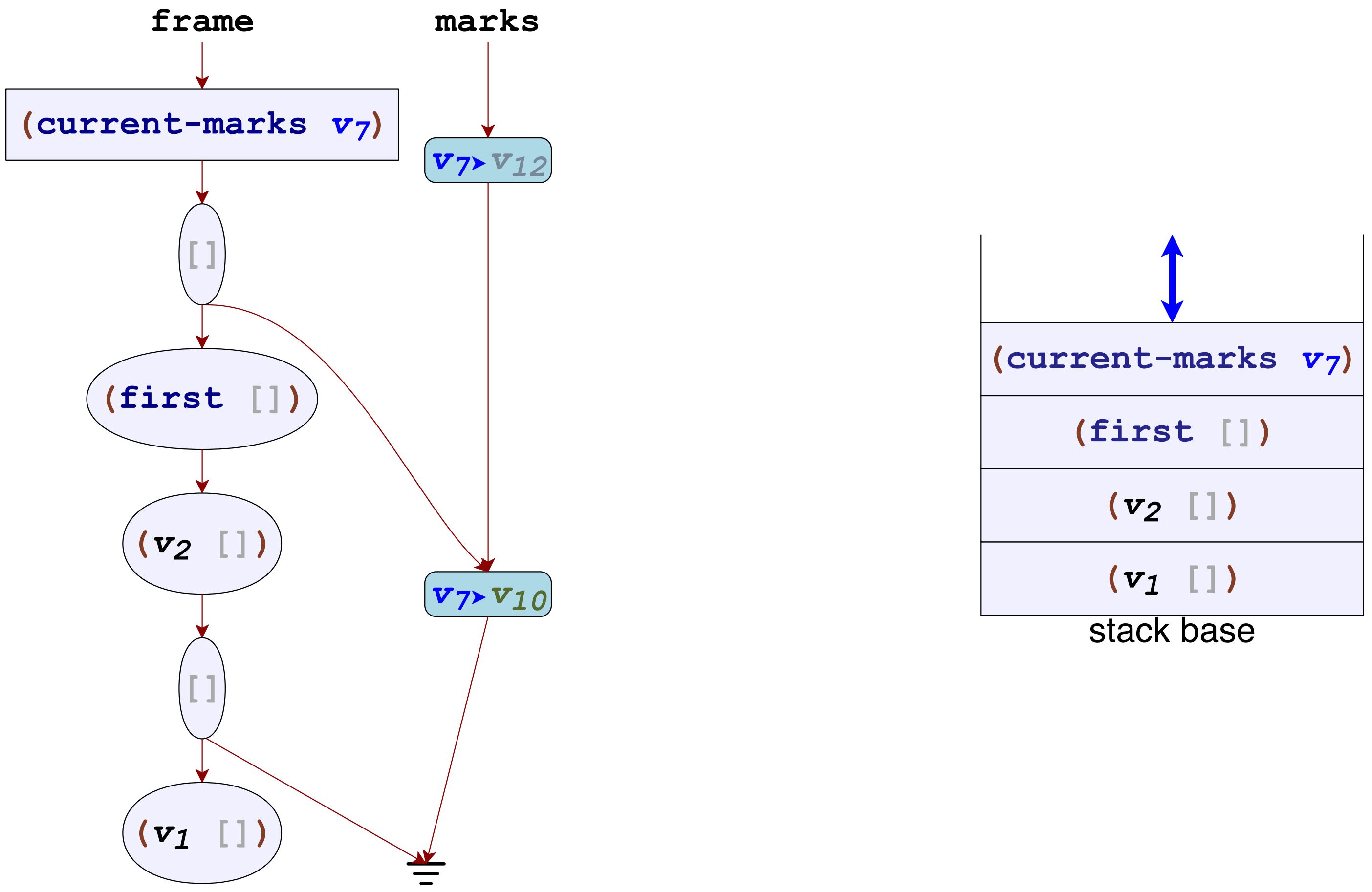
Functional Heap-Allocated Frames



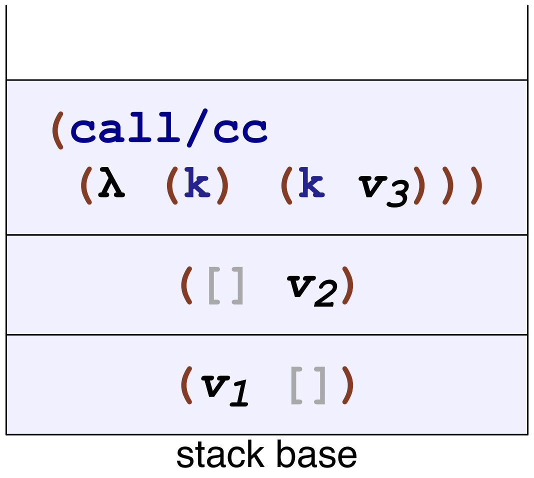
Functional Heap-Allocated Frames



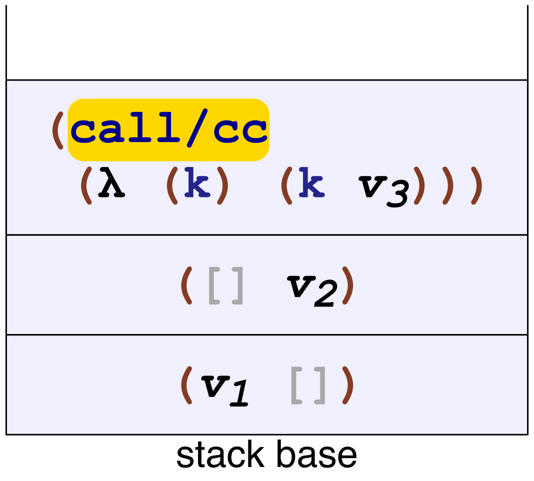
Heap versus Stack



Stack-Allocated Frames



Capturing Stack-Based Continuations



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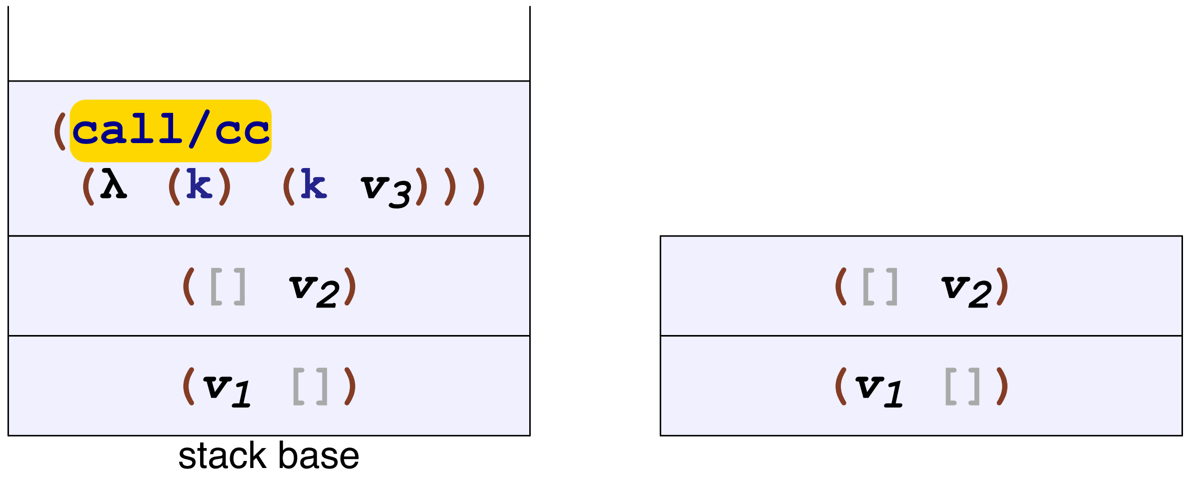

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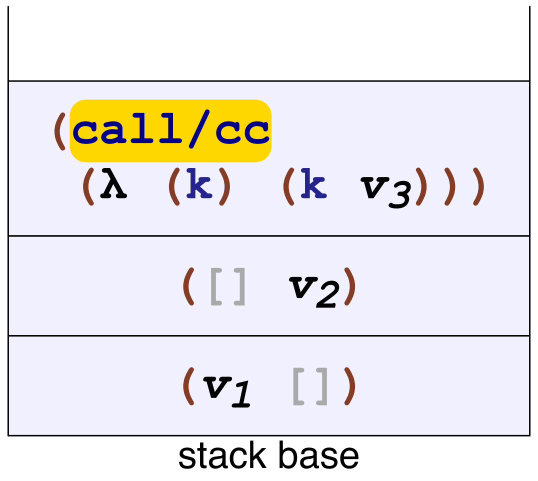
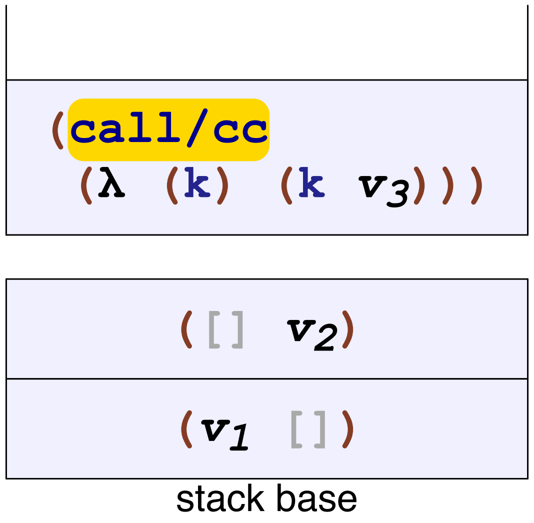


Capturing Stack-Based Continuations



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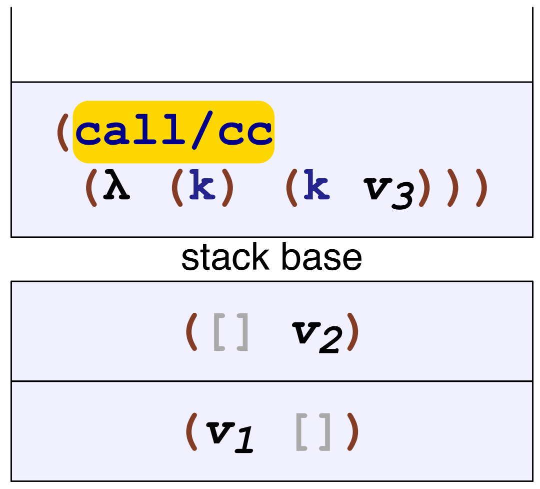

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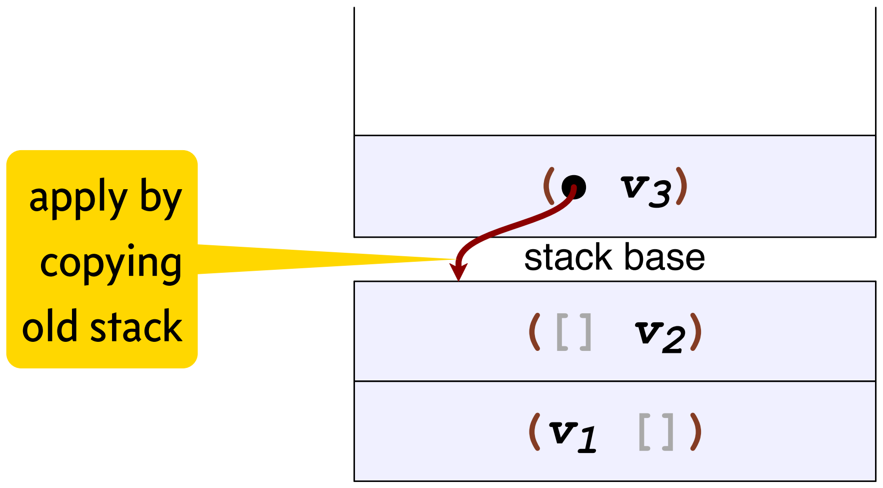

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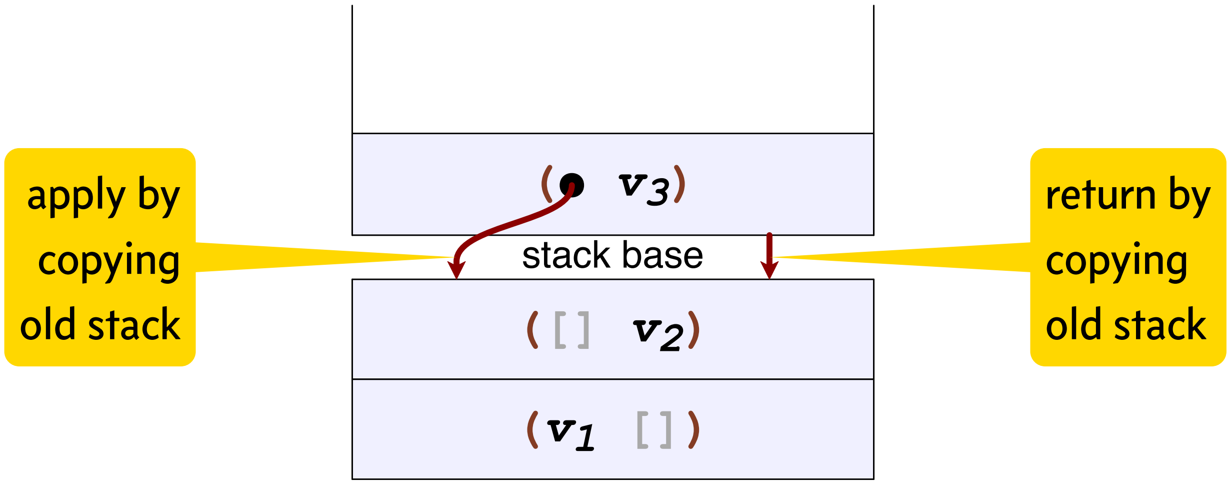
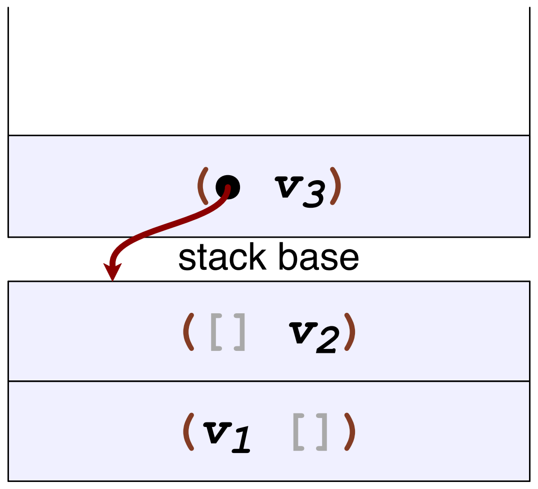
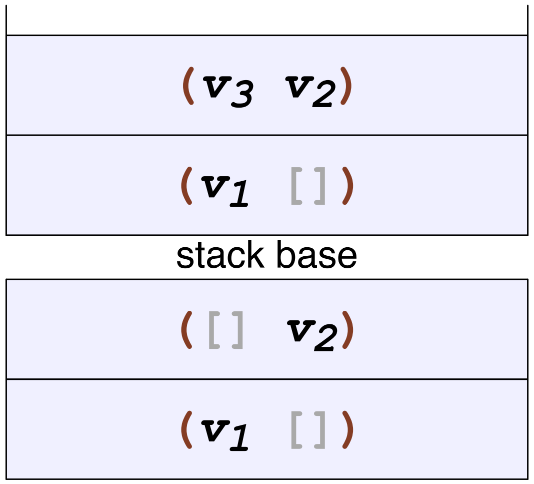


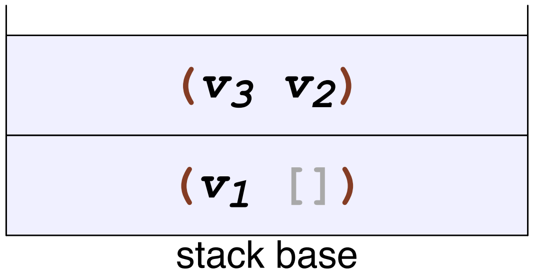
Applying Stack-Based Continuations



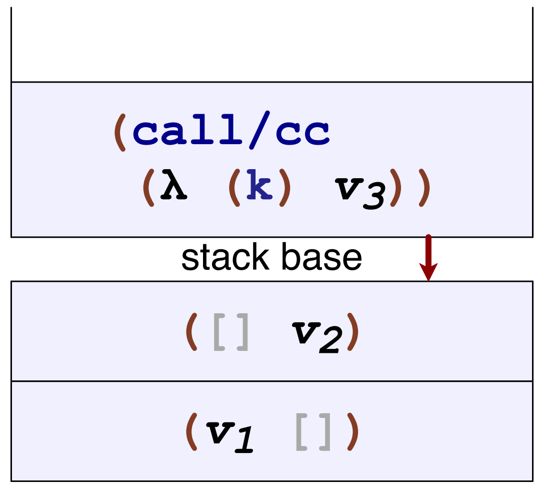
Applying Stack-Based Continuations



Applying Stack-Based Continuations



Returning After Capture



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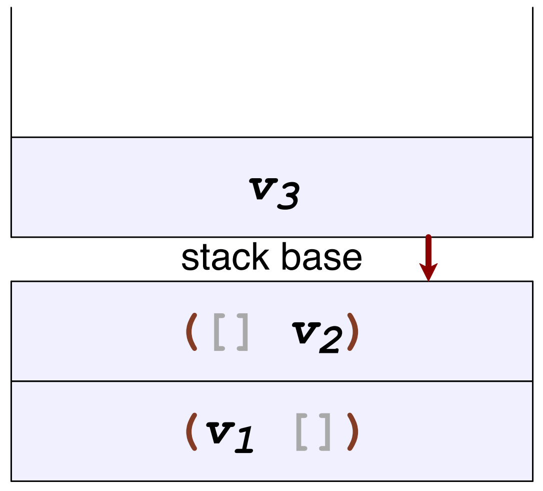

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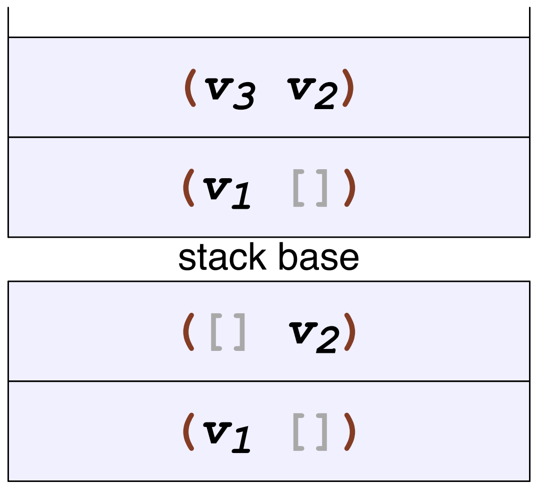
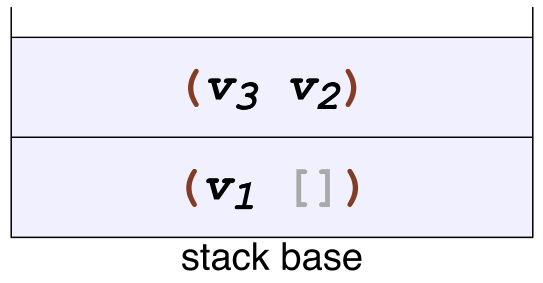
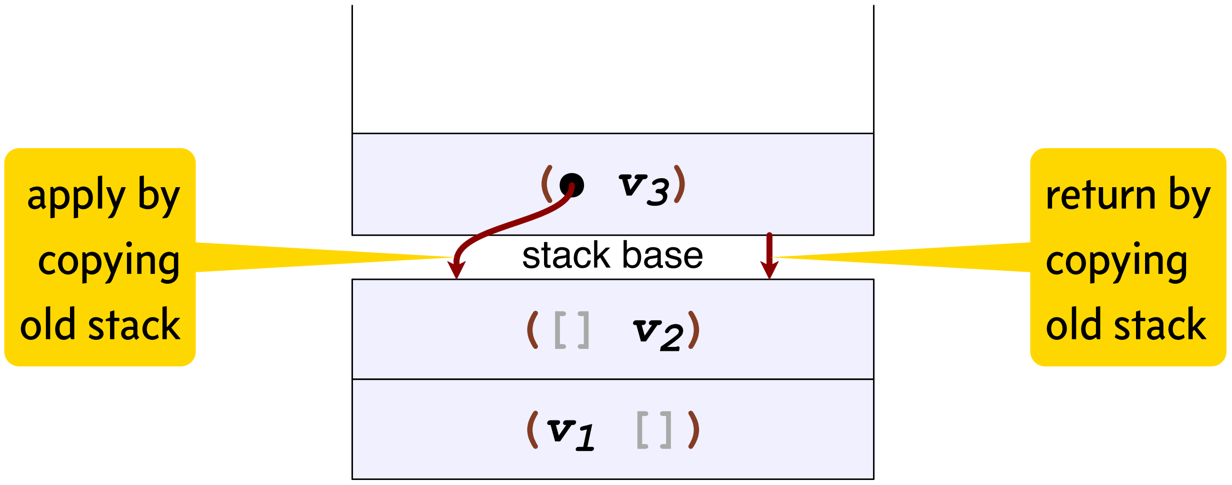


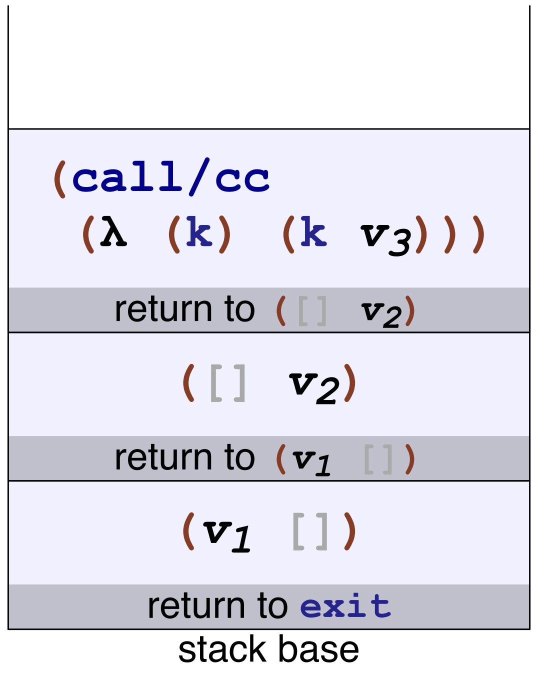
Returning After Capture



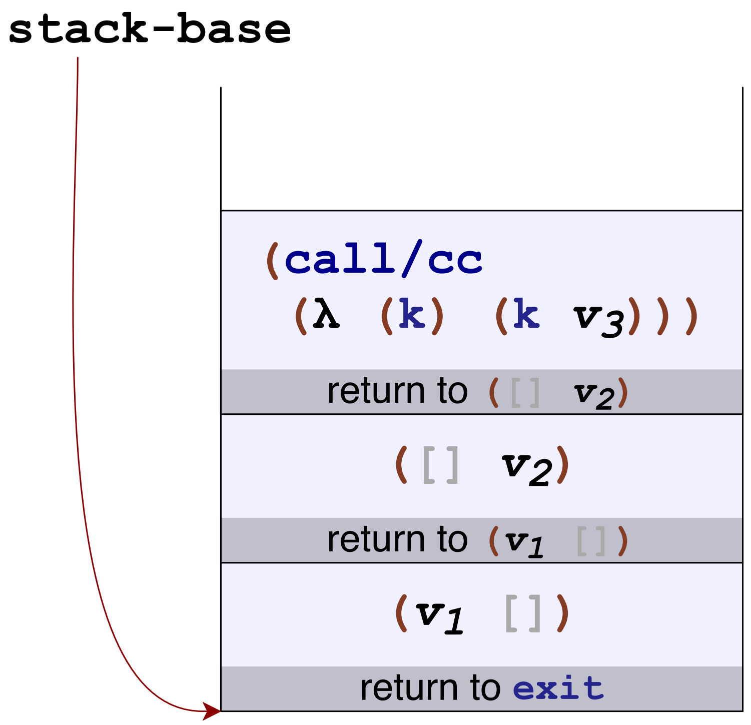
Two Kinds of Continuation Pointers



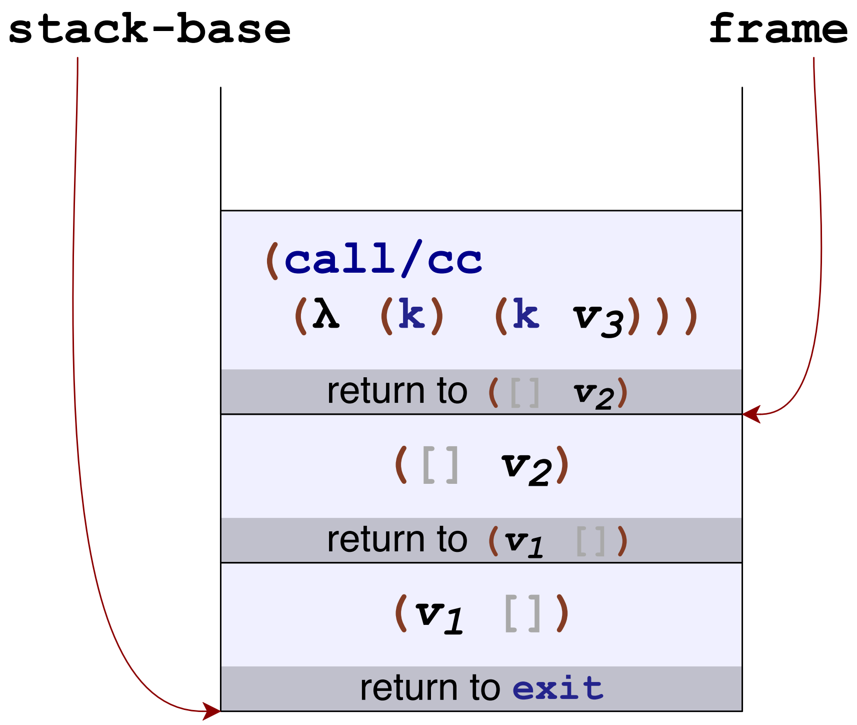
Returns in Stack Frames



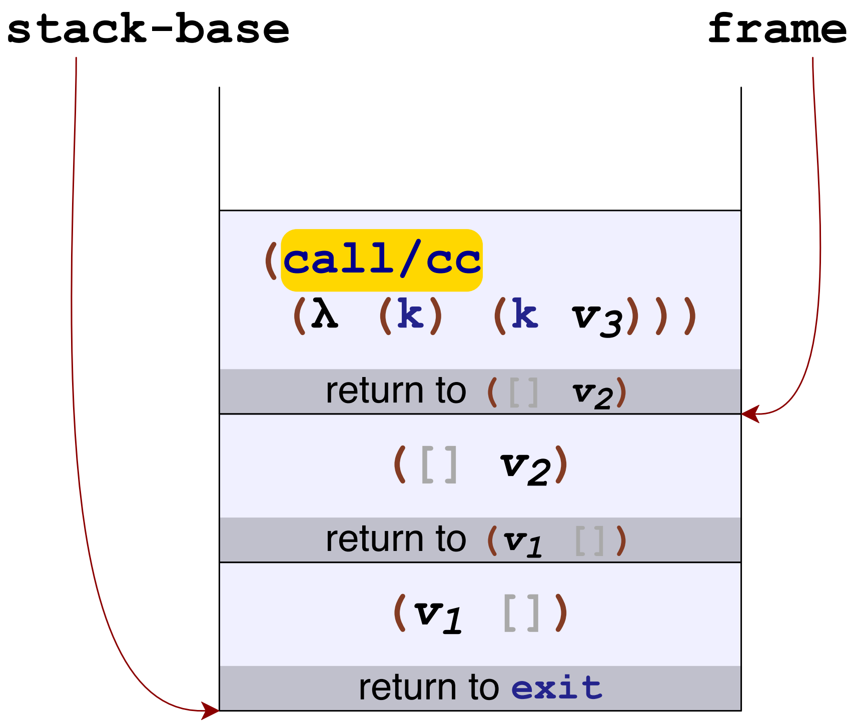
Returns in Stack Frames



Returns in Stack Frames



Capturing Stack-Based Continuations



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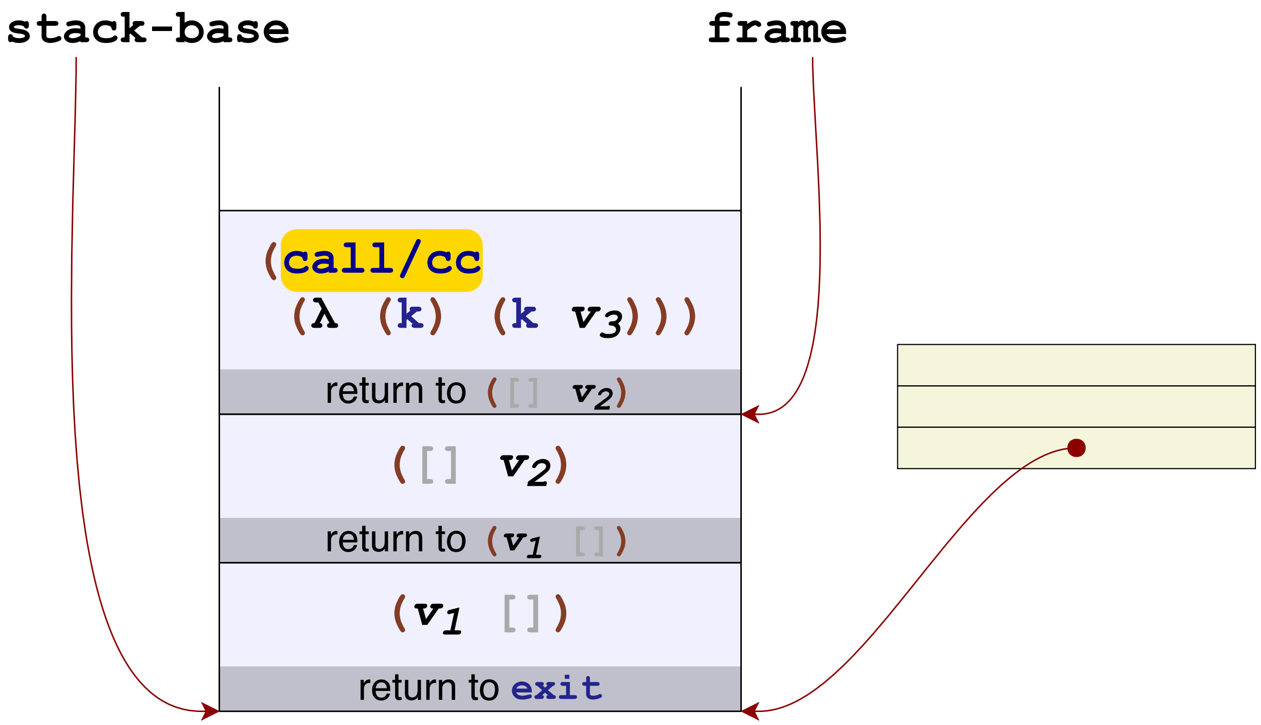

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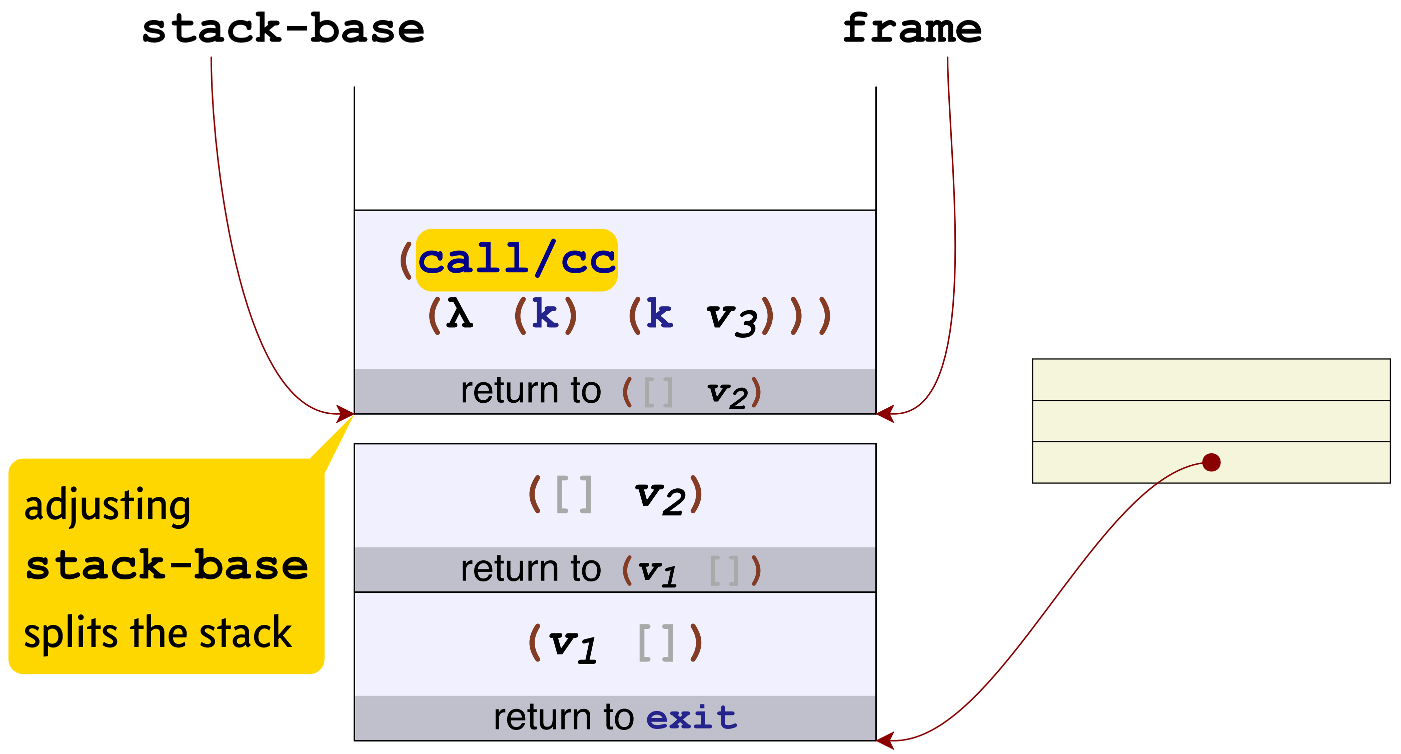

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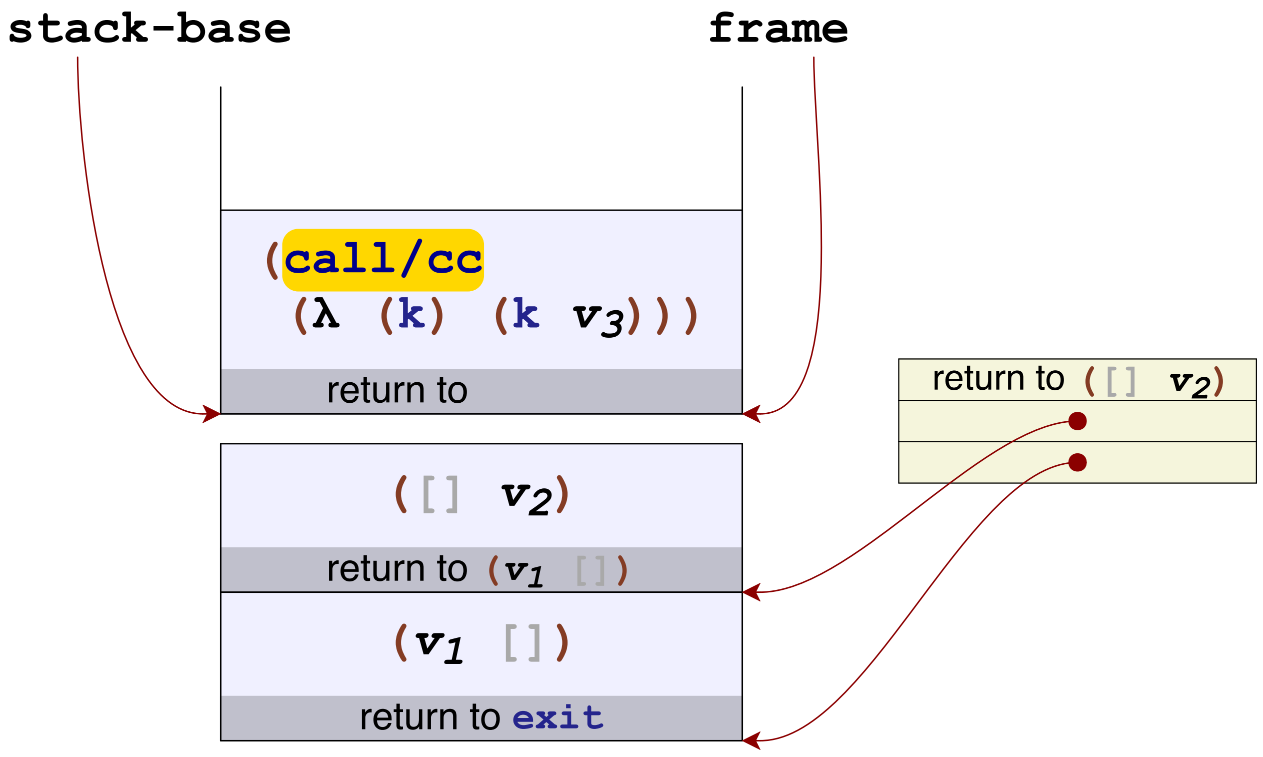
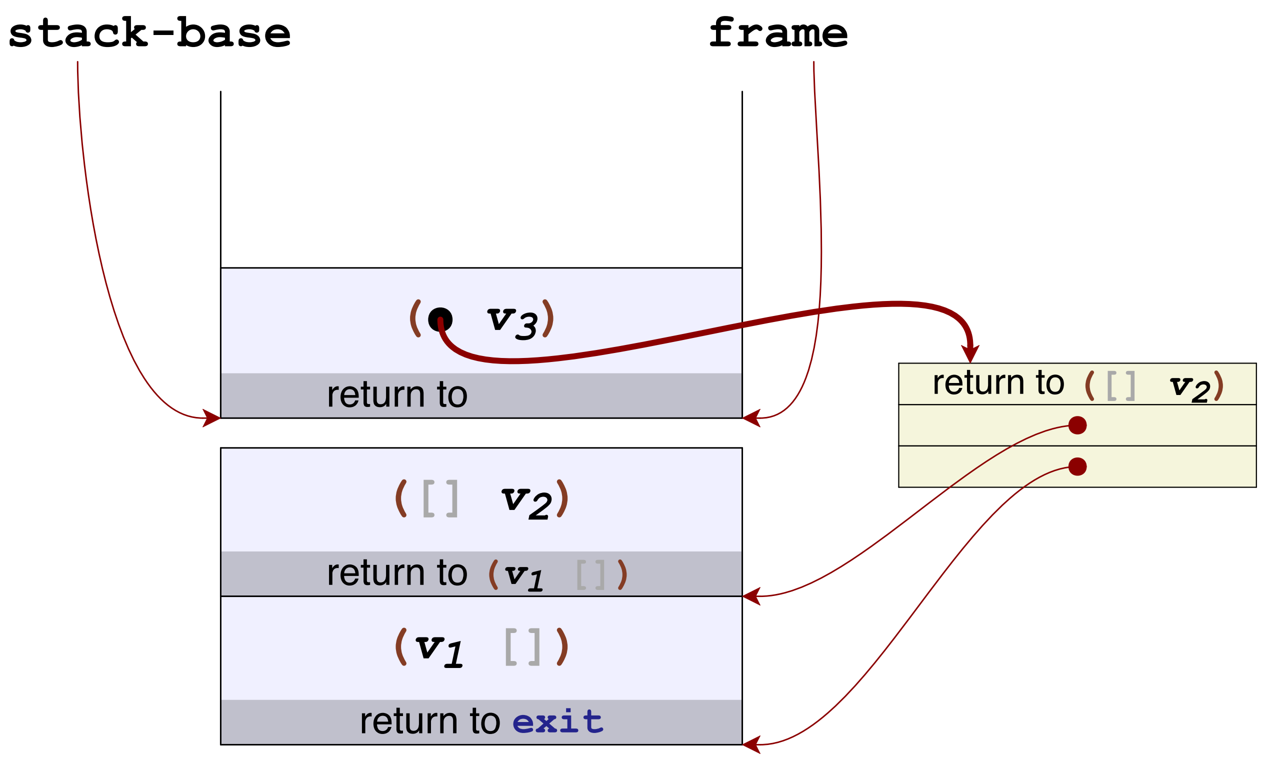
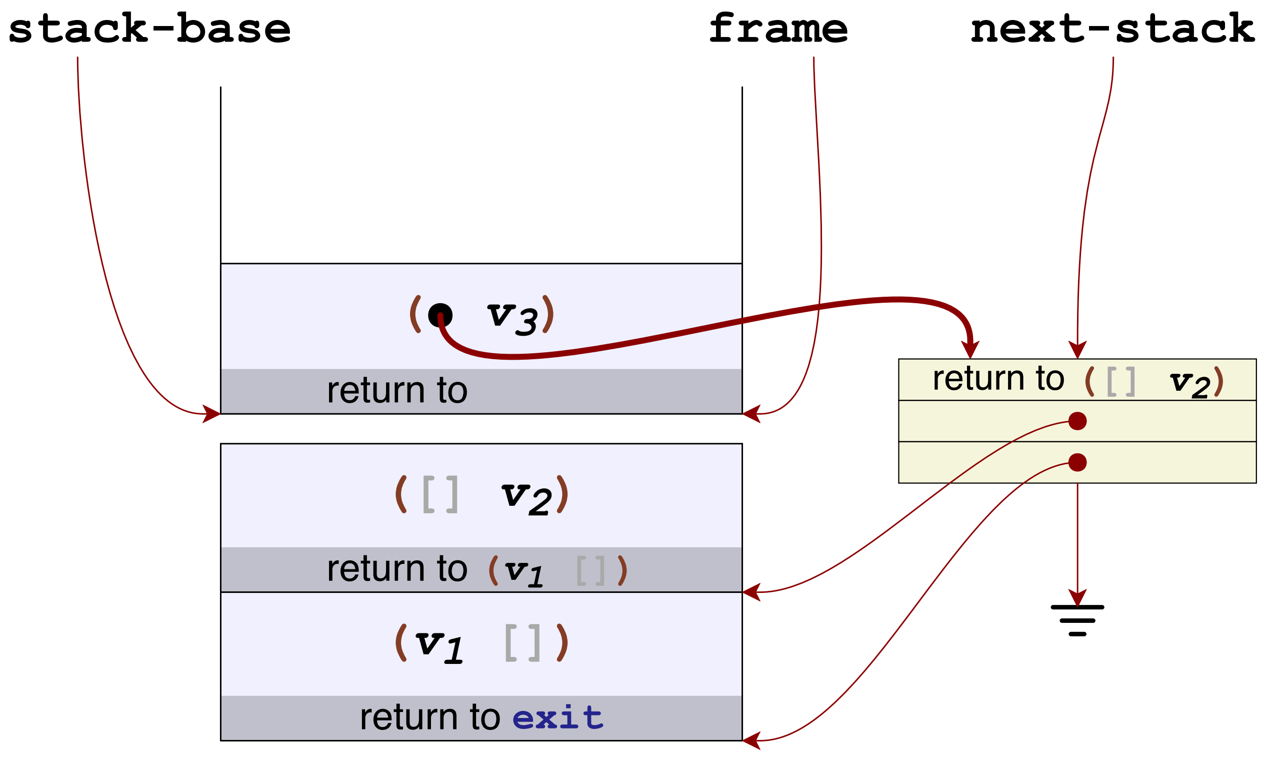


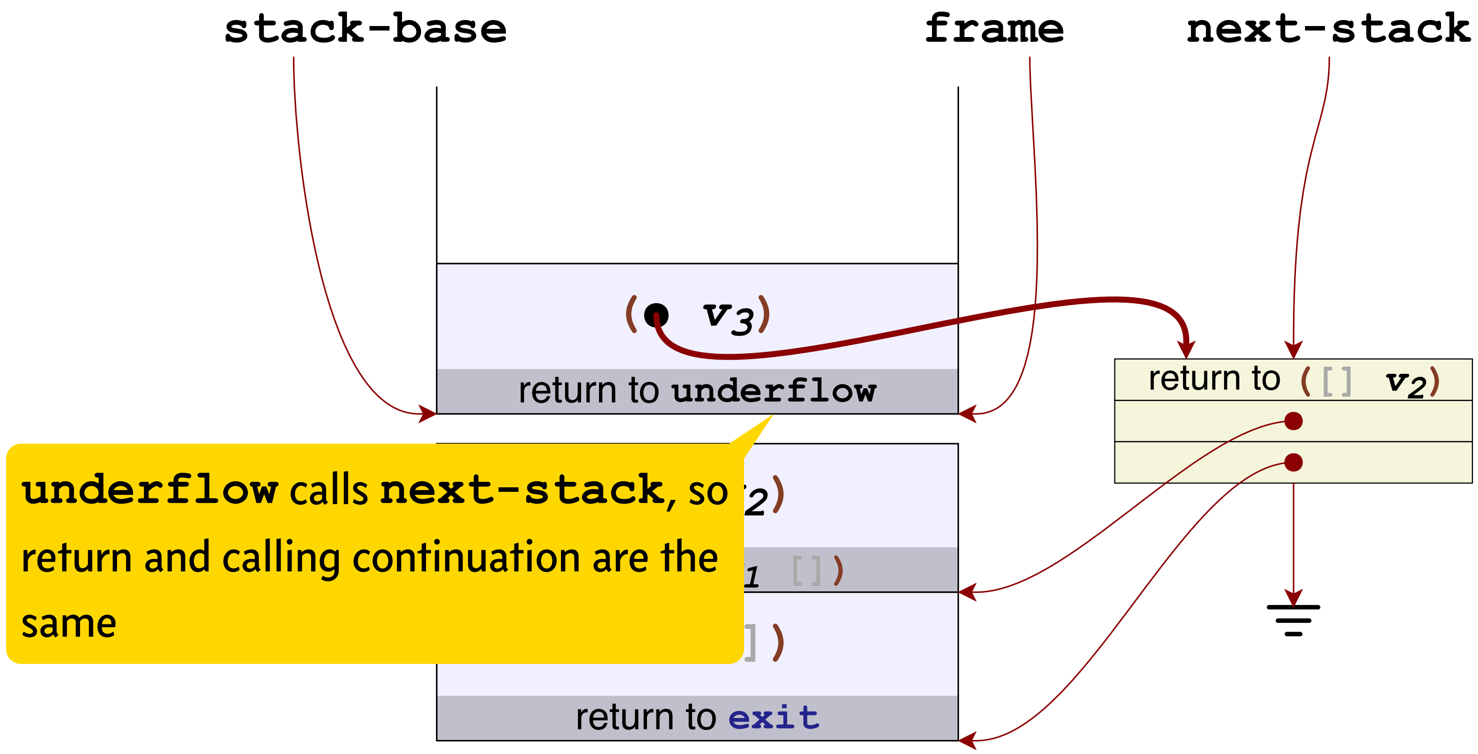
Capturing Stack-Based Continuations



Capturing Stack-Based Continuations

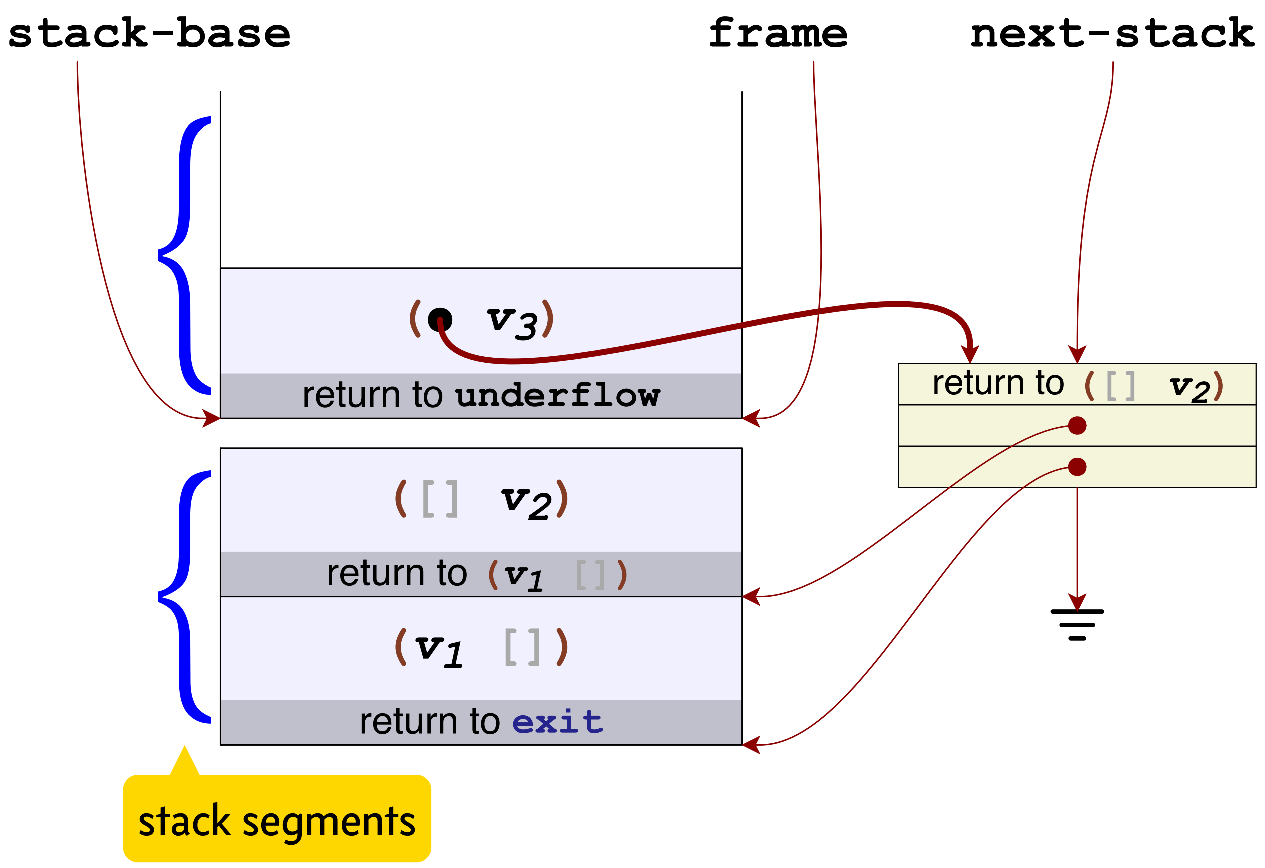


Capturing Stack-Based Continuations



underflow calls **next-stack**, so return and calling continuation are the same

Hybrid Stack–Heap Continuation



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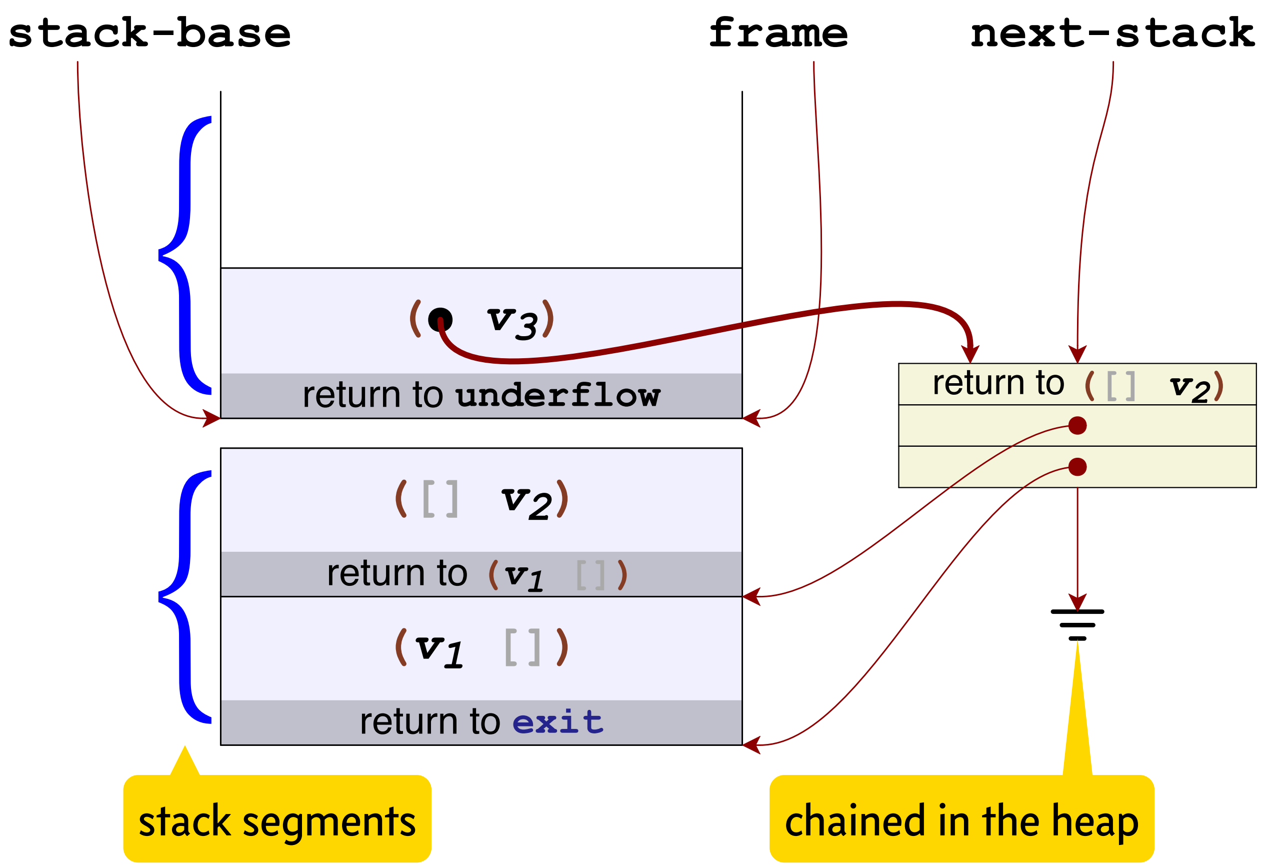
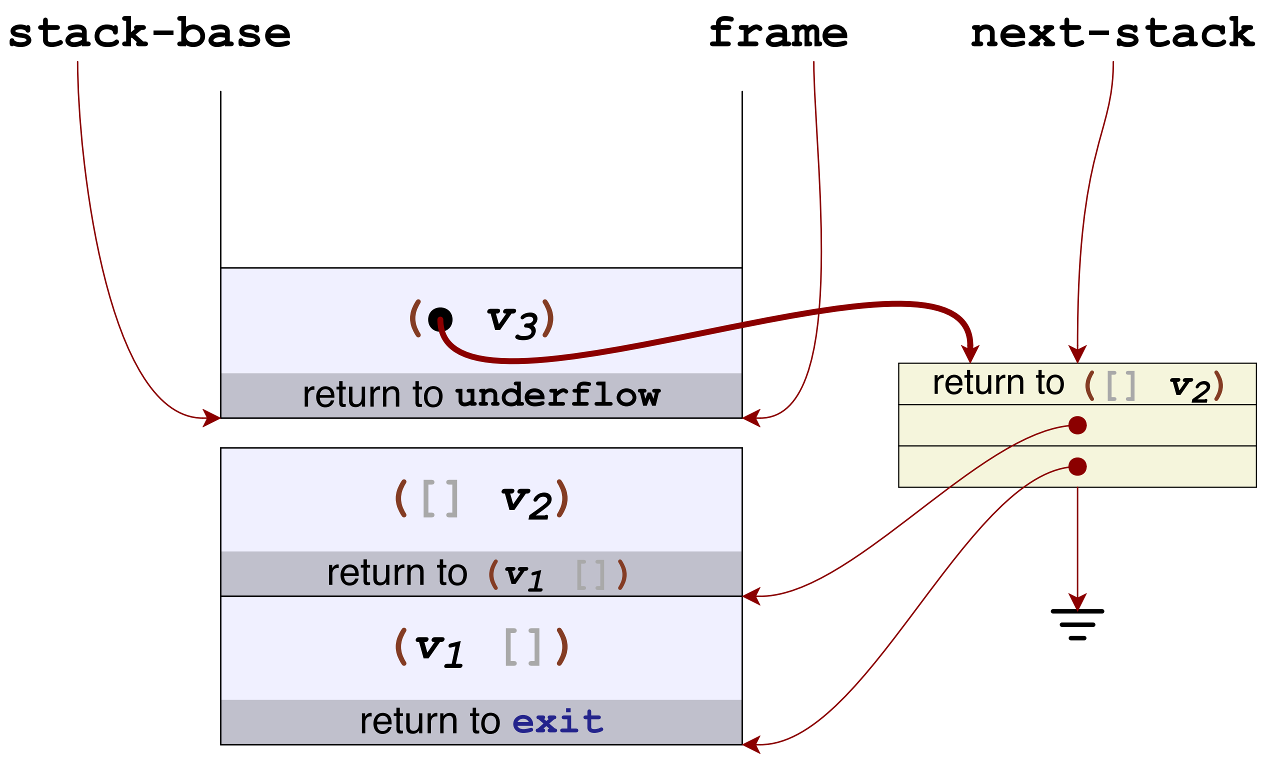


Applying Stack-Based Continuations



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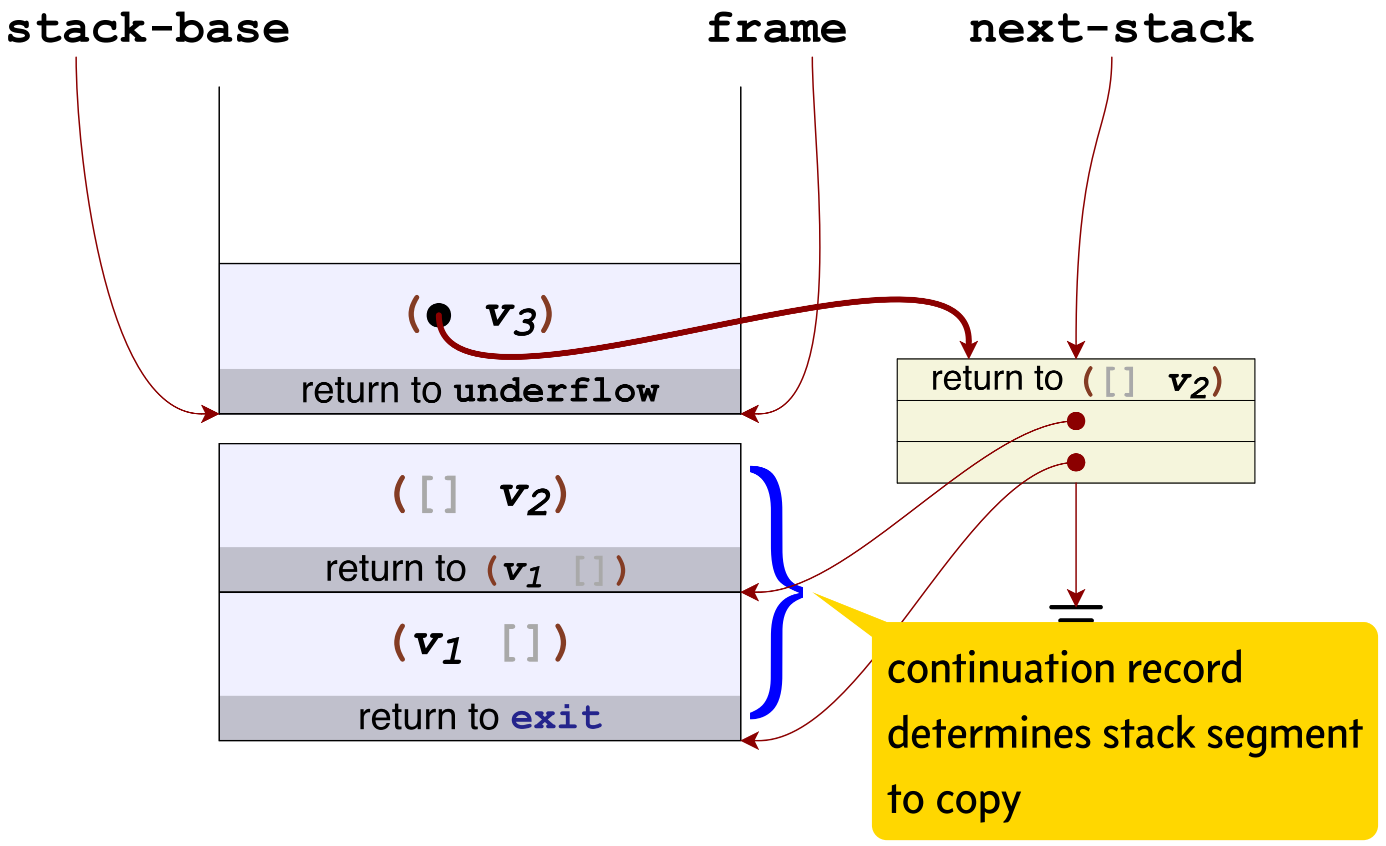
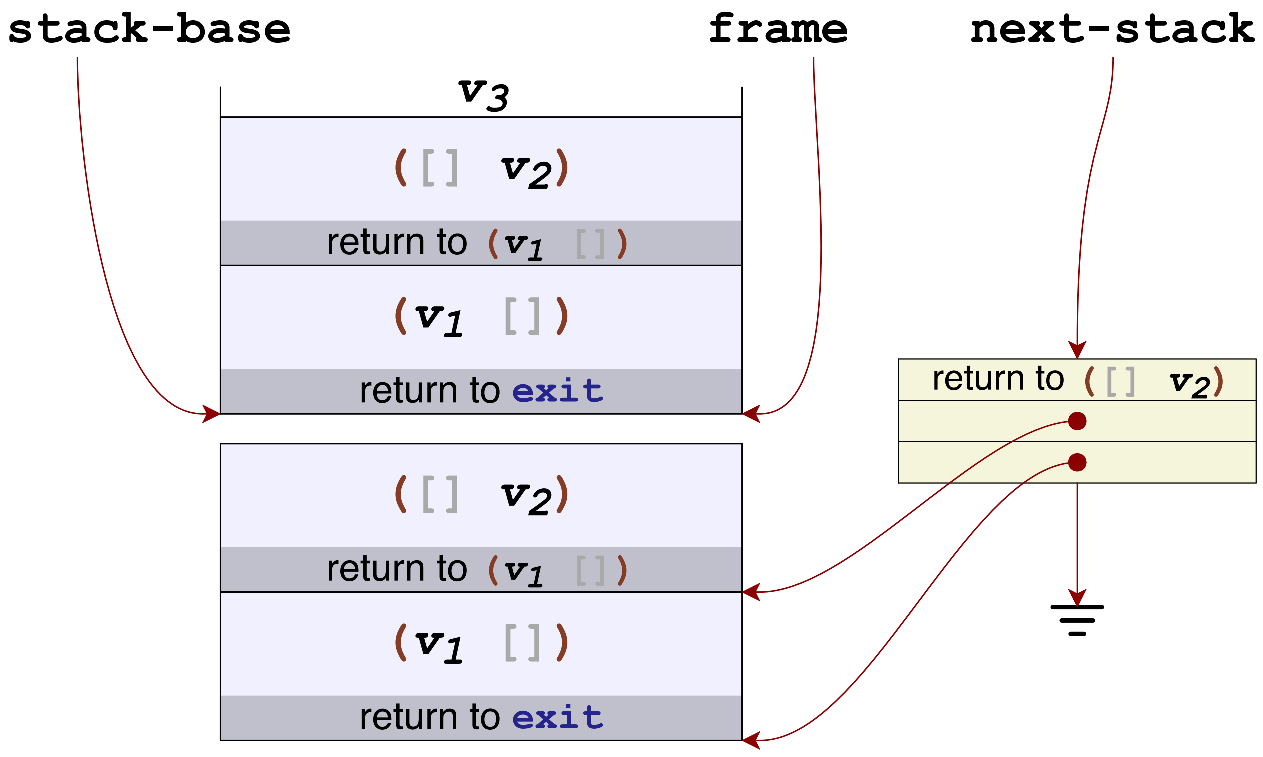


Applying Stack-Based Continuations



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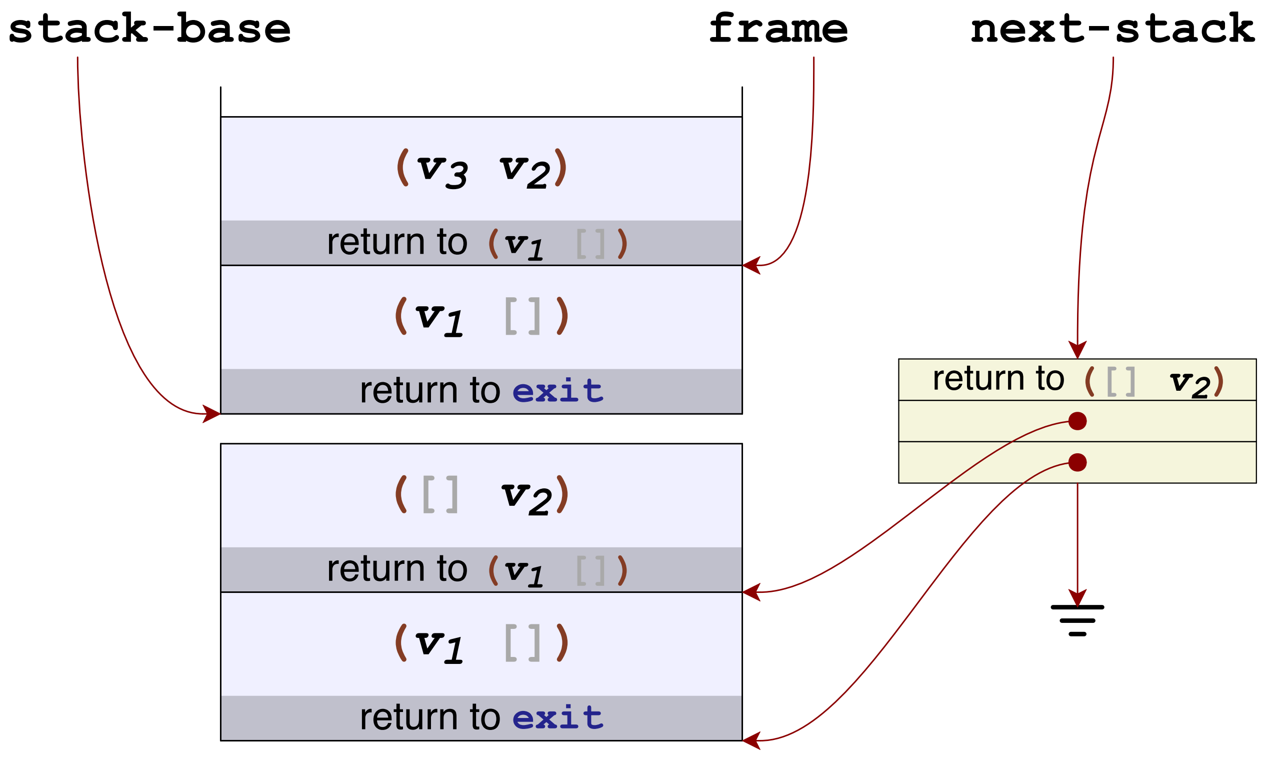

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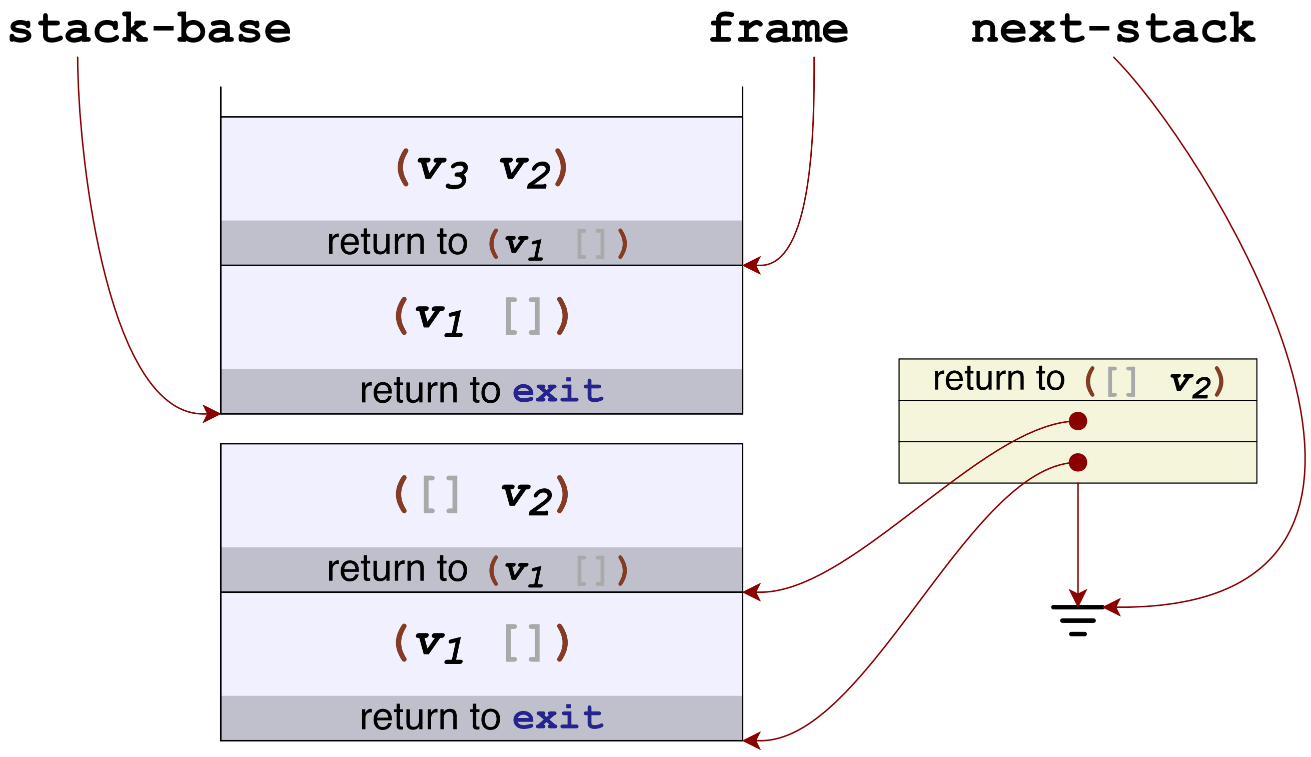
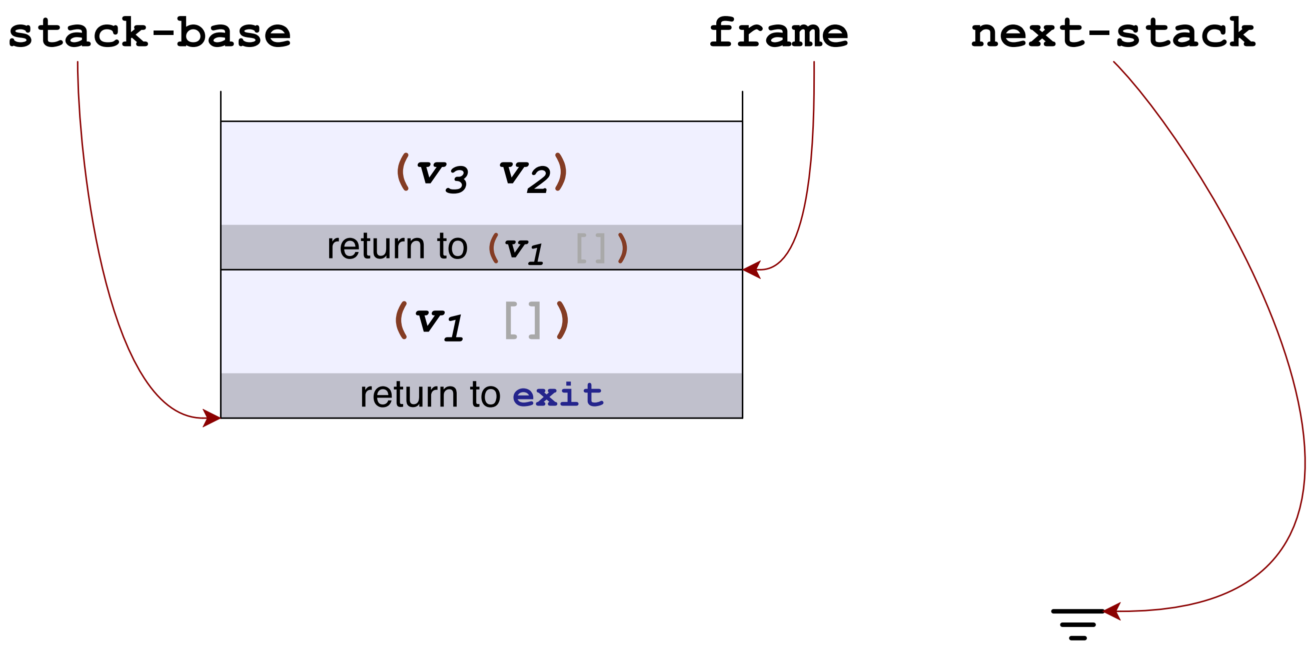
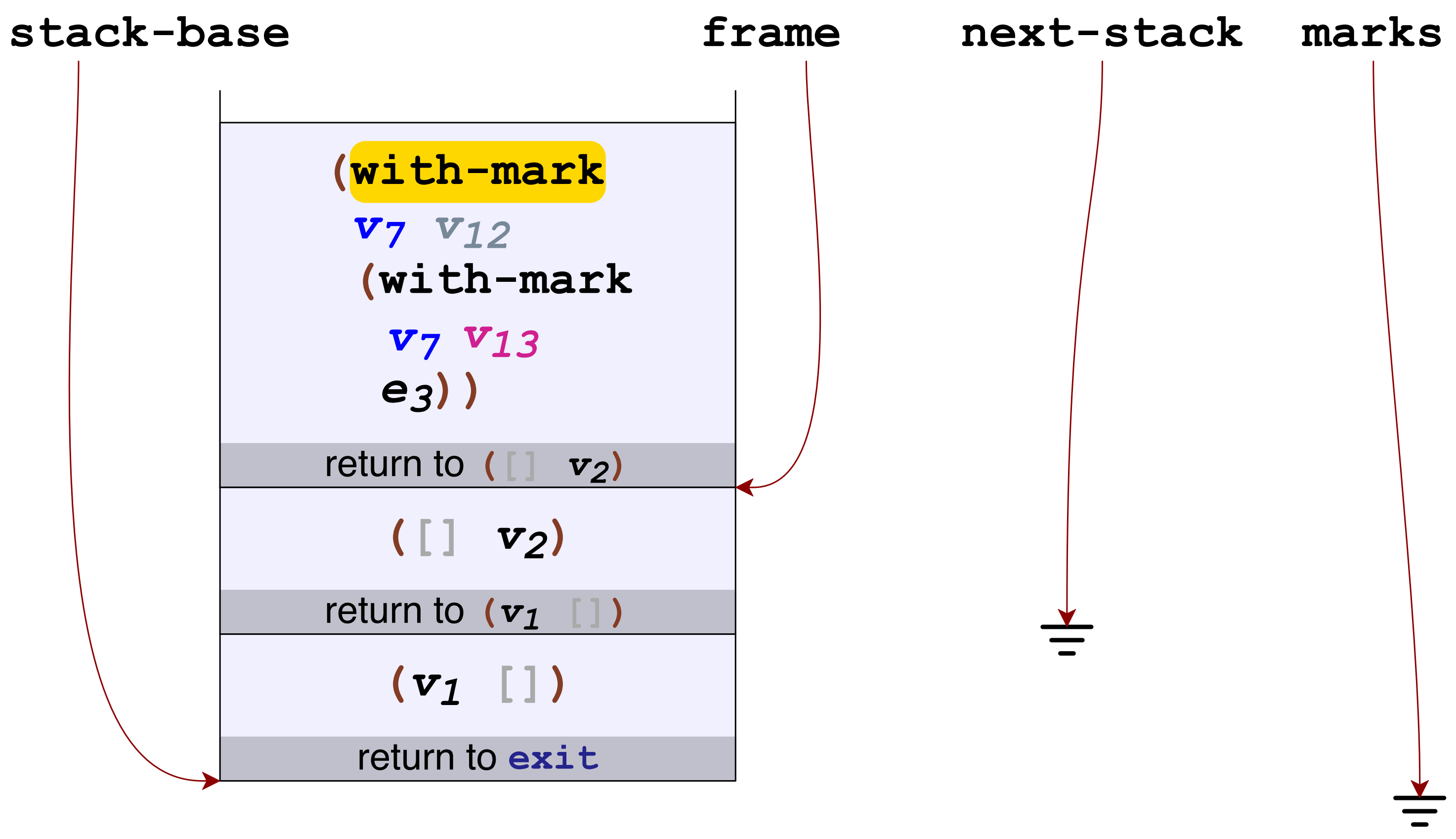


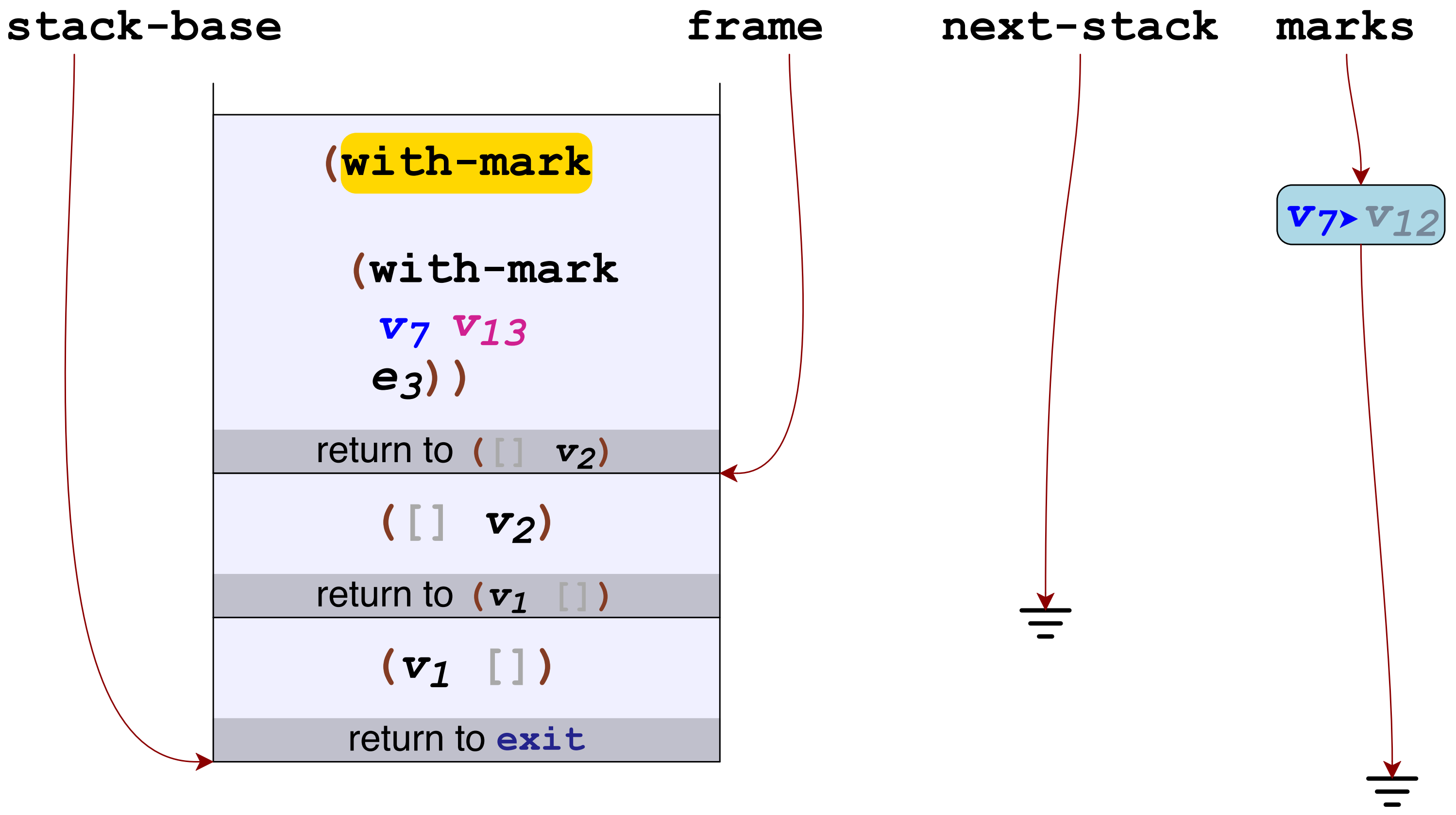
Applying Stack-Based Continuations



Setting Continuation Marks



Setting Continuation Marks



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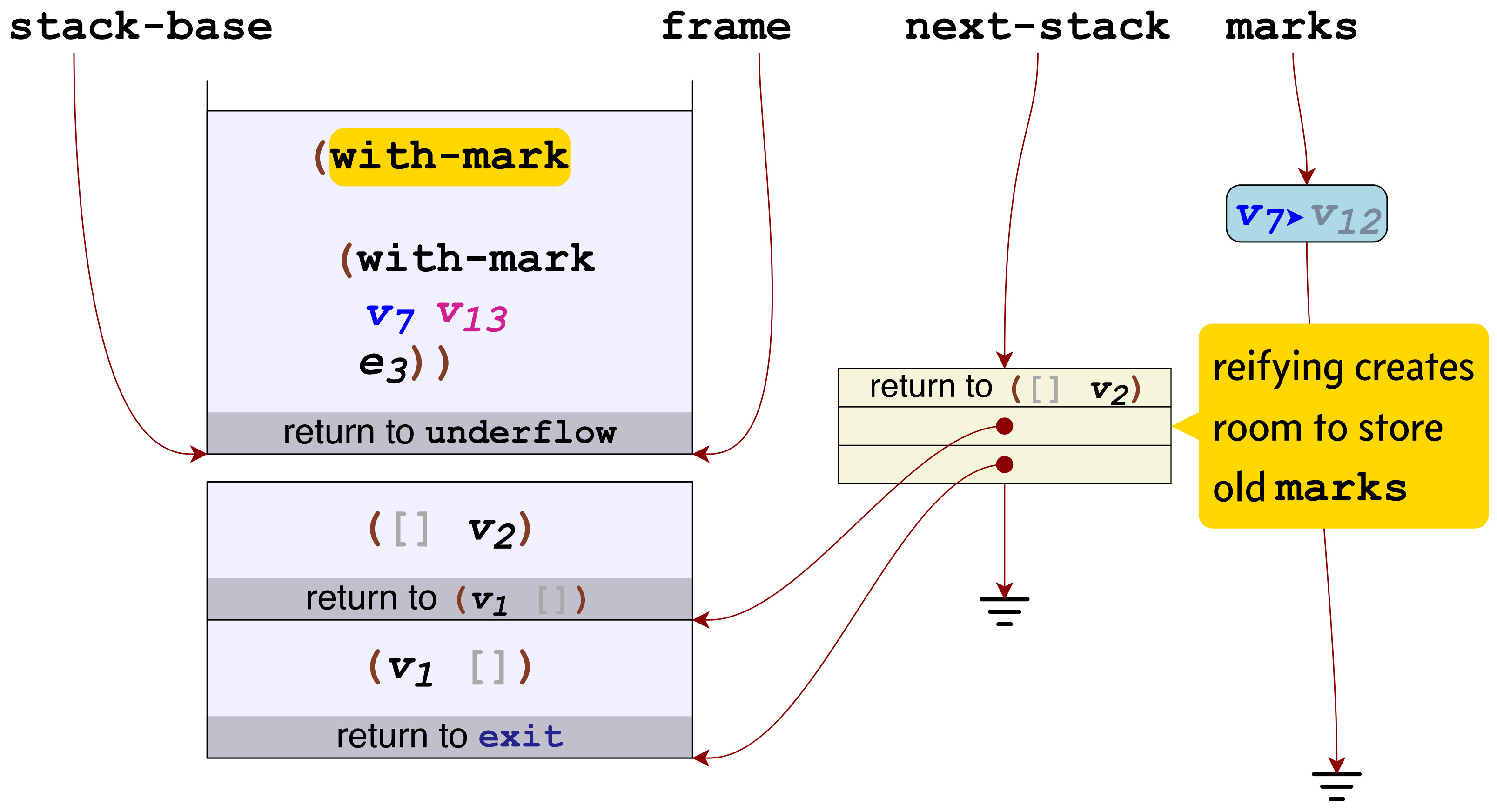

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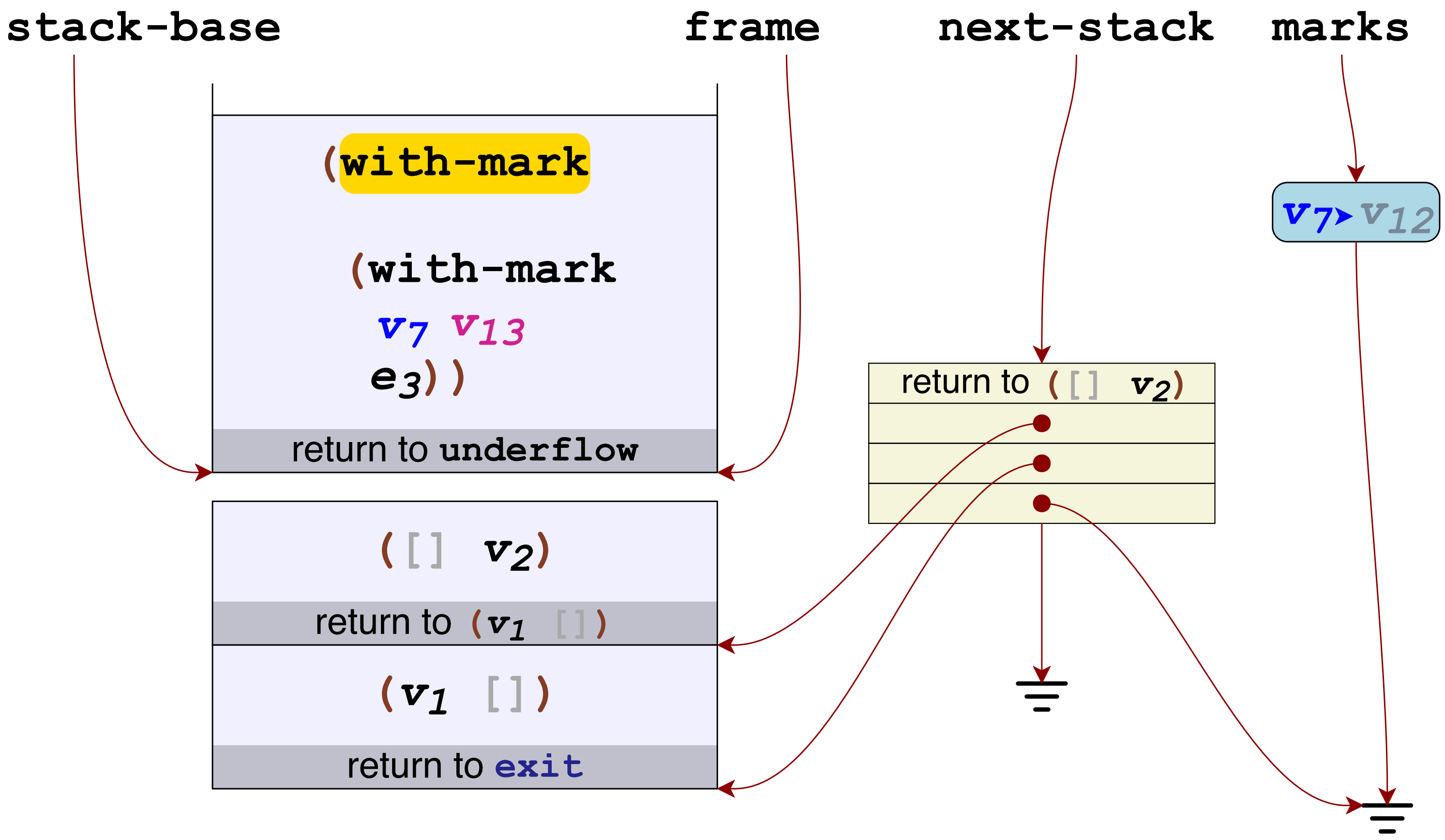
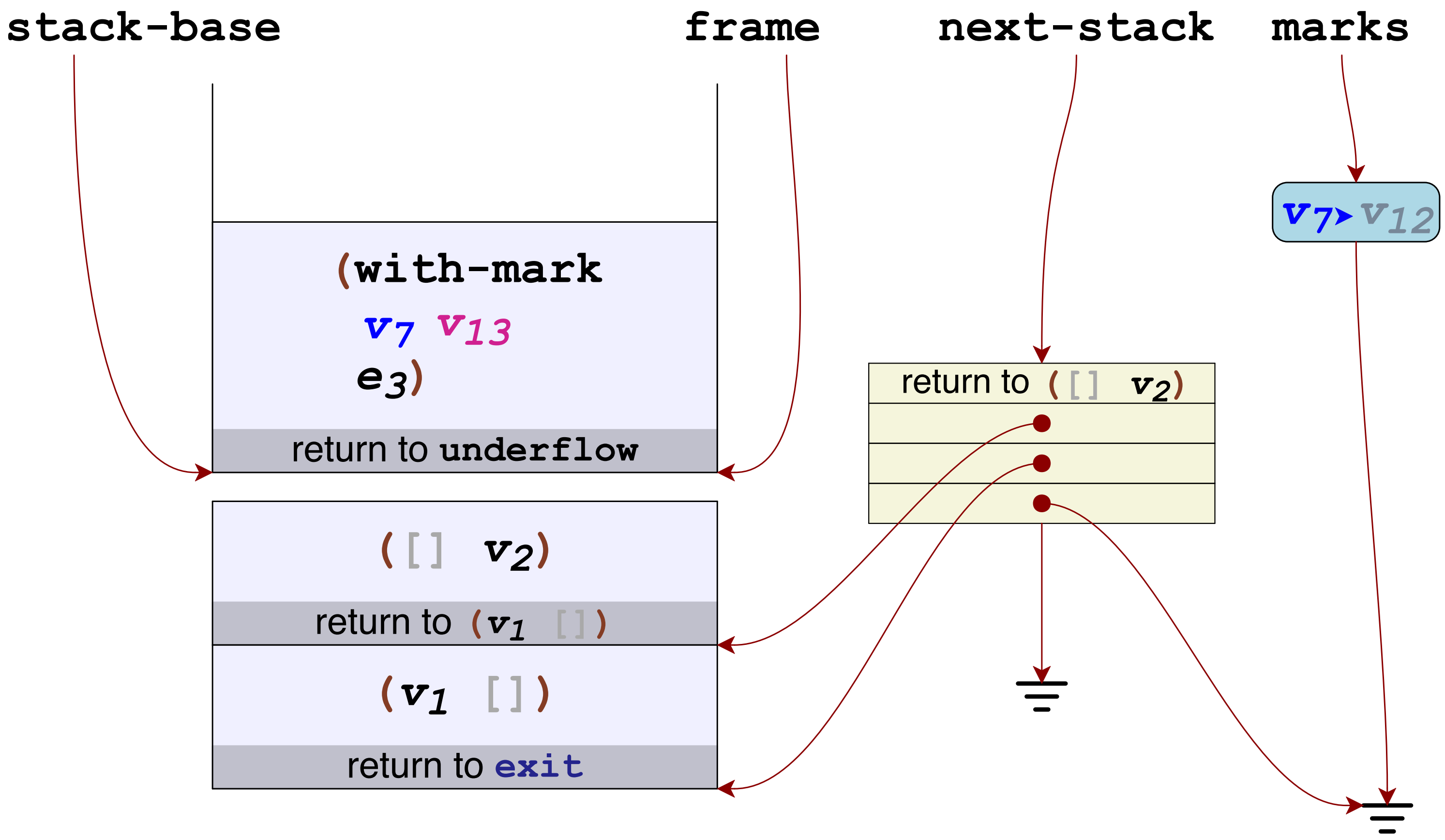


Setting Continuation Marks



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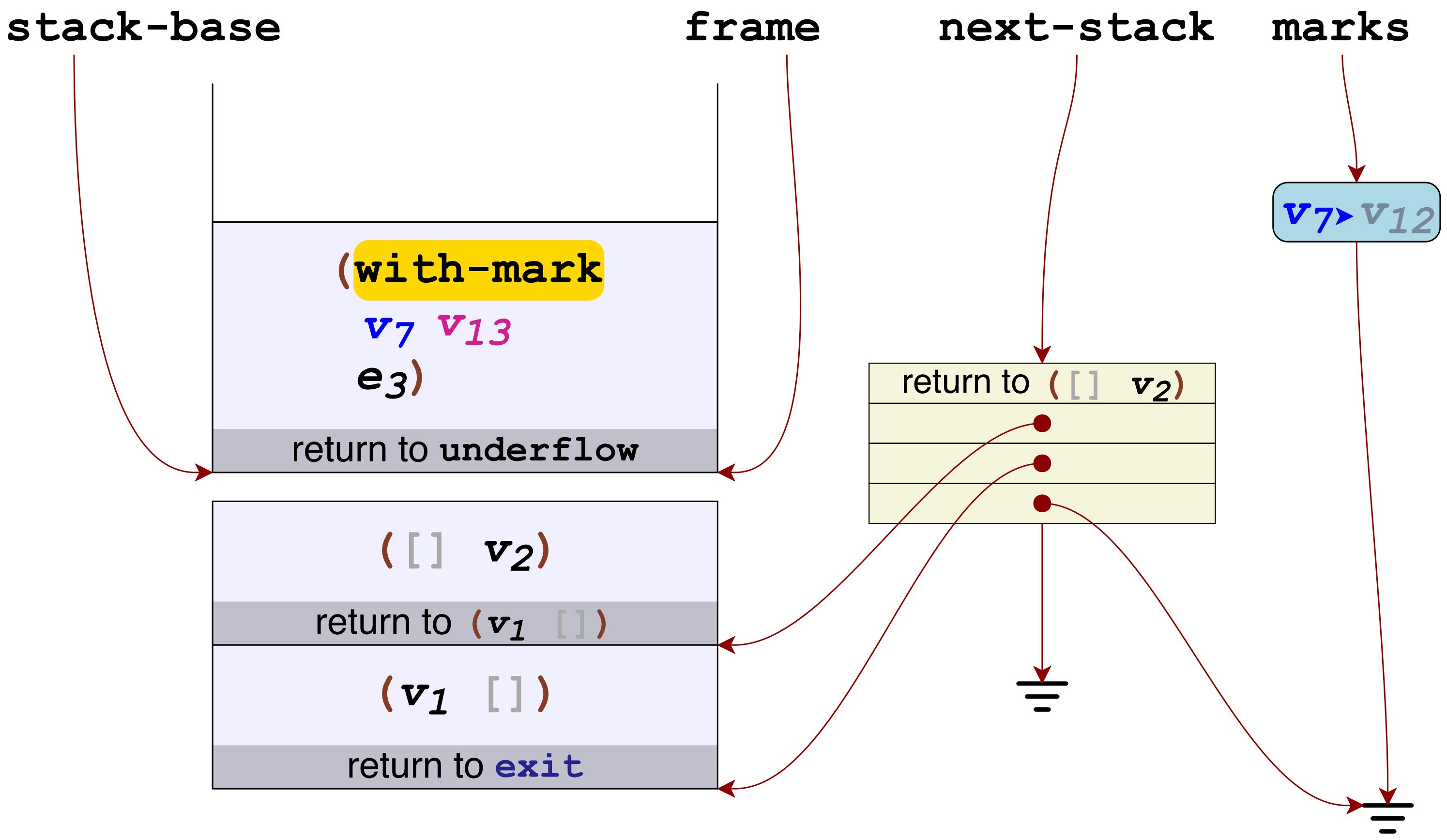

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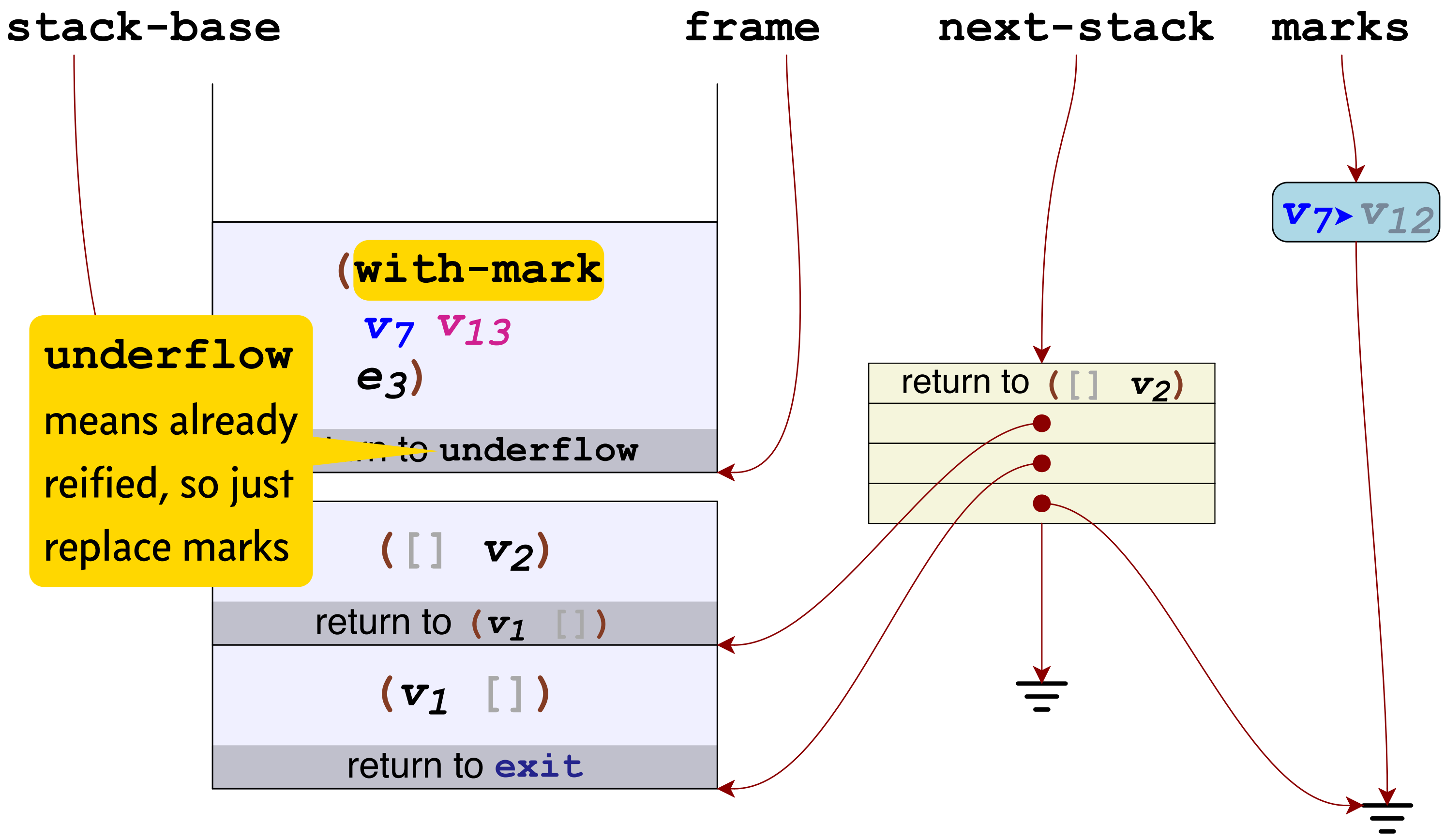

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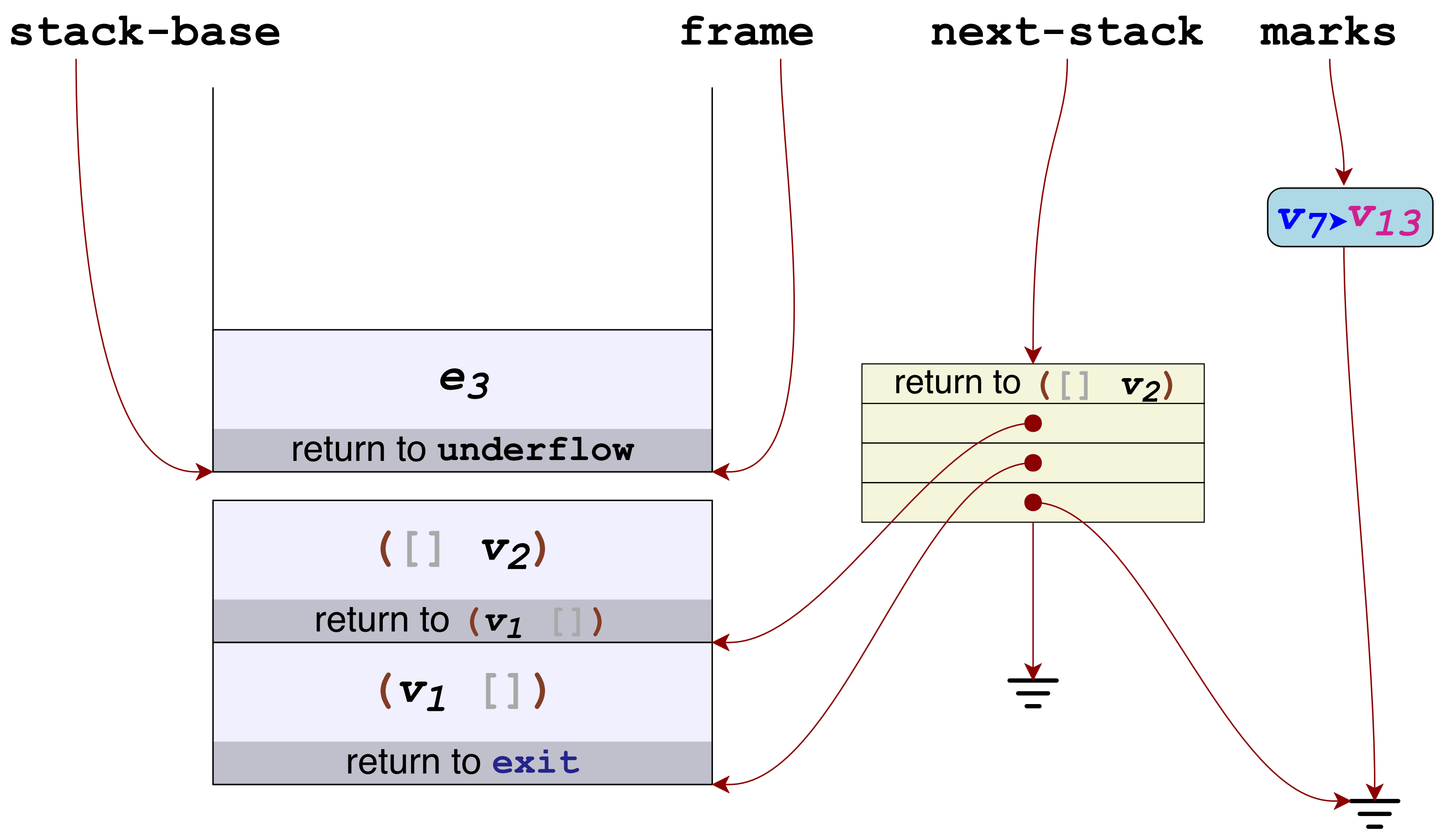

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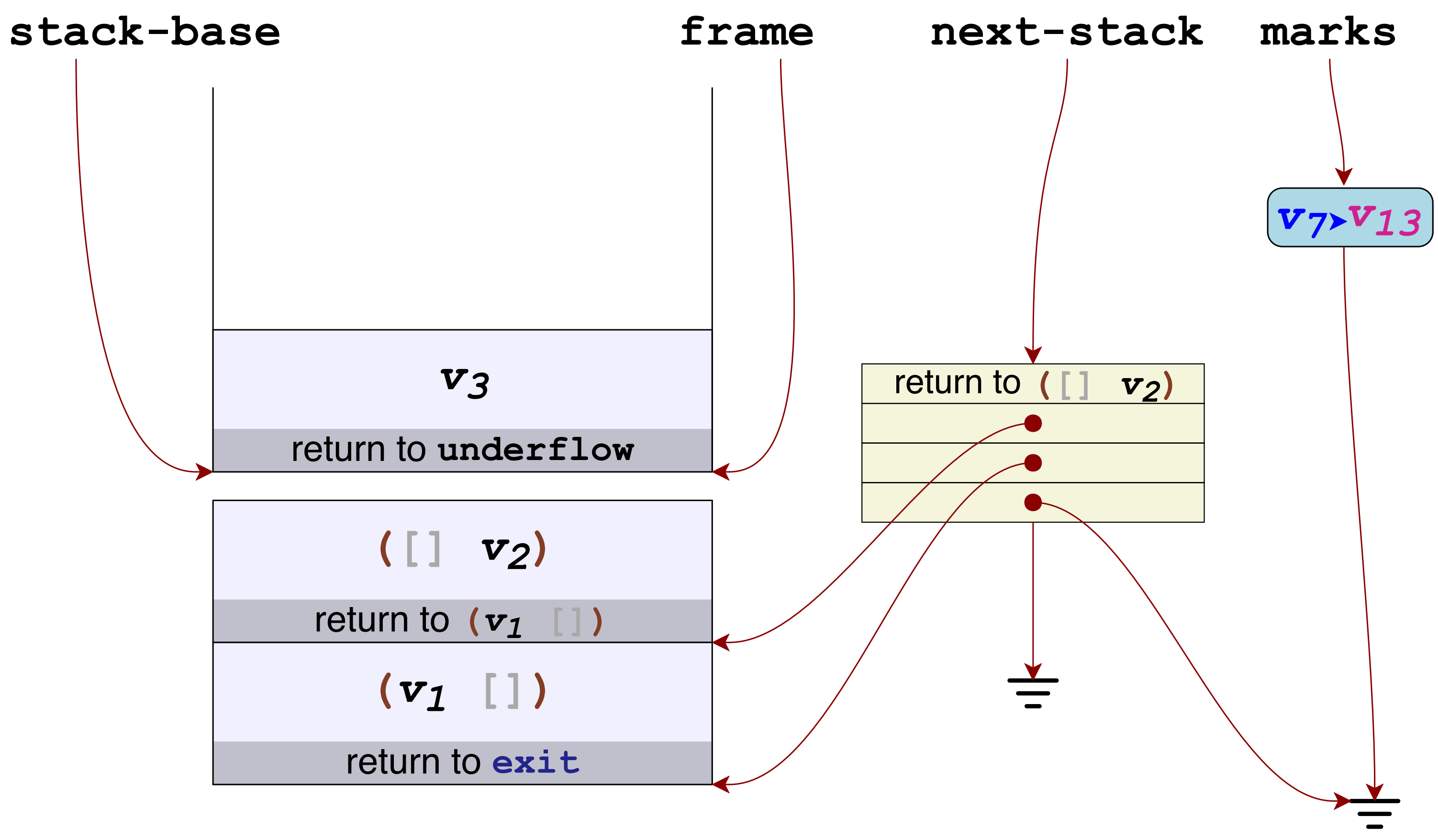
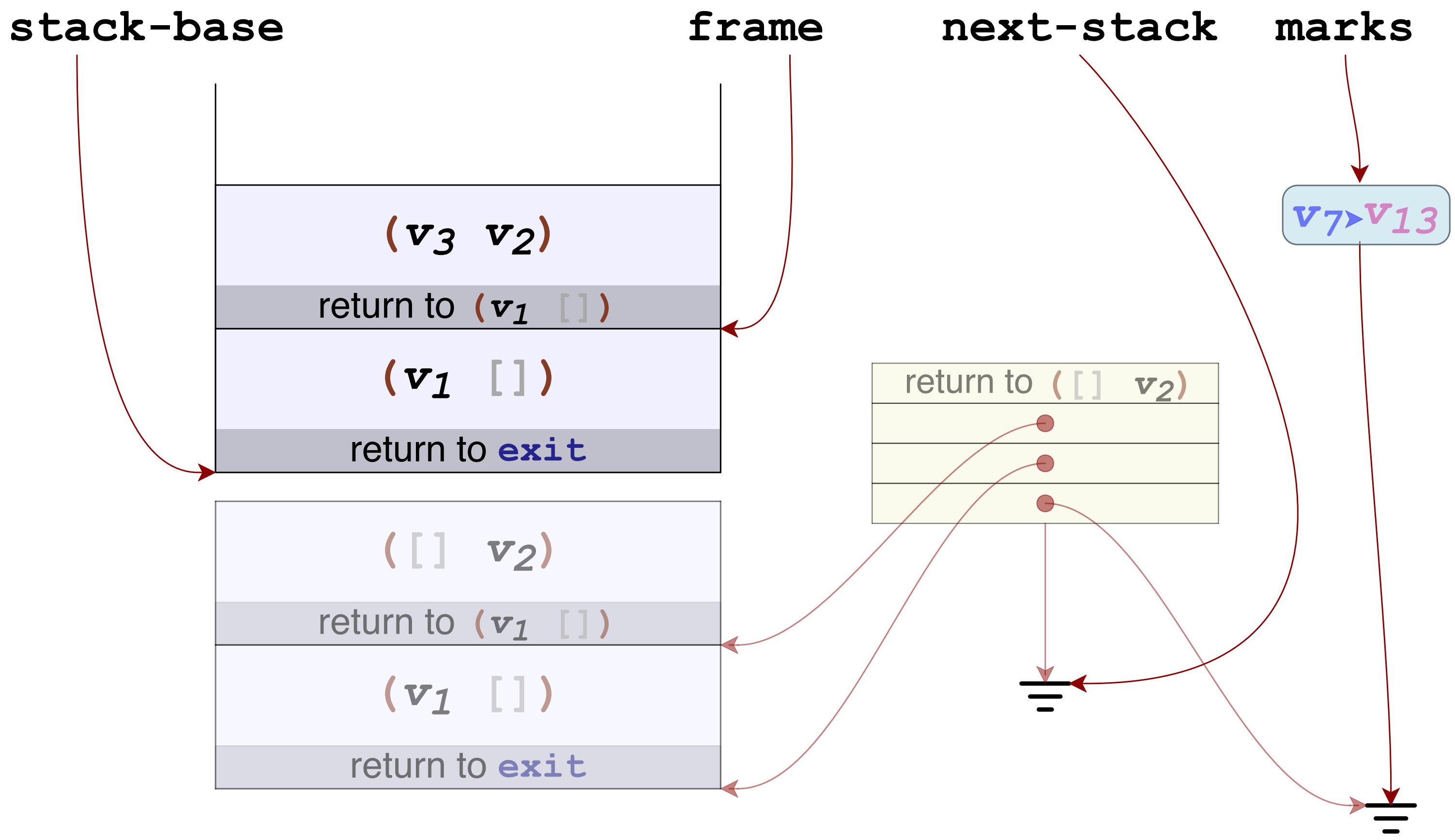


Removing Continuation Marks



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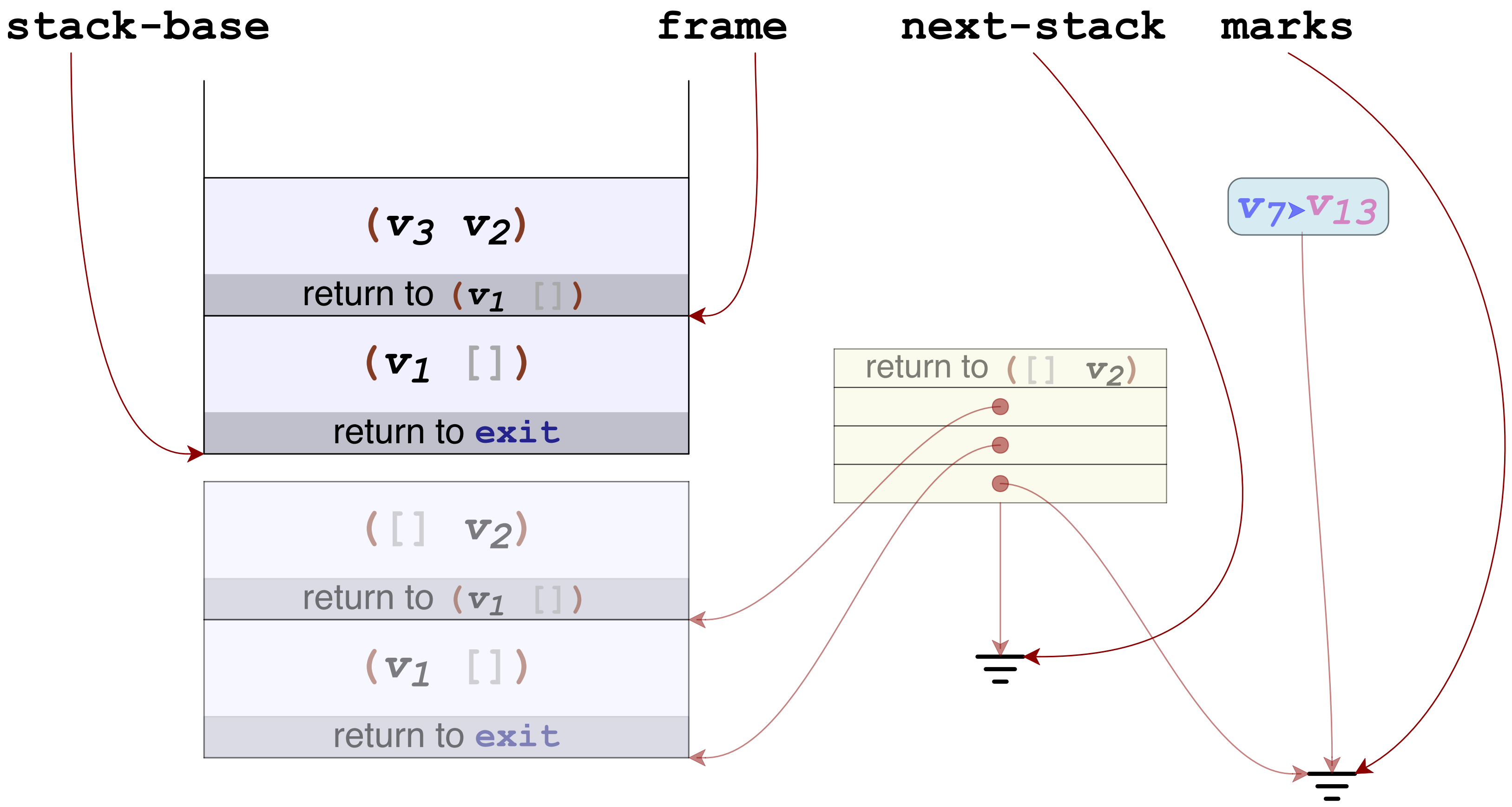
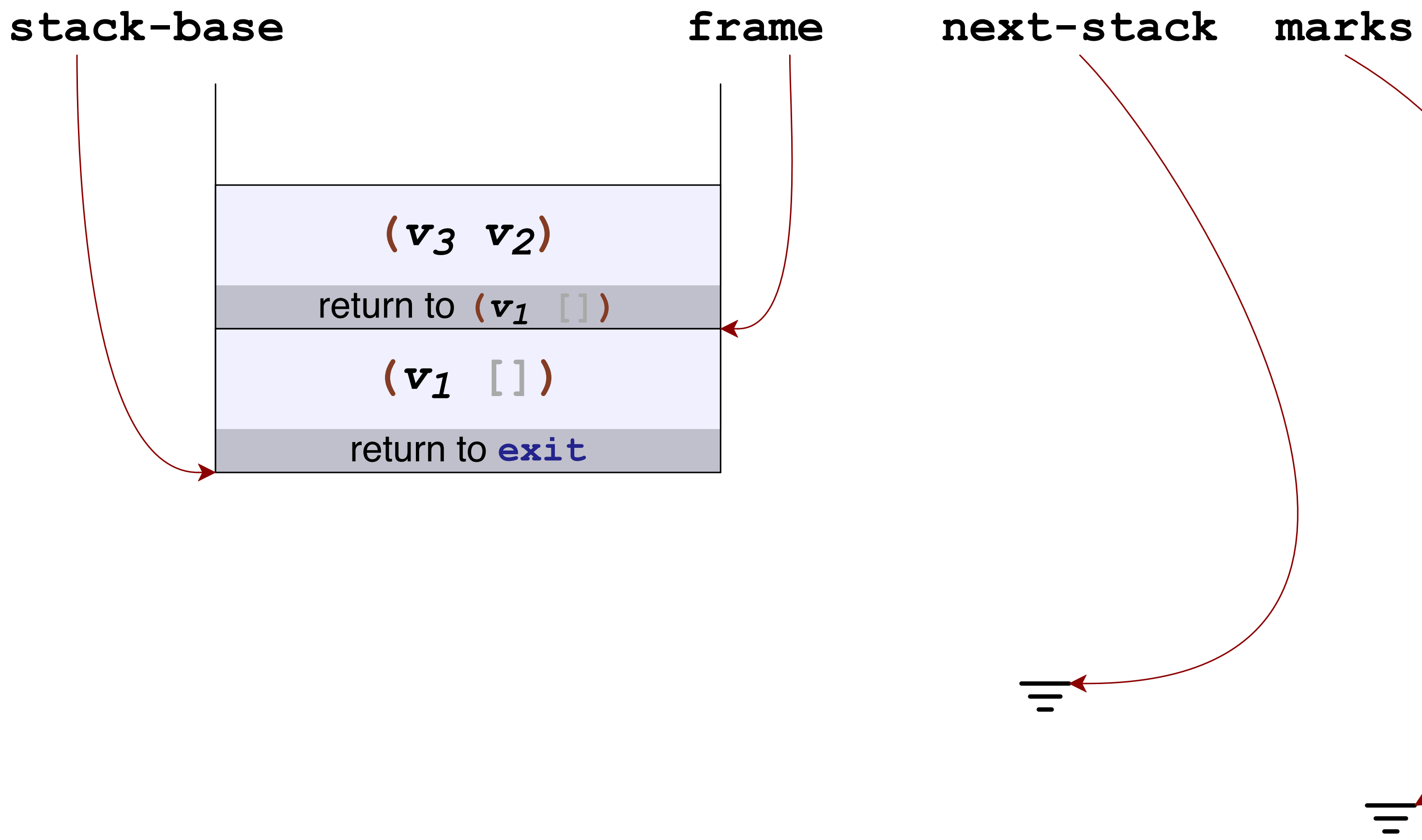
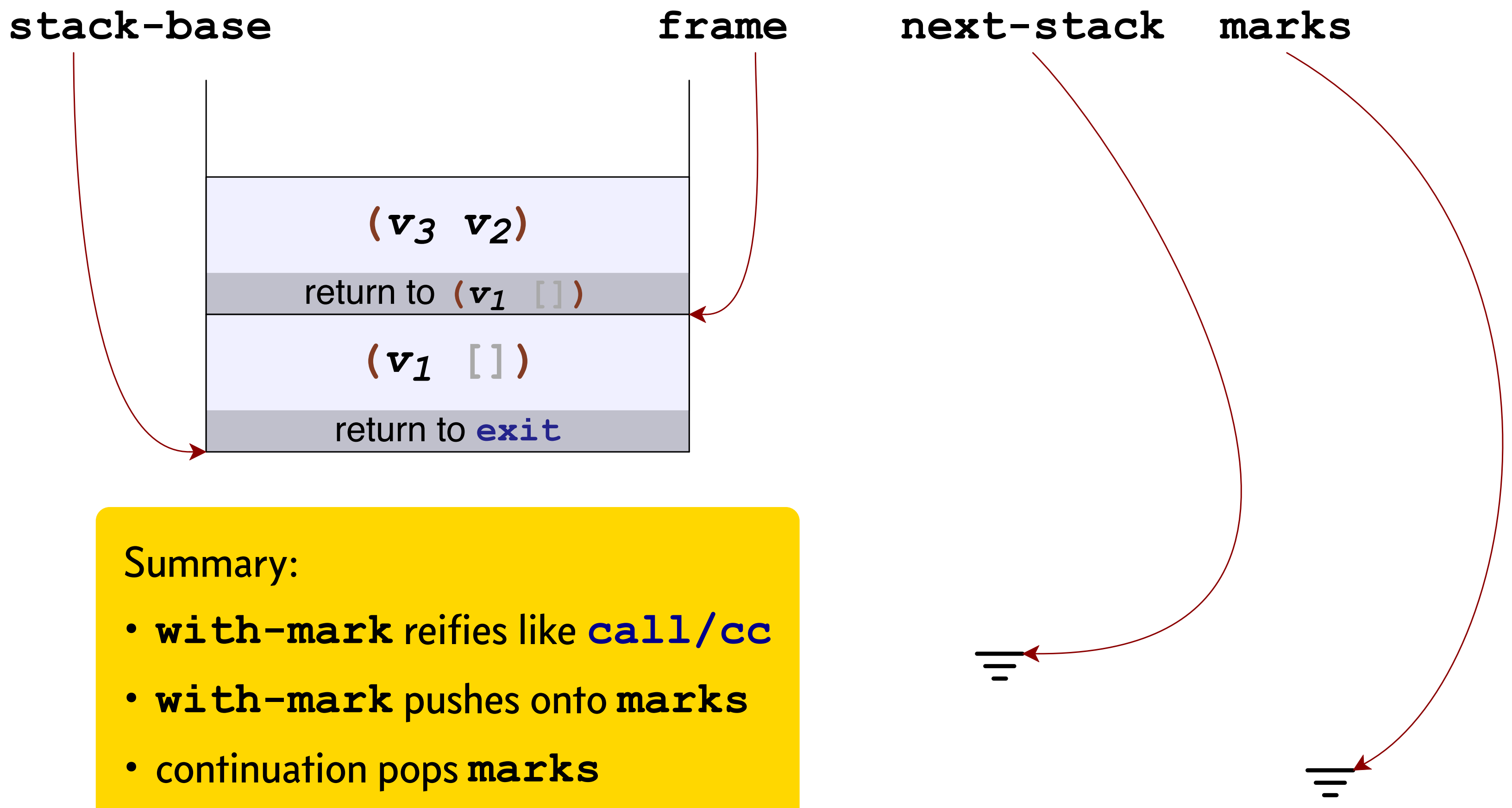


Removing Continuation Marks



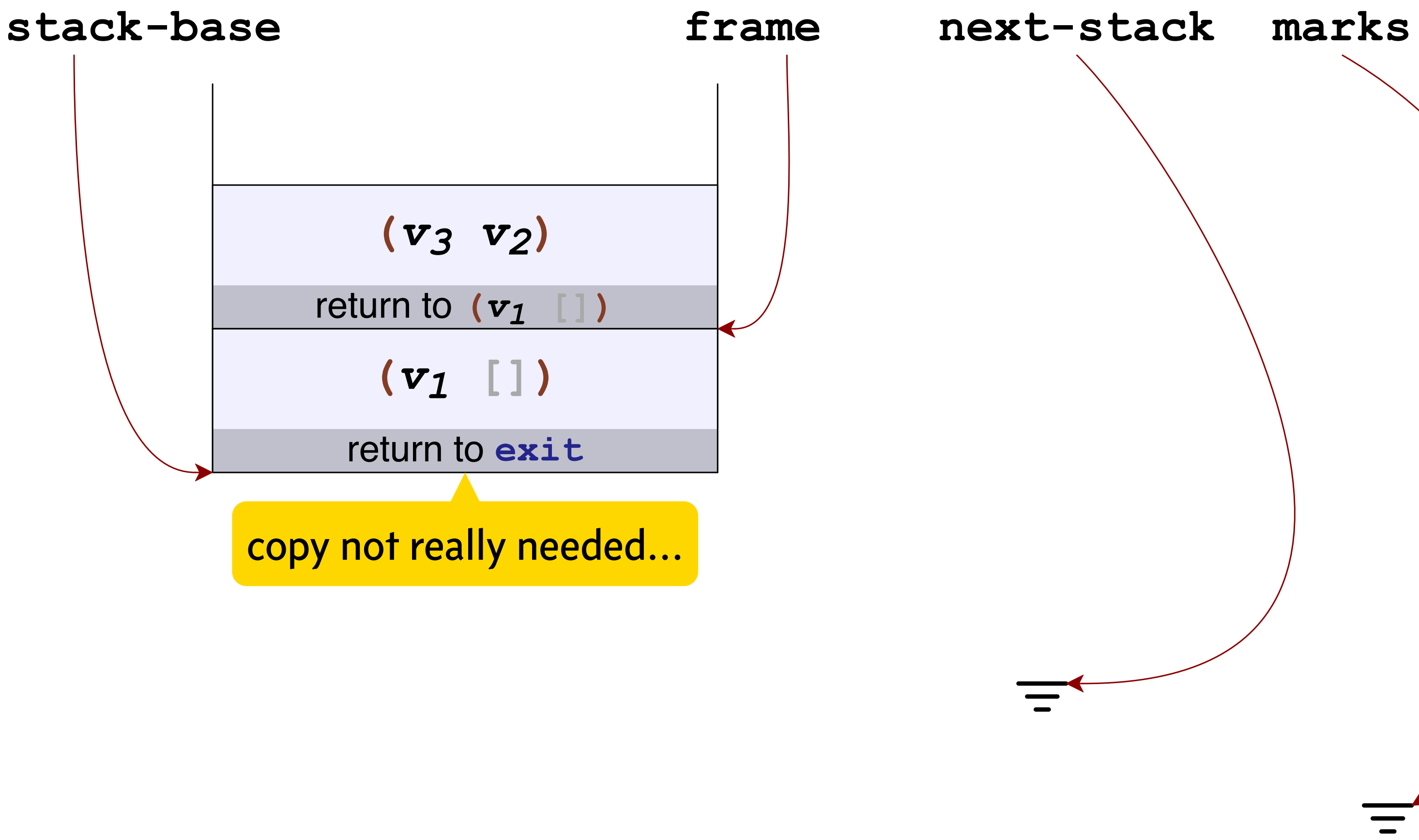
Implementing Continuation Marks



Summary:

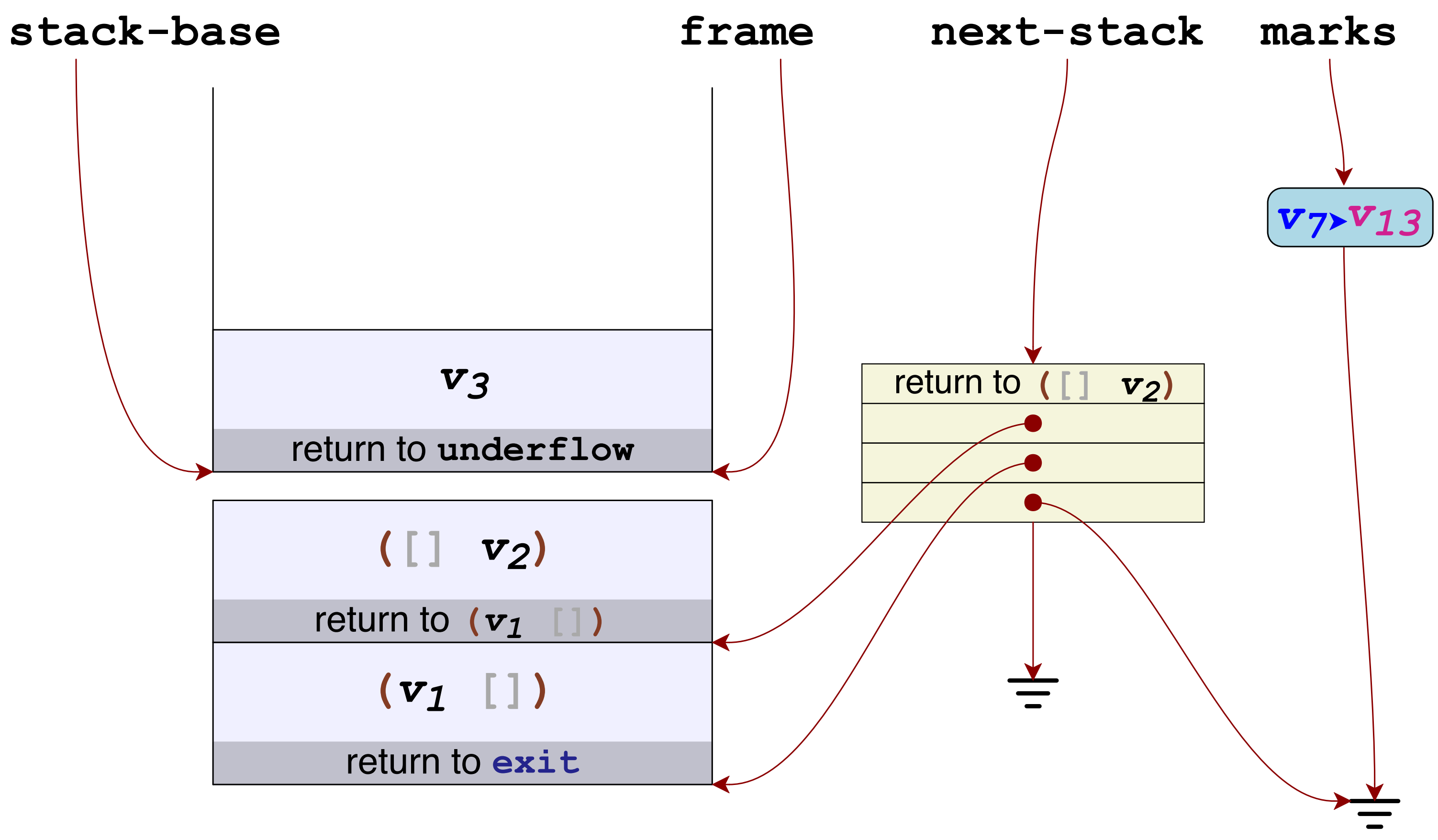
- **with-mark** reifies like **call/cc**
- **with-mark** pushes onto **marks**
- continuation pops **marks**

Implementing Continuation Marks

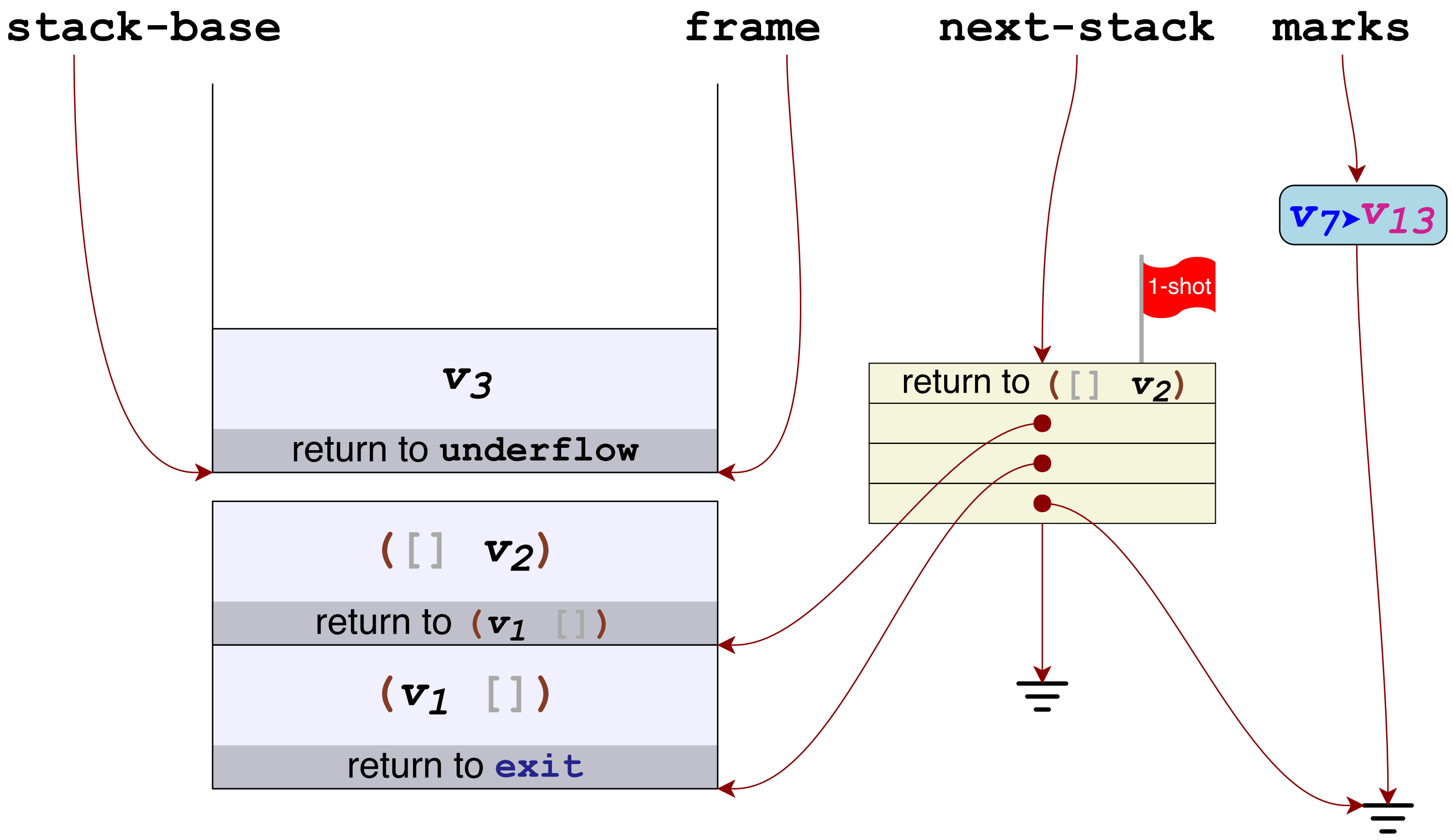


copy not really needed...

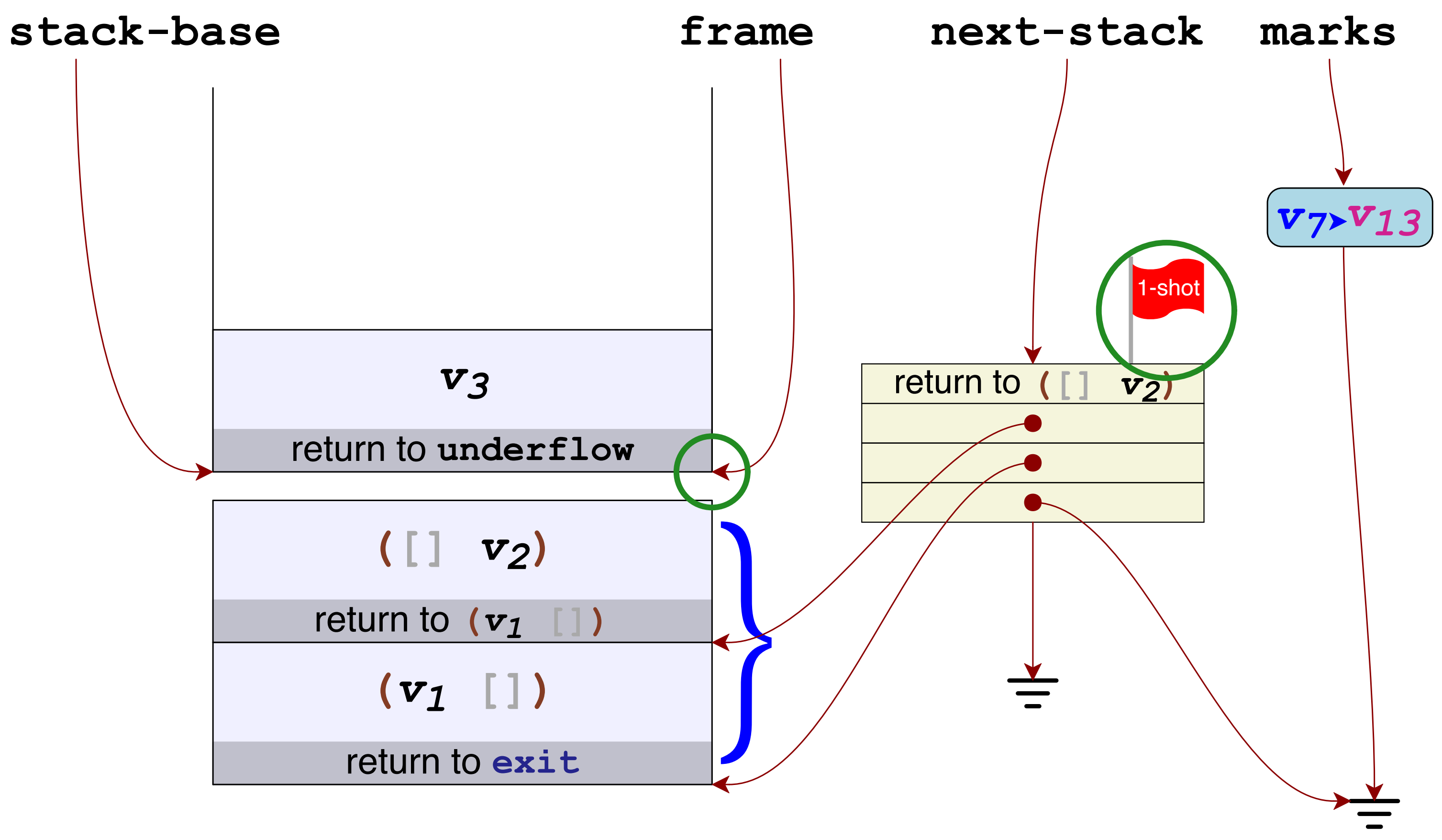
Opportunistic One-Shot Continuations



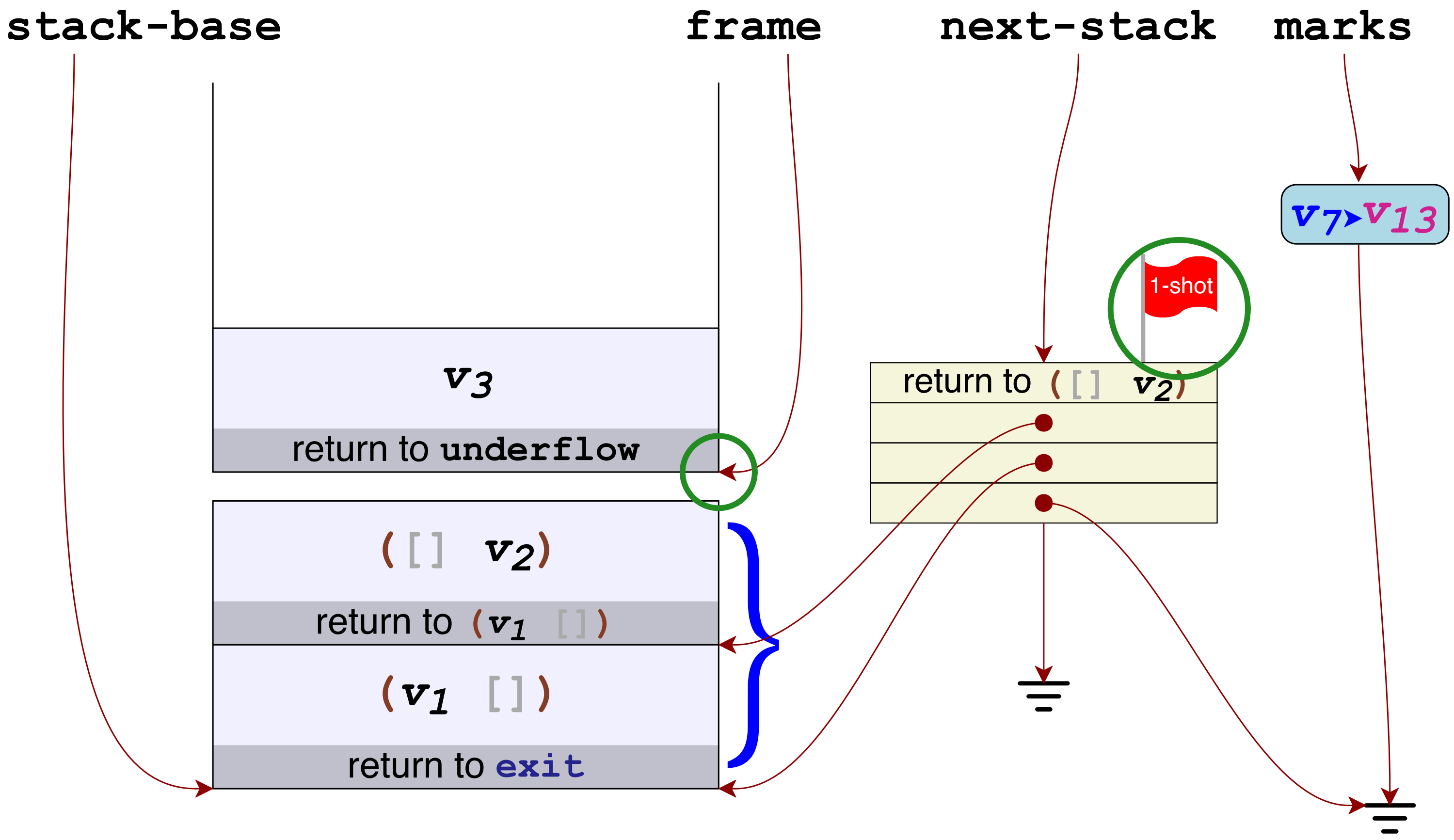
Opportunistic One-Shot Continuations



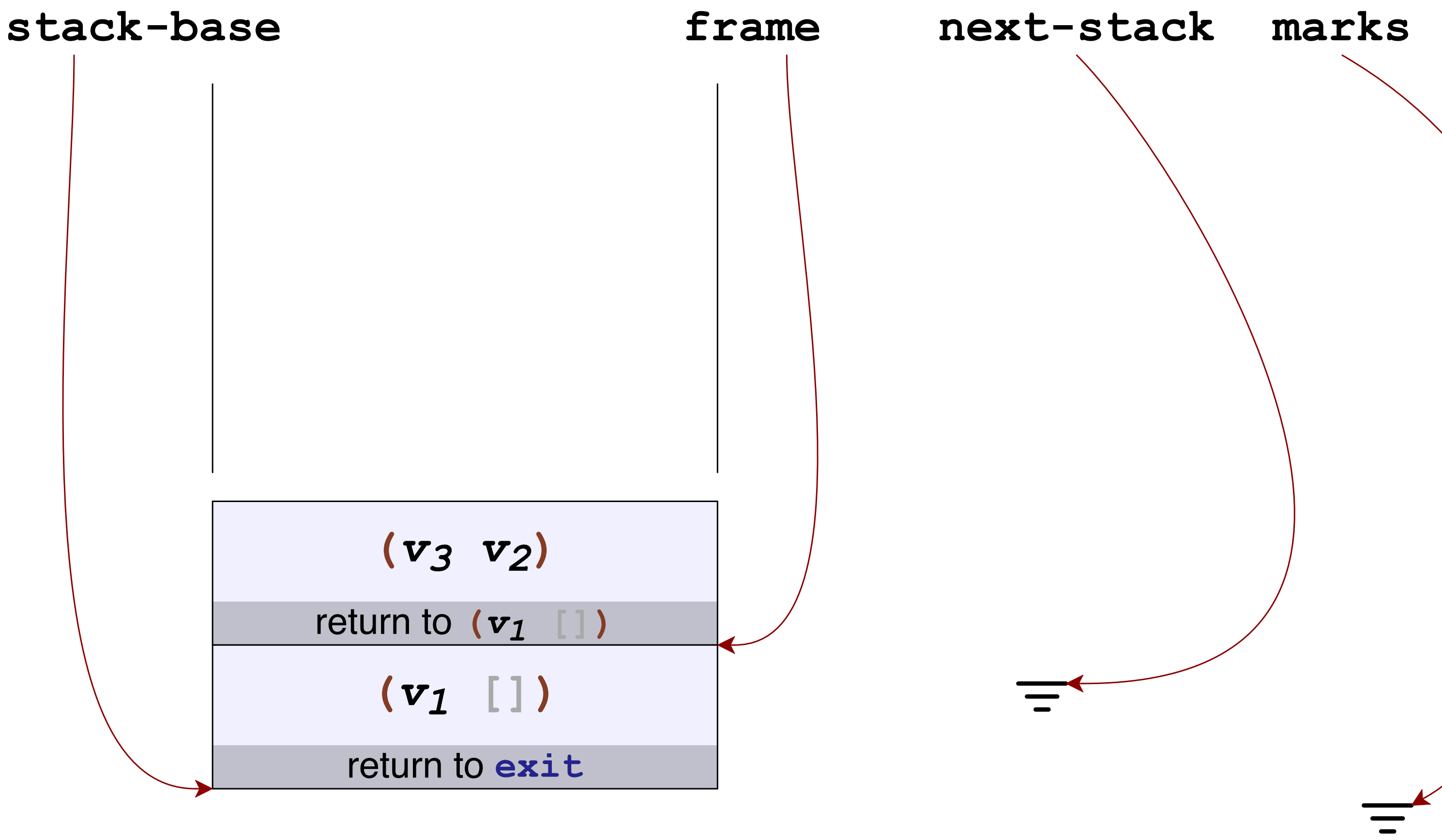
Opportunistic One-Shot Continuations



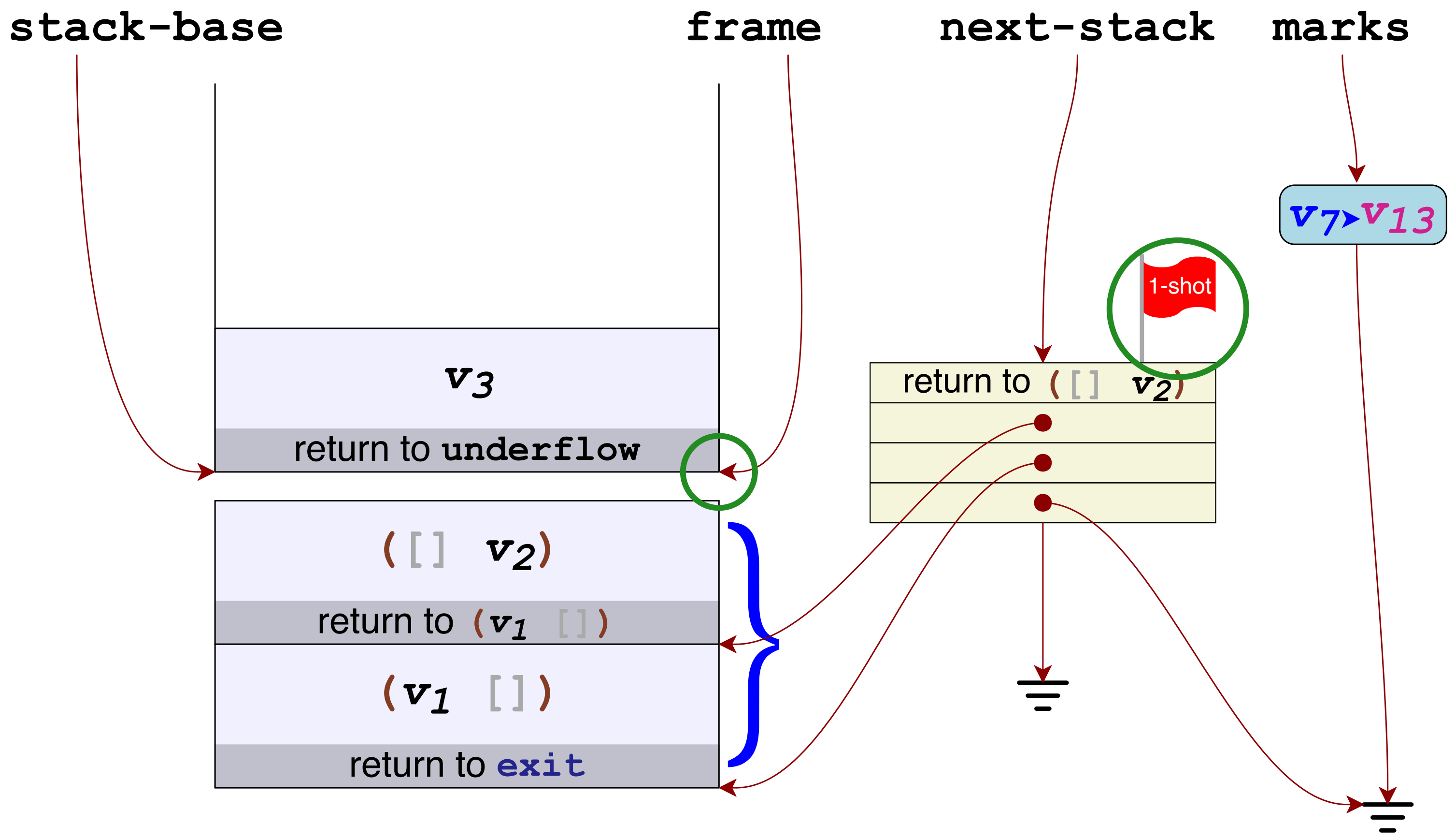
Opportunistic One-Shot Continuations



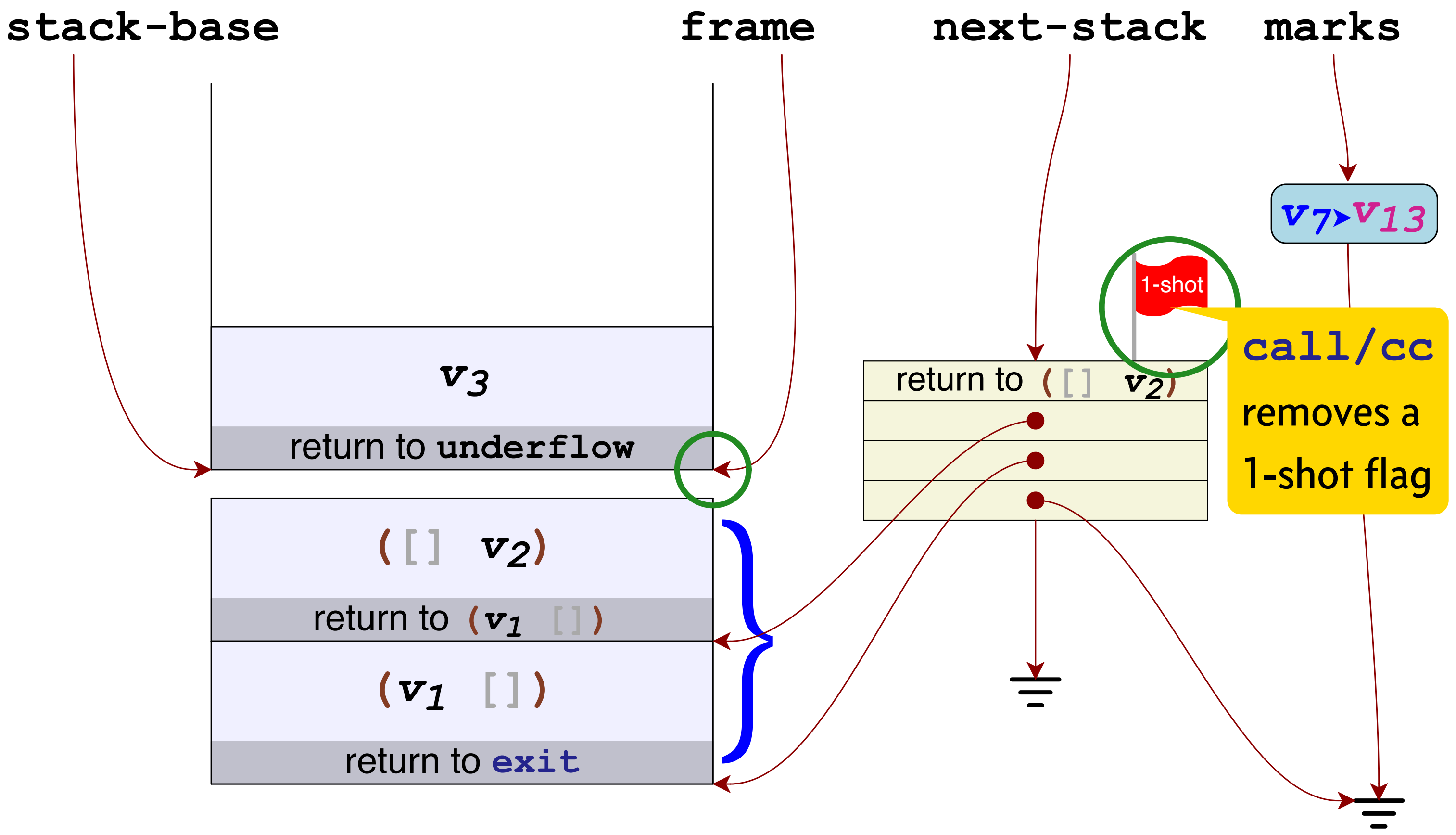
Opportunistic One-Shot Continuations



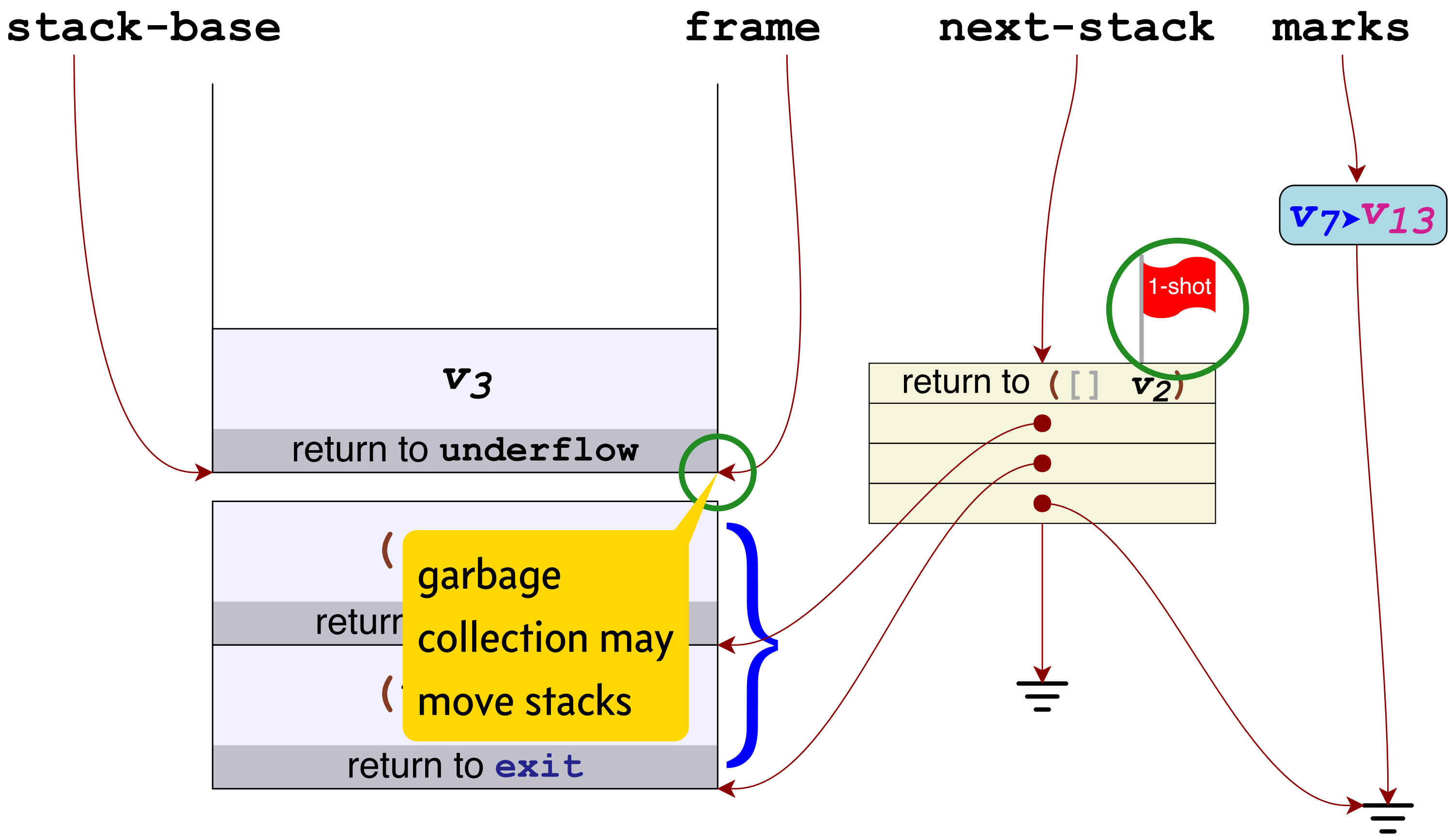
Opportunistic One-Shot Continuations



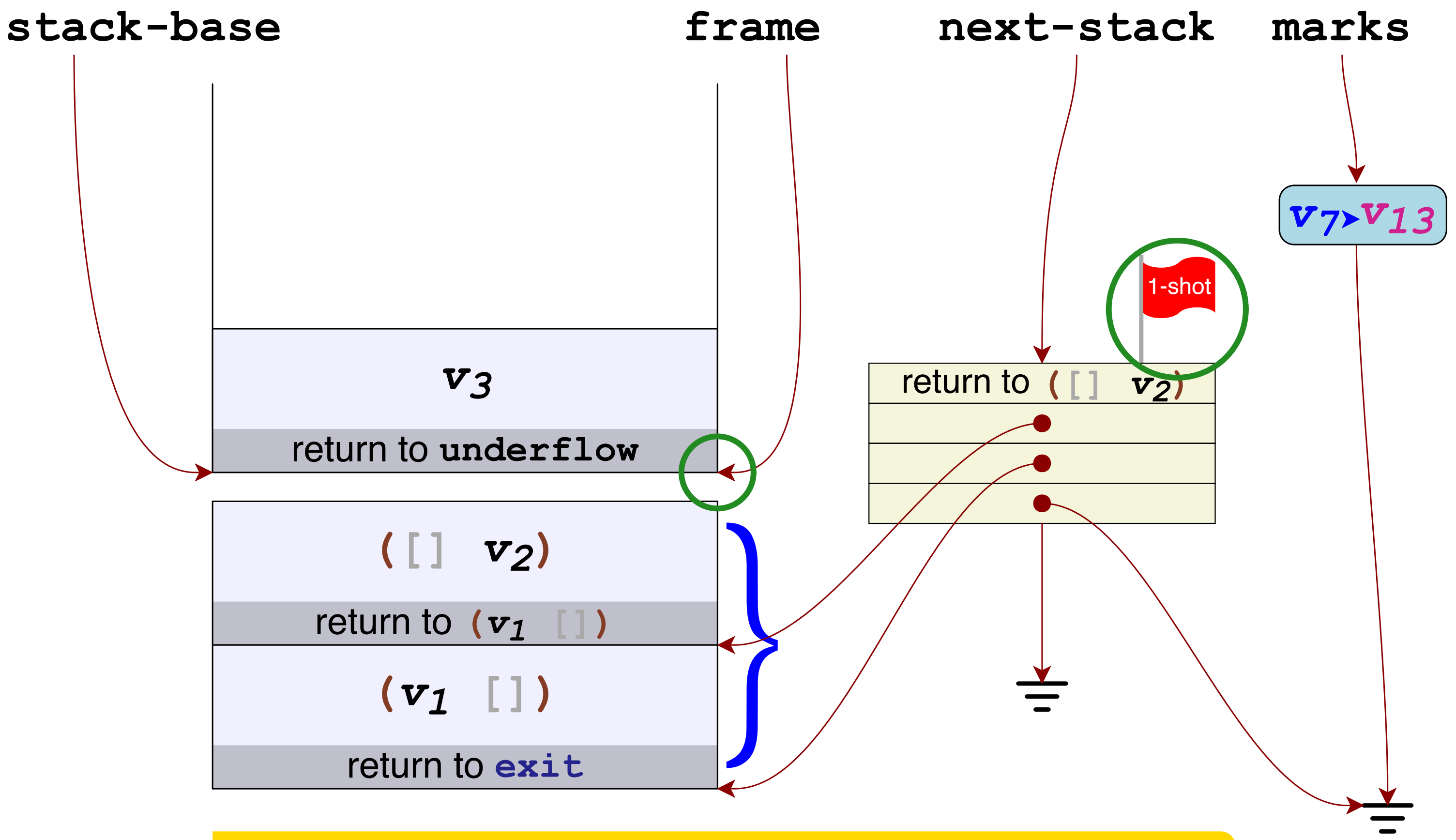
Opportunistic One-Shot Continuations



Opportunistic One-Shot Continuations

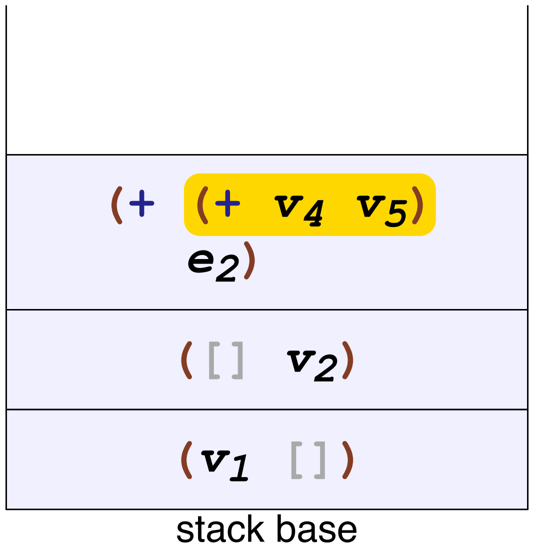


Opportunistic One-Shot Continuations

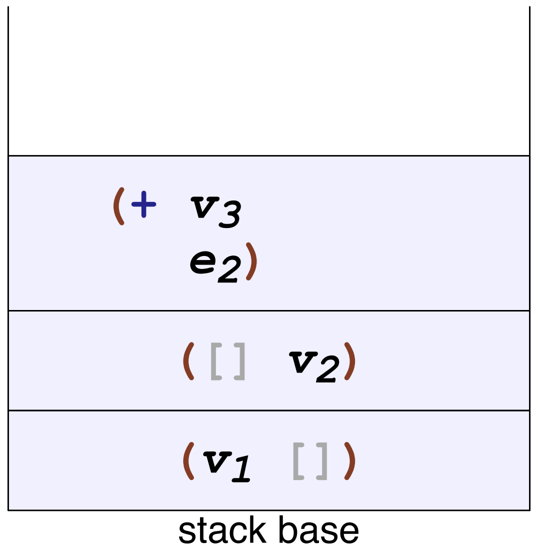


with-mark without **call/cc**: frequent opportunity

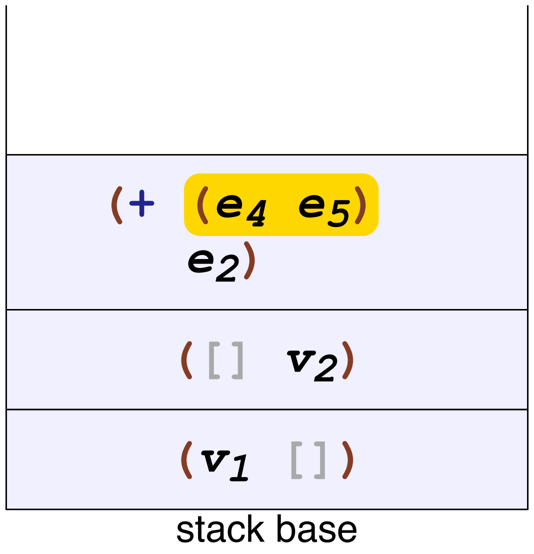
Primitives: Don't Create a Frame



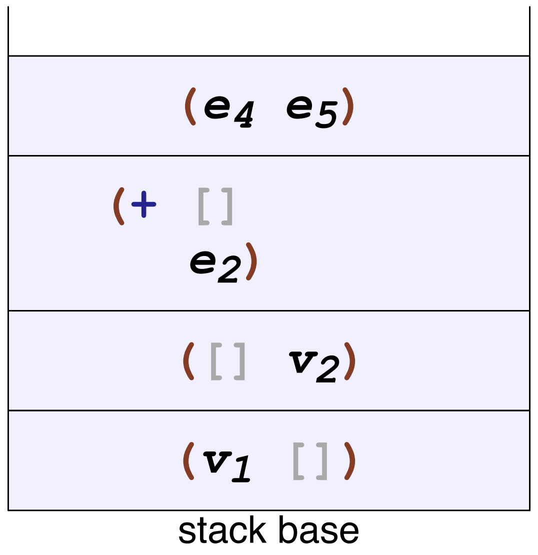
Primitives: Don't Create a Frame



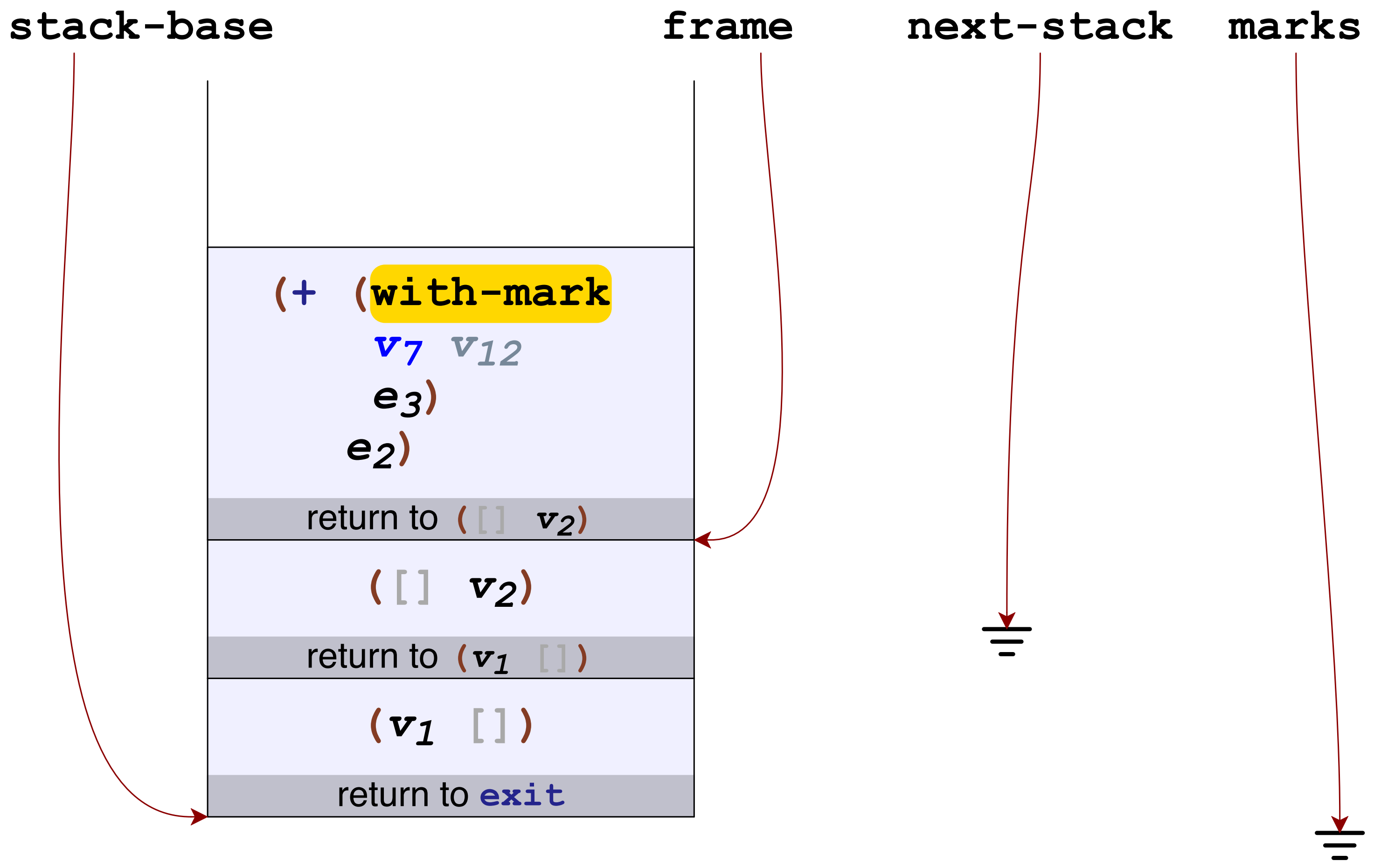
Function Call: Do Create a Frame



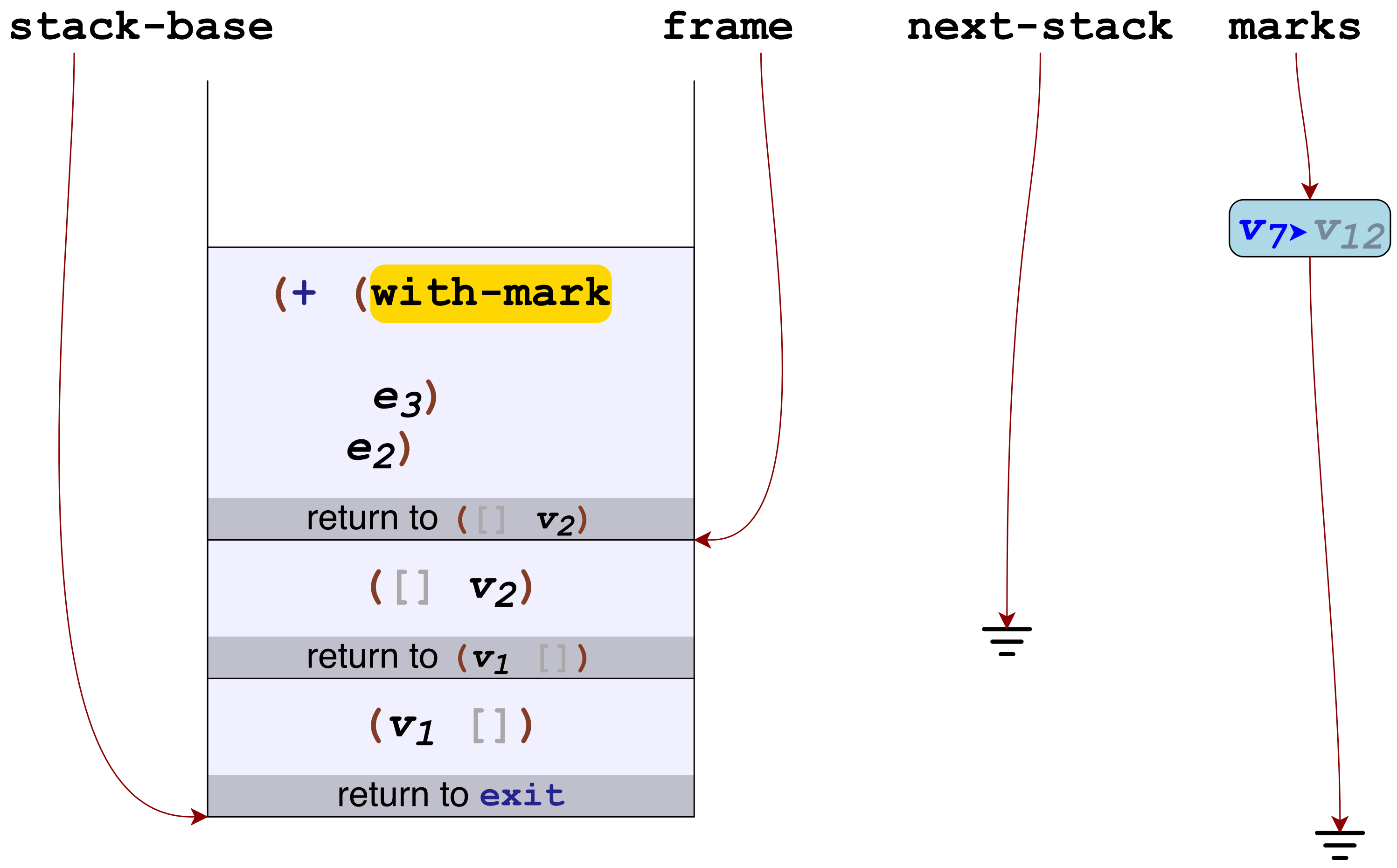
Function Call: Do Create a Frame



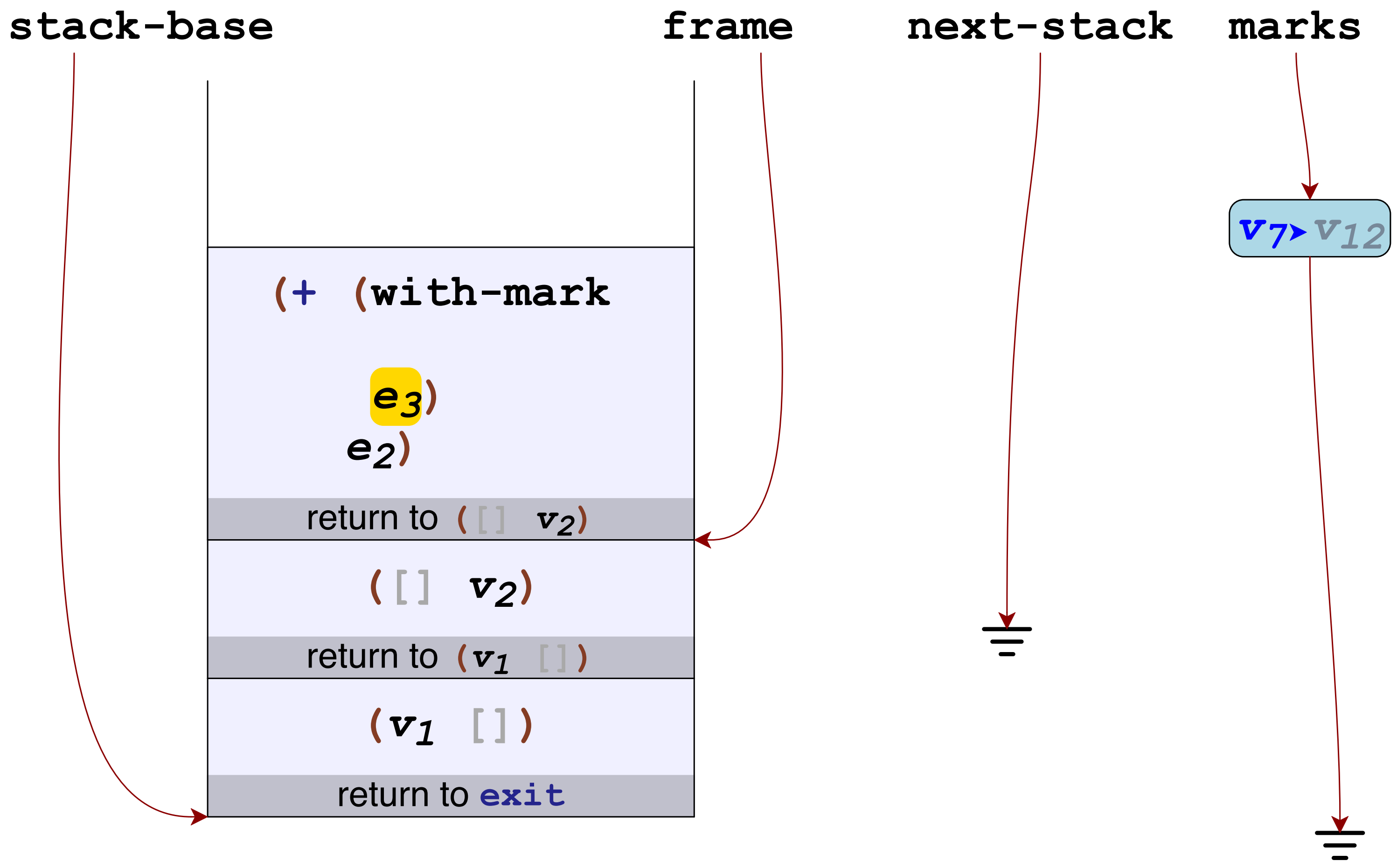
Non-Tail Mark: Don't Create a Frame



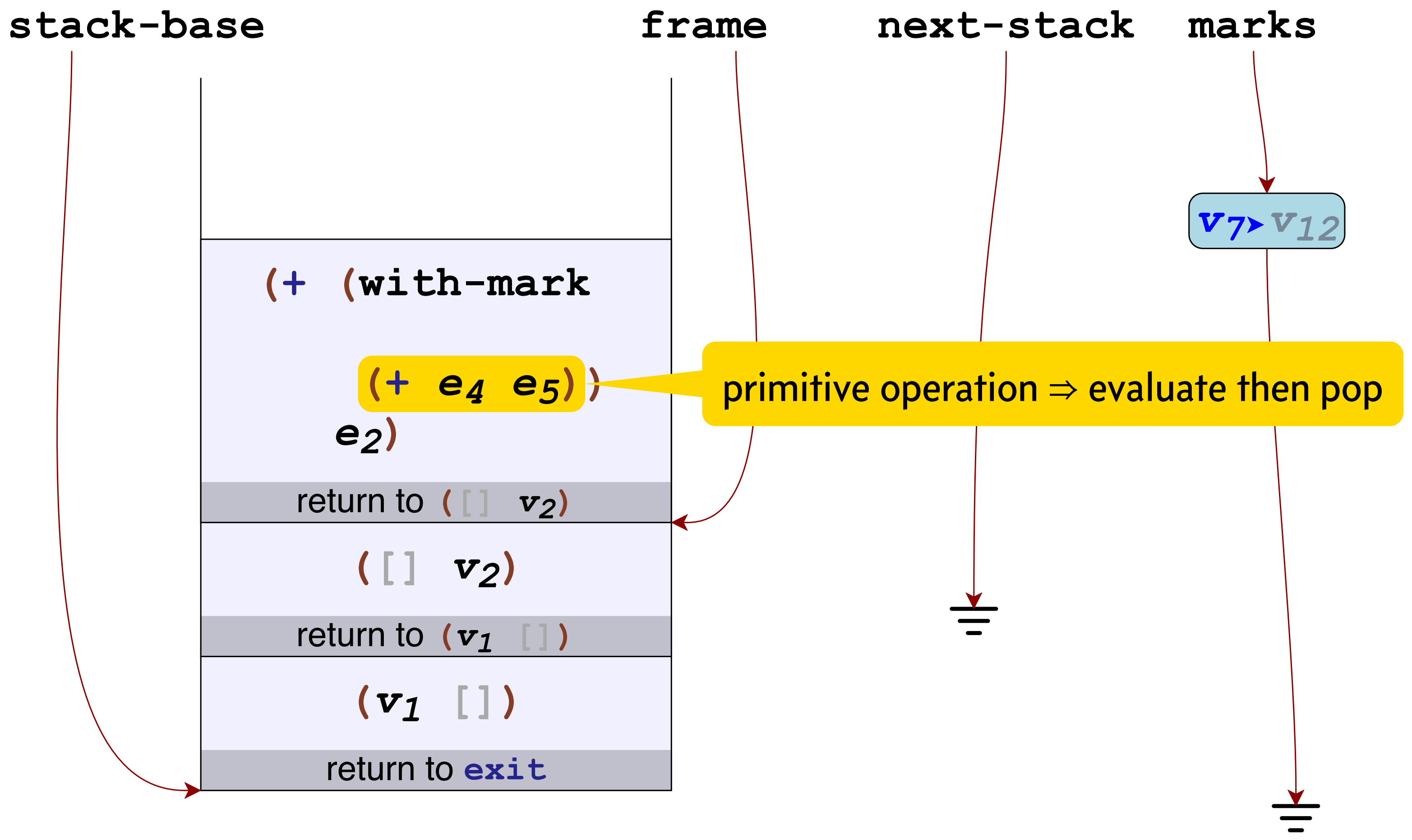
Non-Tail Mark: Don't Create a Frame



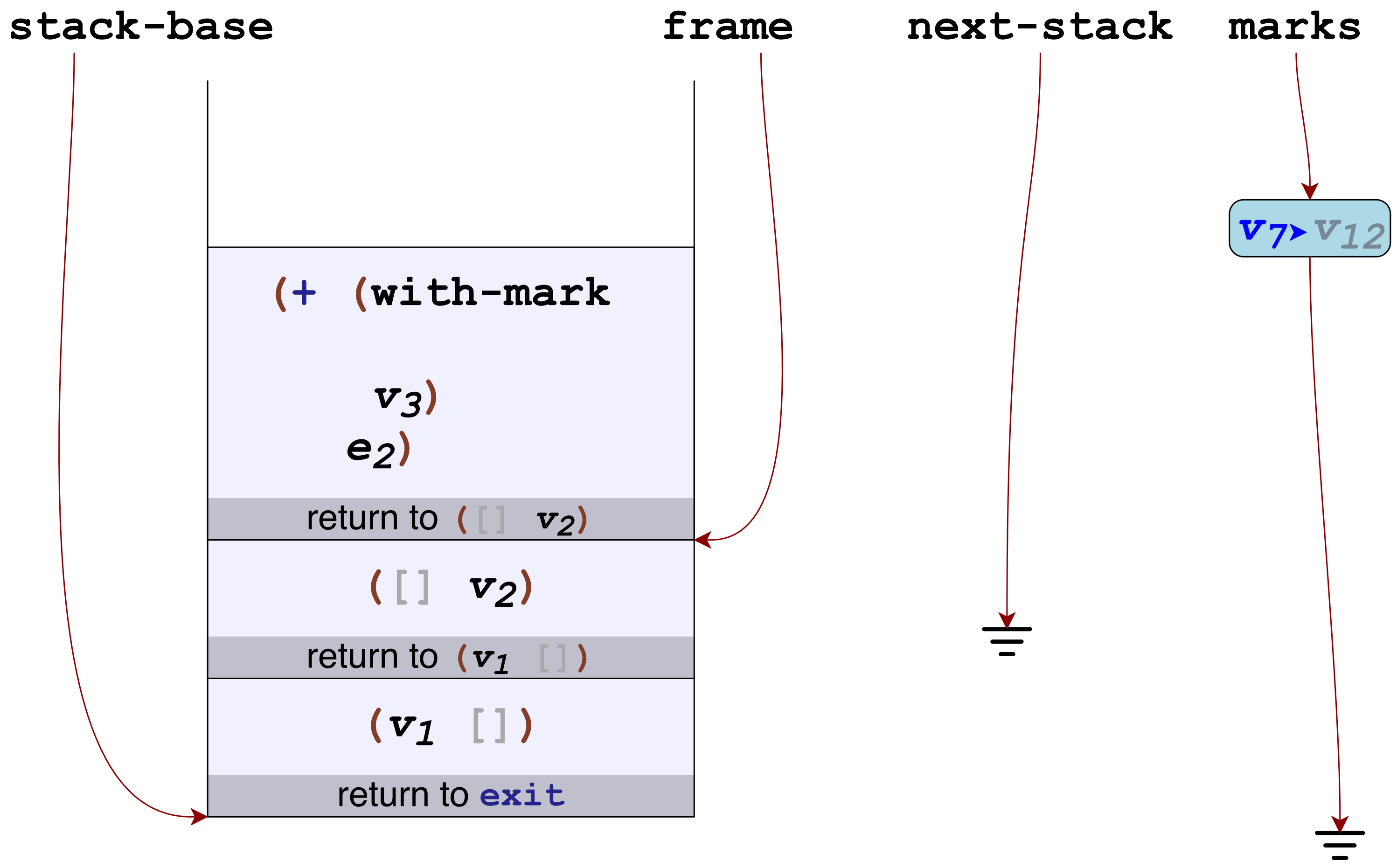
Non-Tail Mark: Don't Create a Frame



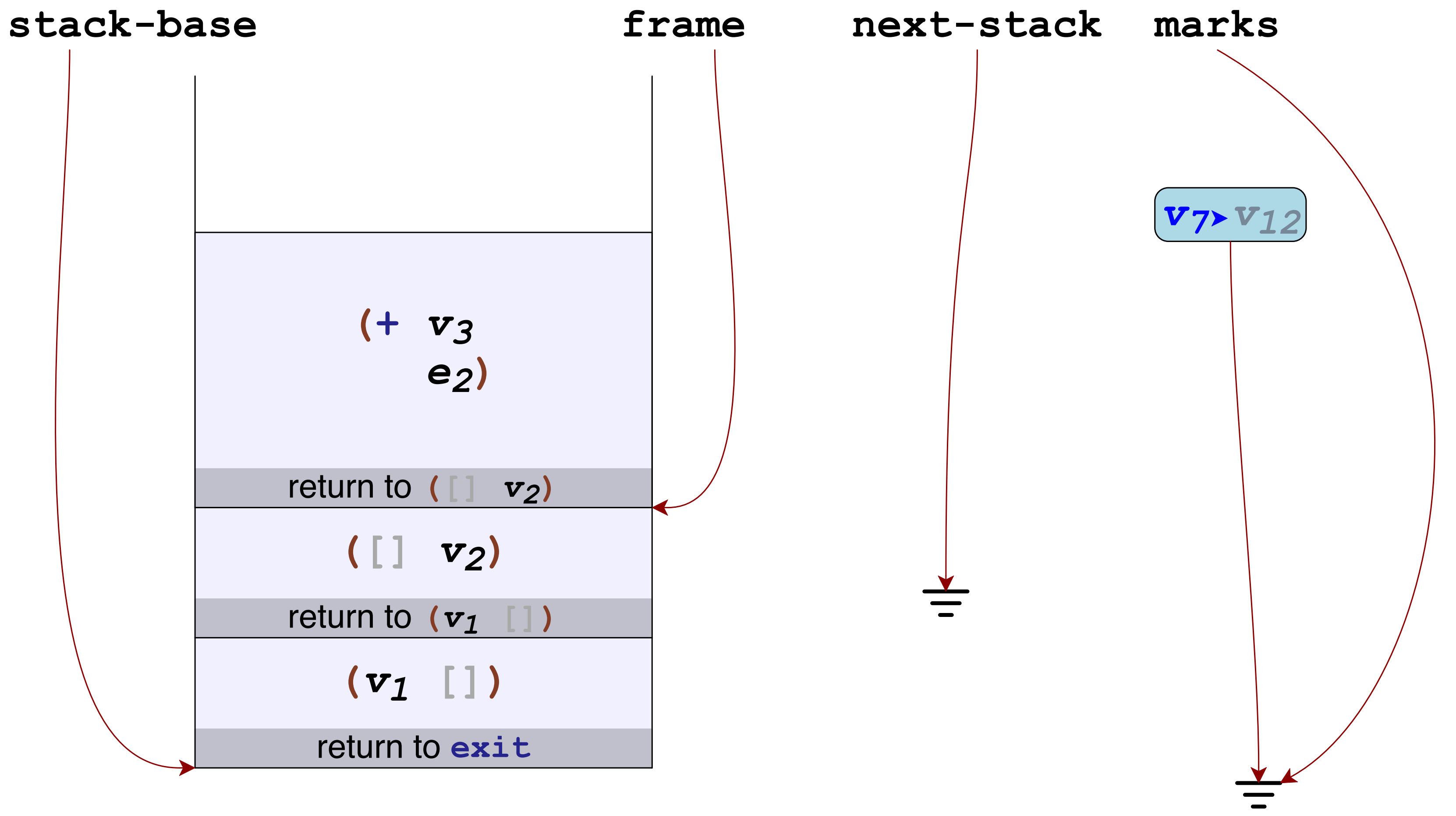
Non-Tail Mark with a Primitive Operation



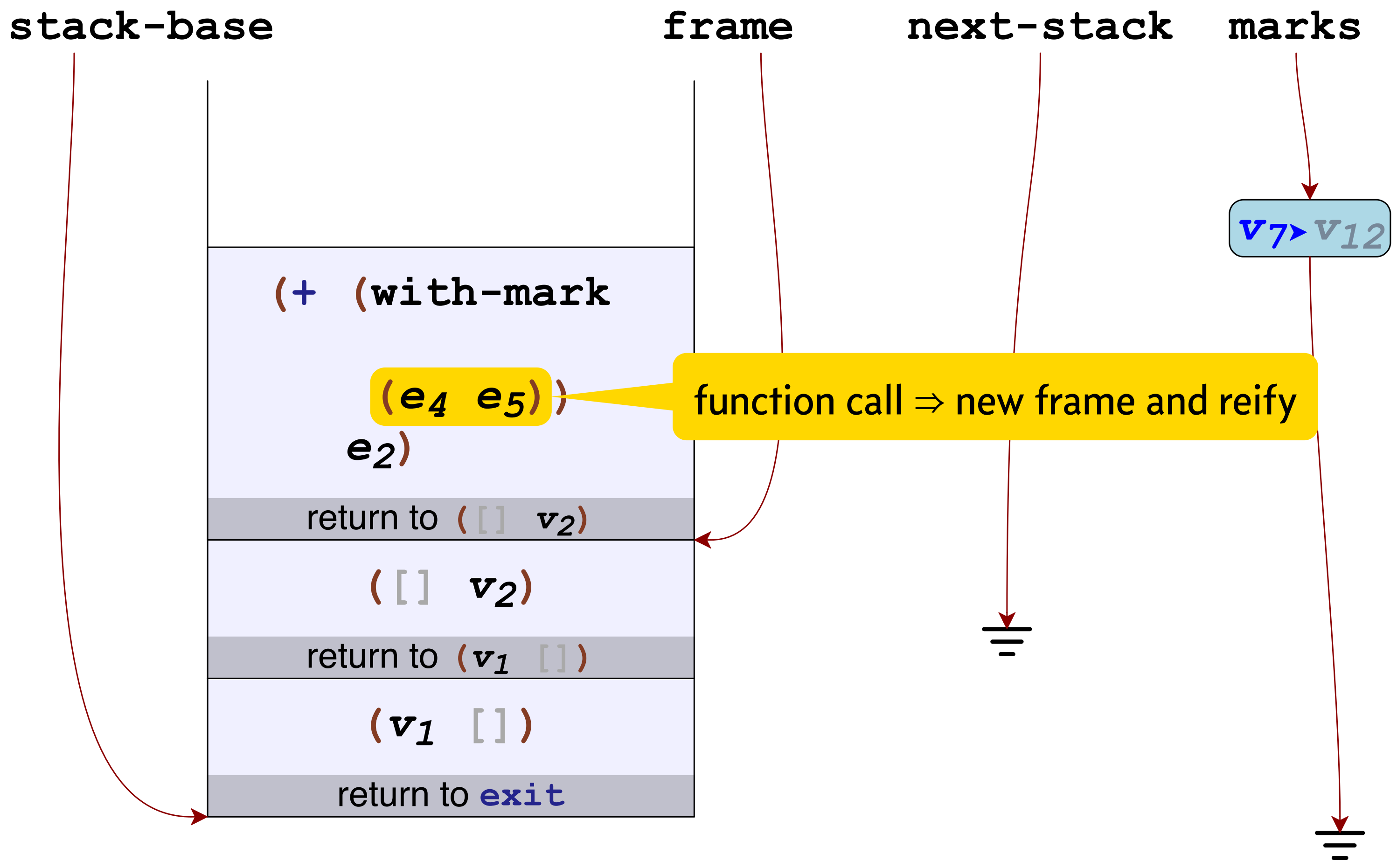
Non-Tail Mark with a Primitive Operation



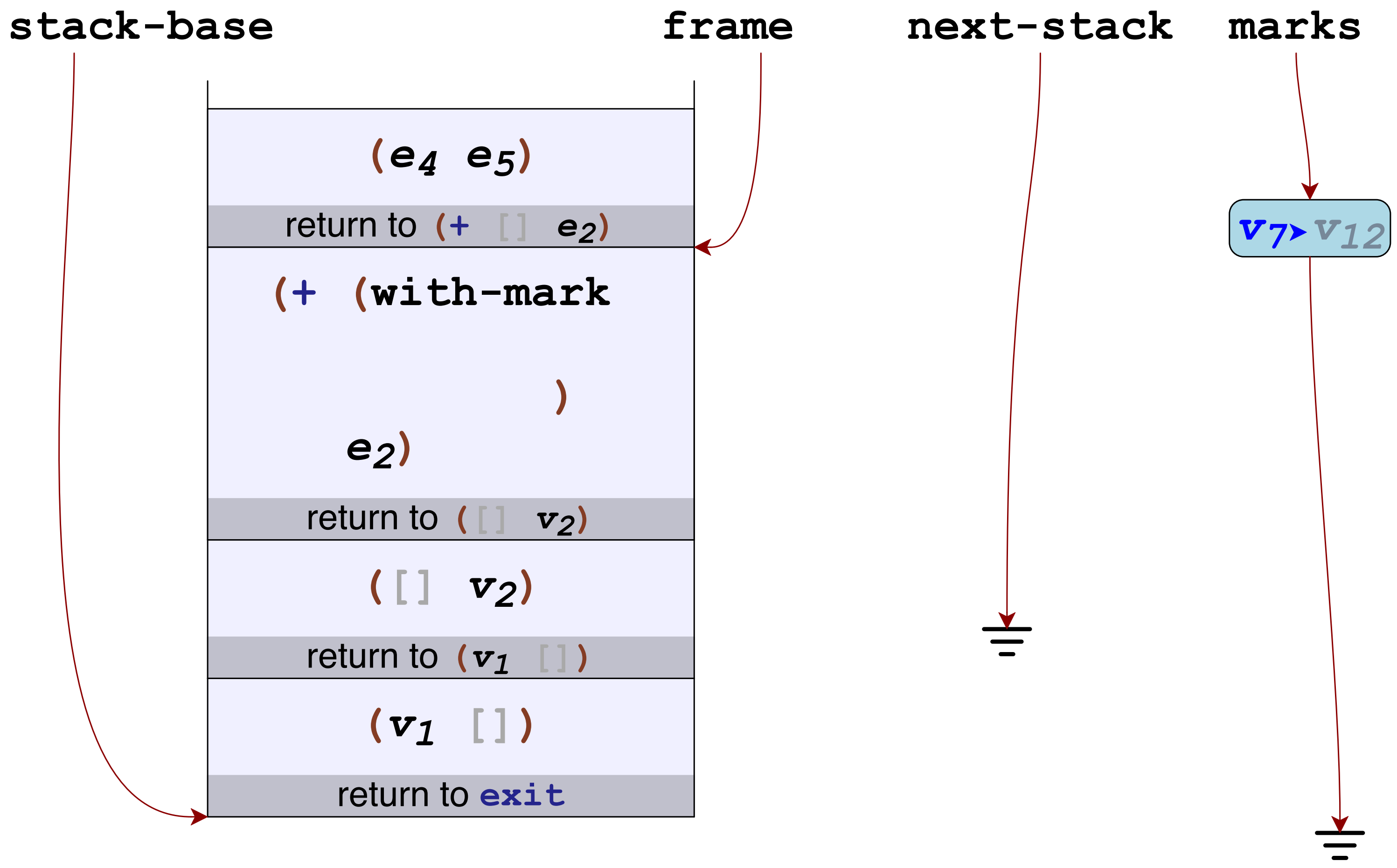
Non-Tail Mark with a Primitive Operation



Non-Tail Mark with a Function Call



Non-Tail Mark with a Function Call



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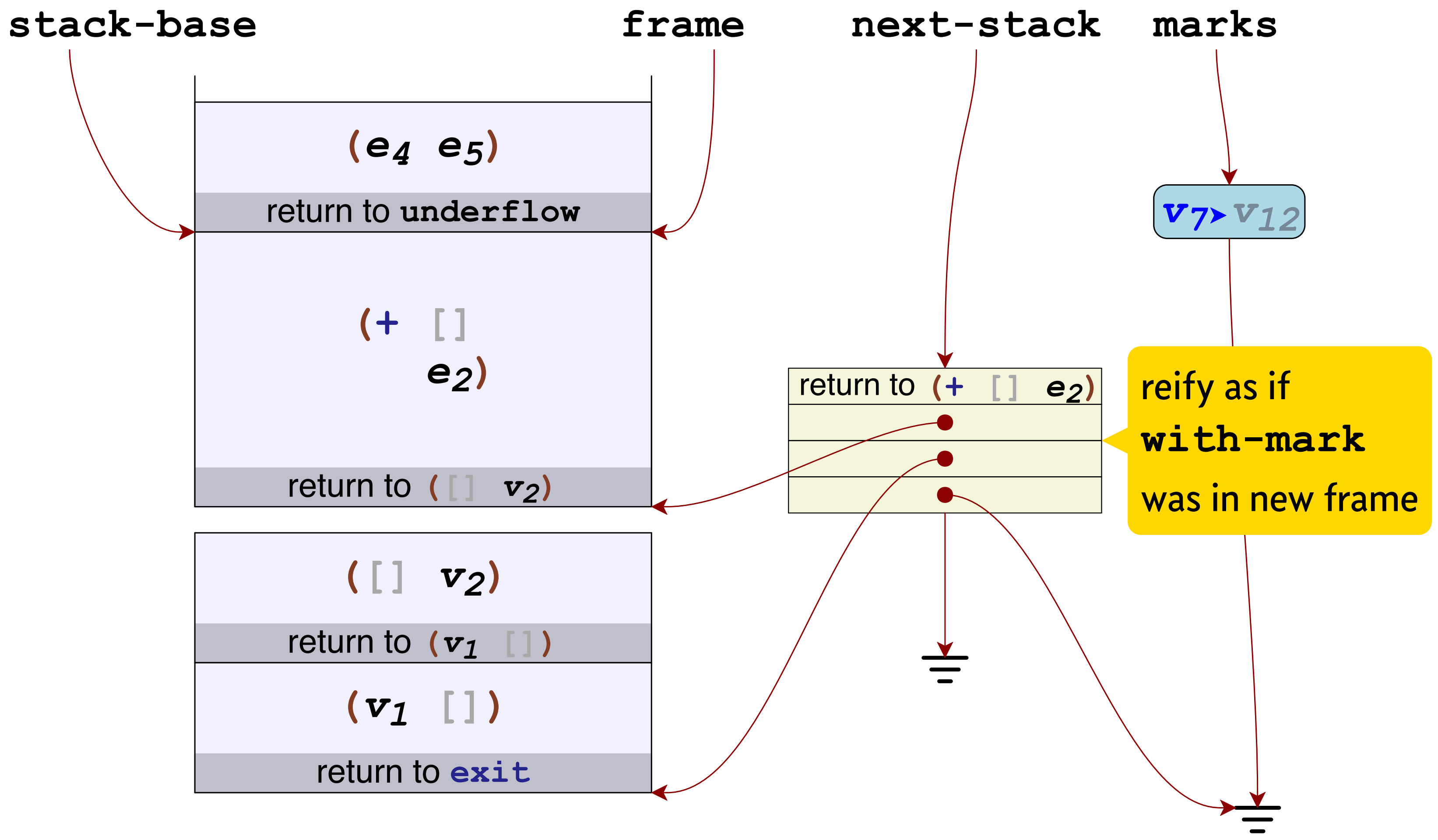
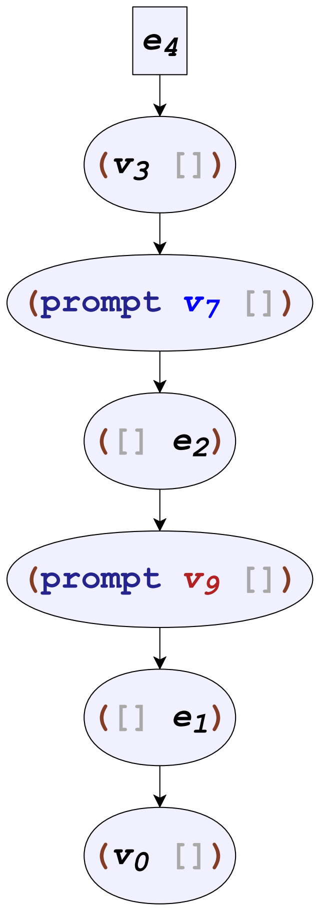


Capturing Delimited Continuations



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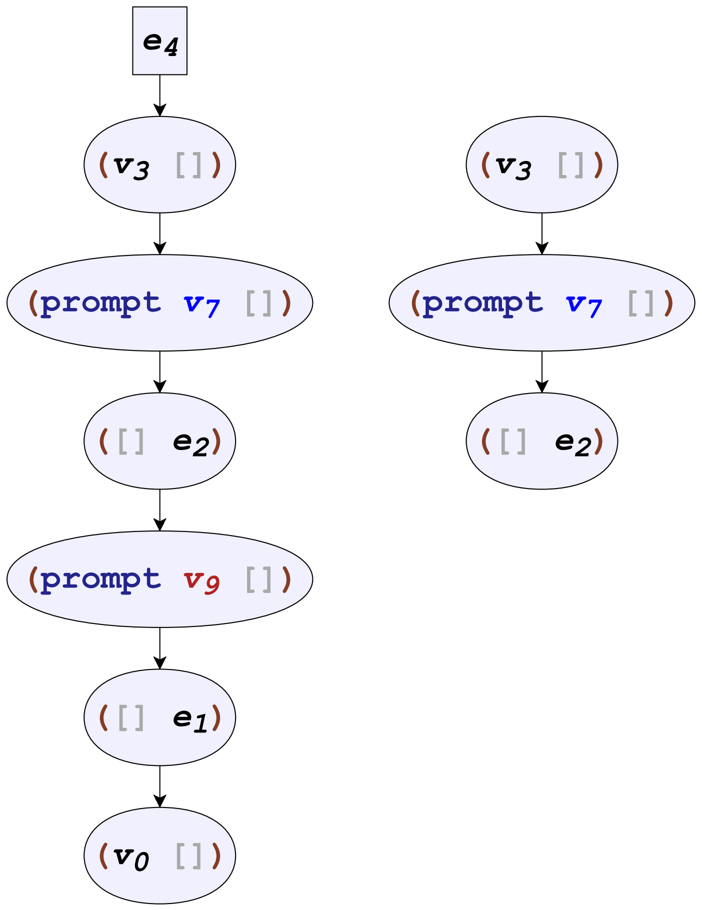
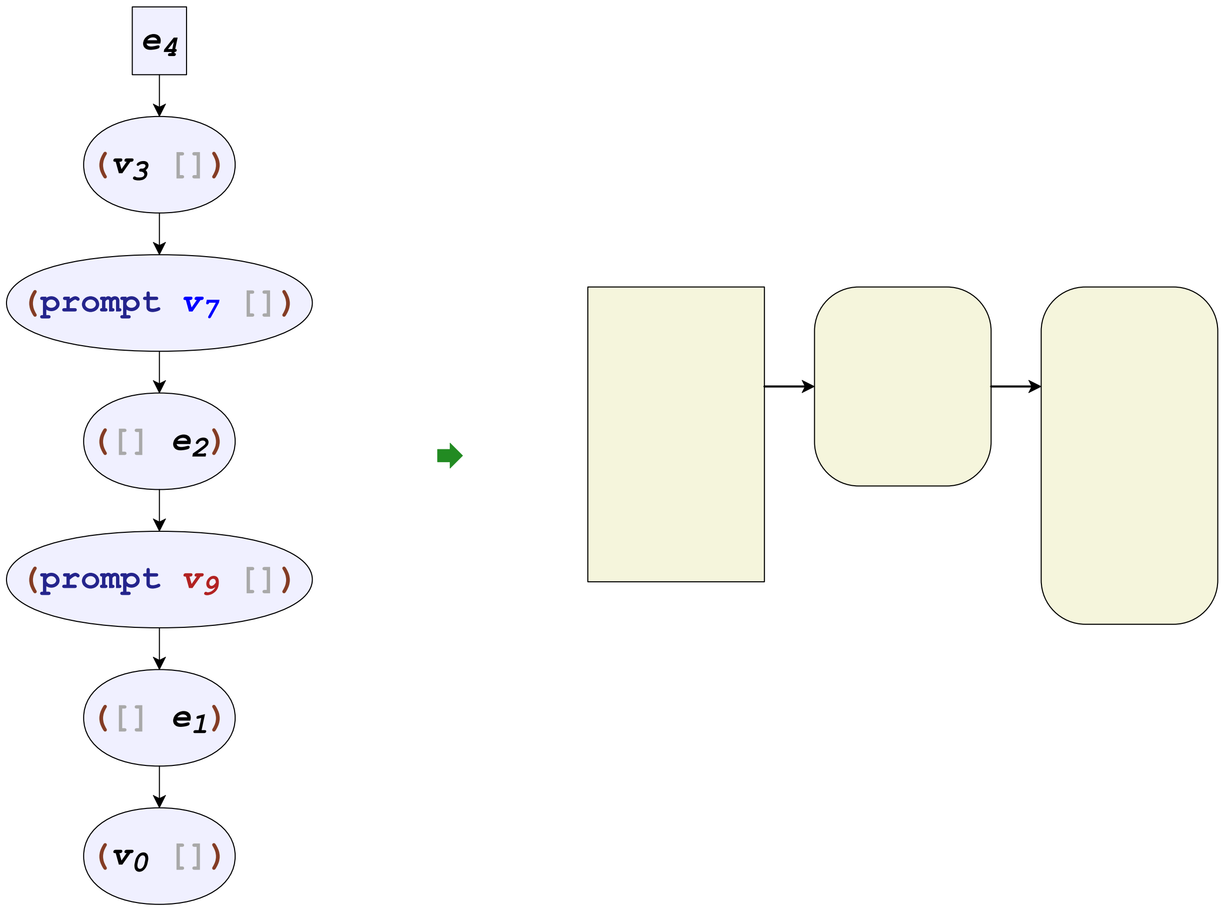


Delimited Continuations via Metacontinuations



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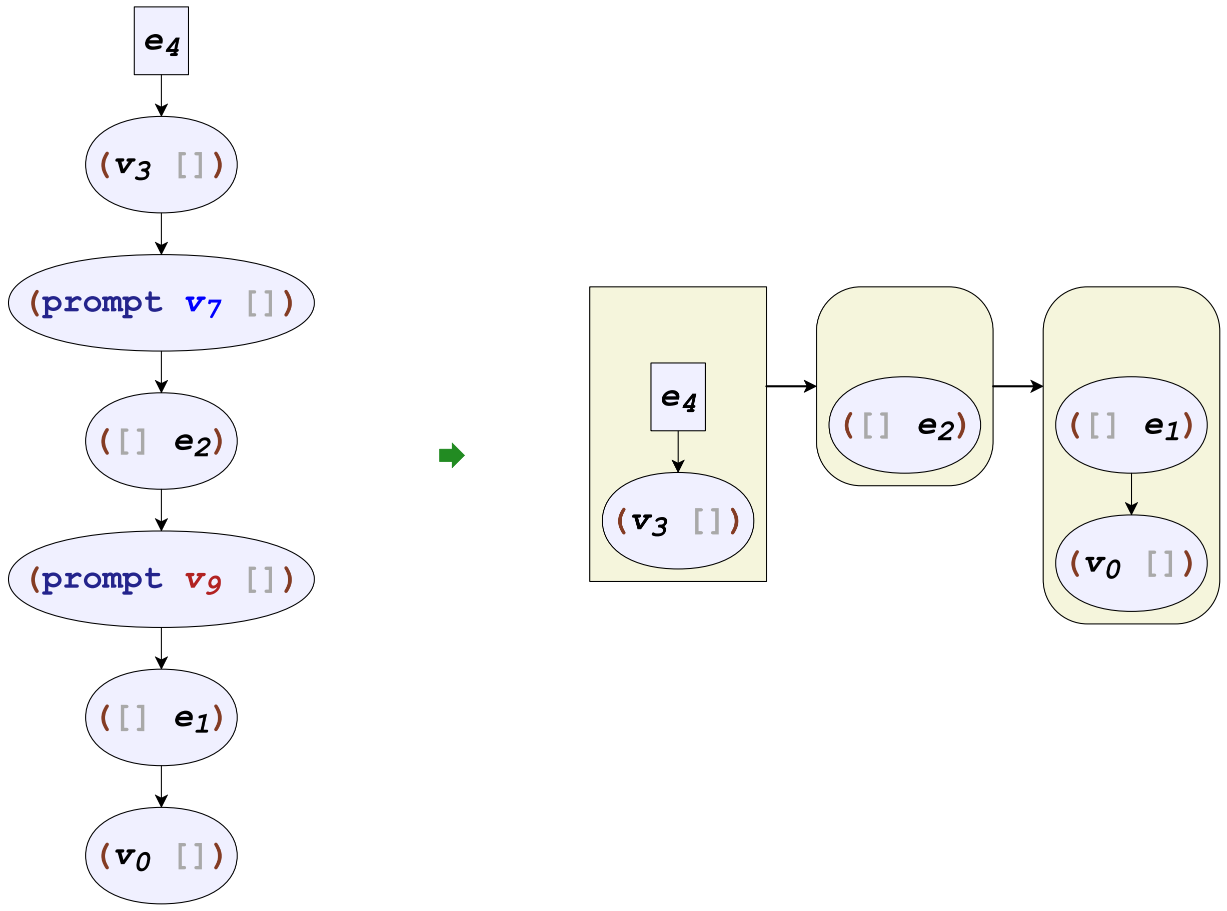

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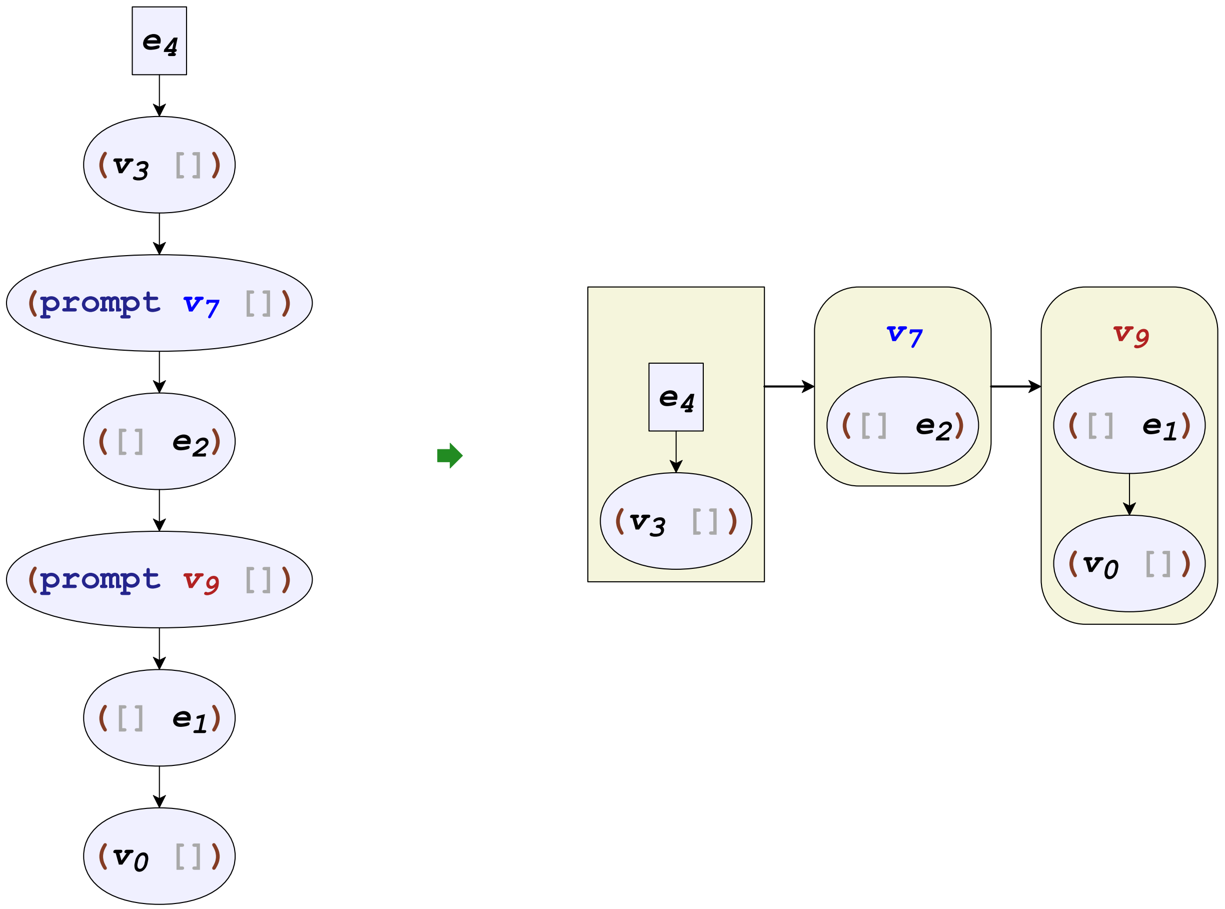

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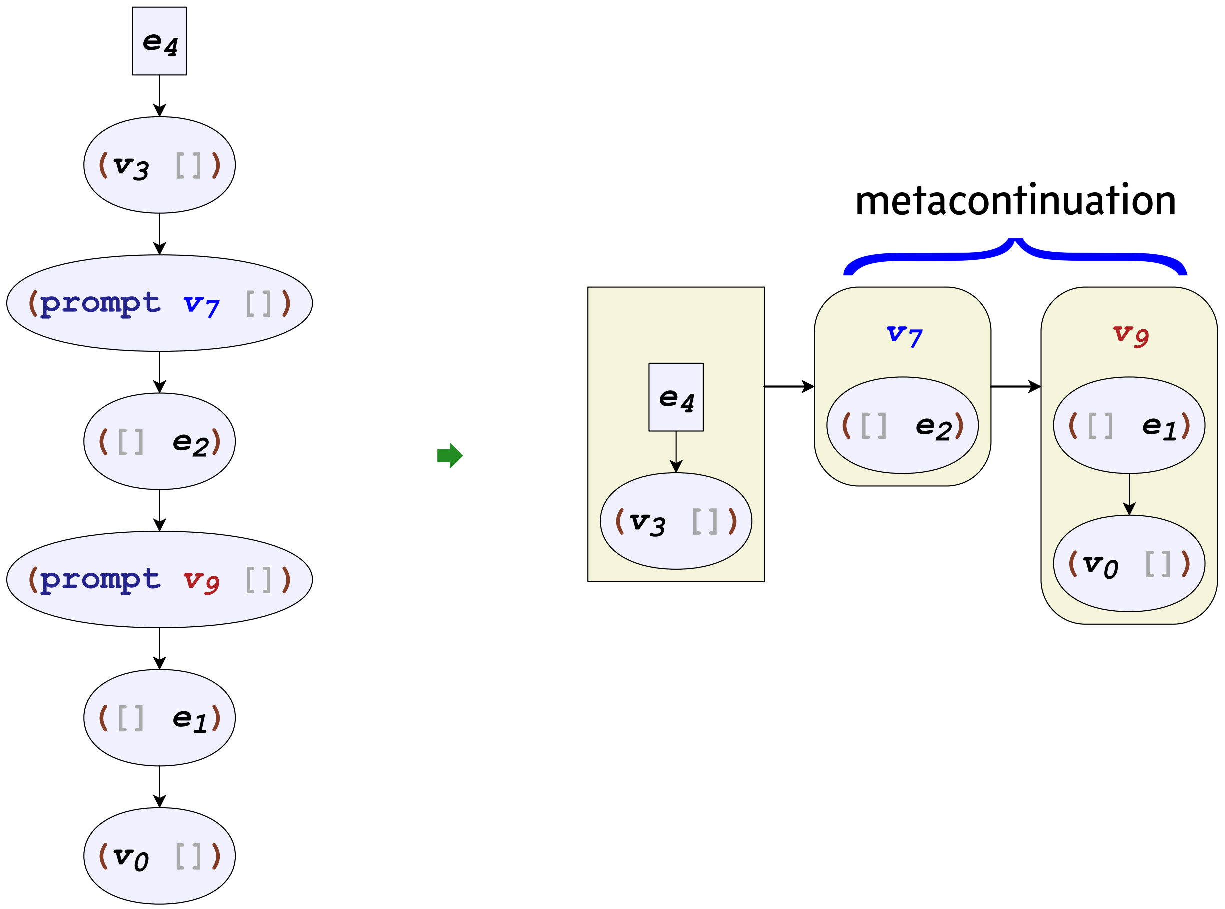

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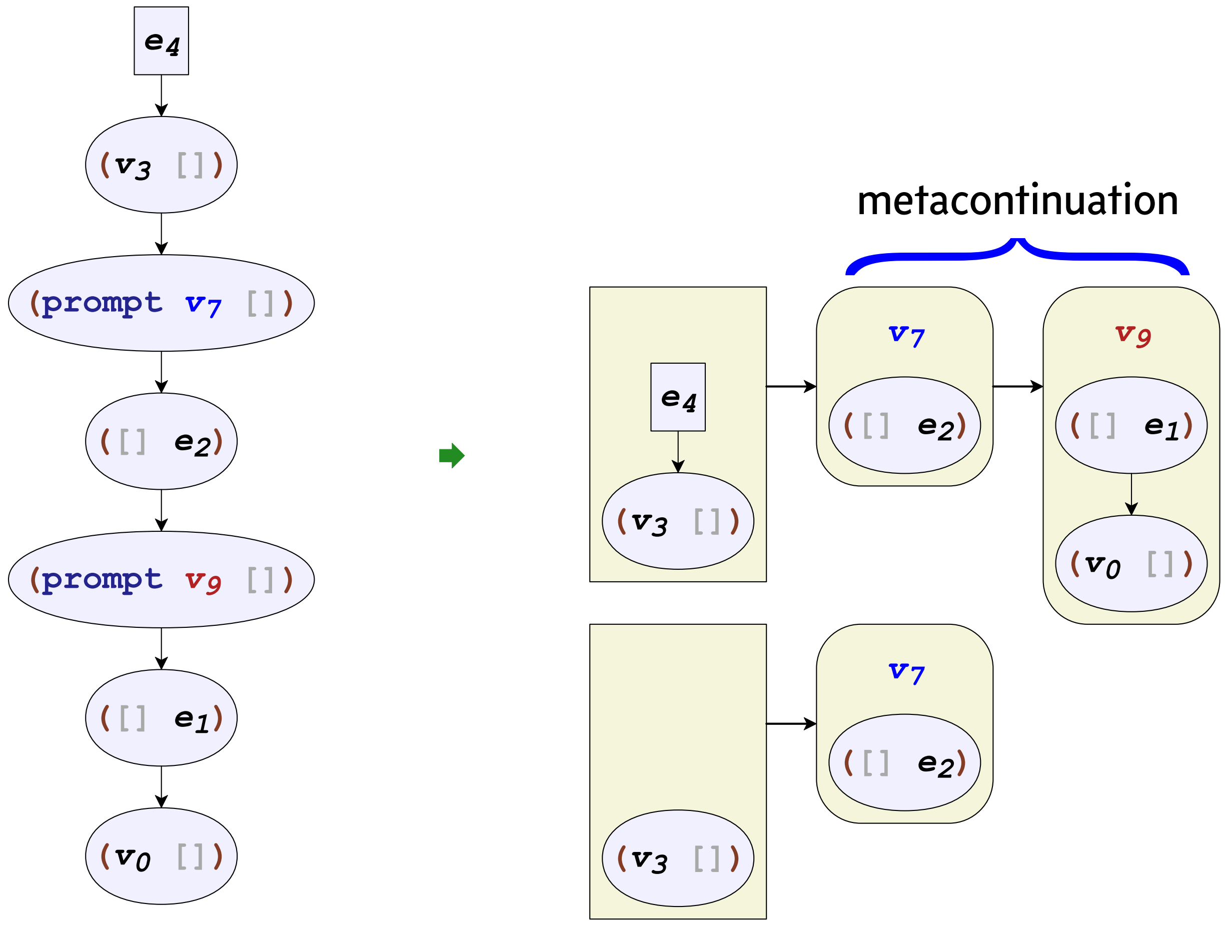
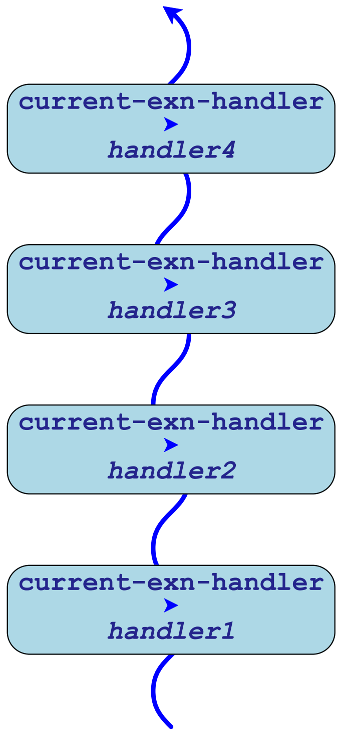


Exceptions

`with-handlers` and `raise` implemented with

- `with-mark` to register a handler
- `prompt` to escape
- `current-marks` to find a handler



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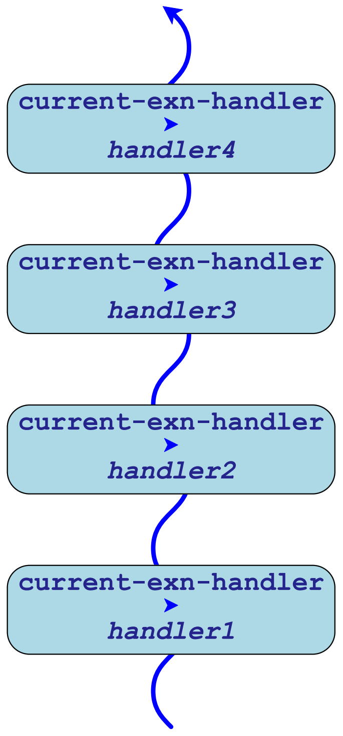

current-exn-handler ➤ handler4
current-exn-handler ➤ handler3
current-exn-handler ➤ handler2
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Engines (proto-threads)

An *engine* runs a thunk for a while:

- Completes or suspends after a given timeout
- Can resume suspended with a new timeout

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(fib 5)
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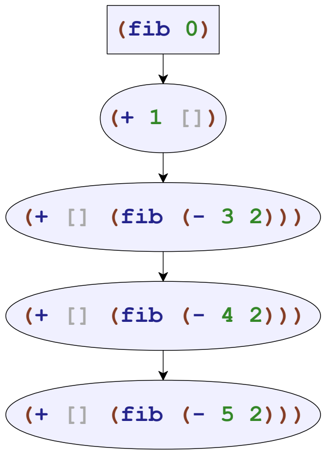

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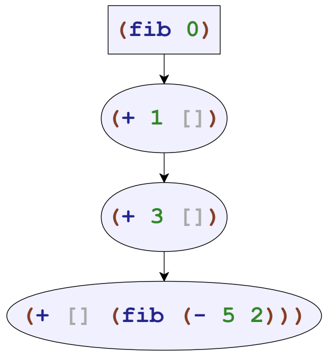

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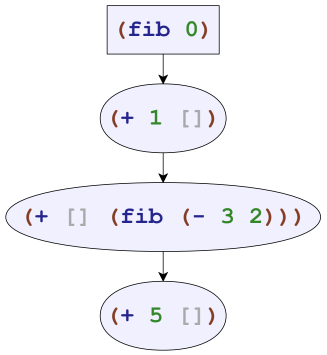

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8

Engines (proto-threads)

`make-engine` implemented with

- **`start-timer`** to interrupt
- **`timer-interrupt-handler`** to handle interrupt
- **`call/cc`** to capture during interrupt
- **`call-in-continuation/no-wind`** to suspend/resume

`start-timer` and **`timer-interrupt-handler`** enabled by **`(check-event)`** calls injected by compiler

Threads (green)

`thread` and events implemented with

- **`make-engine`** to run threads
- **`with-cont-mark`** to enable/disable breaks (Ctl-C)

Initial **`prompt`** in a thread ensures portable continuations

Racket's Intermediate Language for Control

Racket

Continuations
function [tail] calls
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continuation application
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Prompts
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rich set of constructs to support cooperating languages and libaries

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