A Calling Convention for Subroutines

- Put label for continuation in the **`continue`** register
- Goto subroutine entry point (label)
    - Do subroutine computations
    - Put result in identified registers (e.g. **`val`**)
    - Goto (return to) location specified by **`continue`** register

```
  (assign x (op +) (reg x) (reg y))
  (assign inp1 (op *) (reg y) (const 5))
  (assign continue (label after-call))
  (goto (label some-subroutine))
after-call
  (assign y (op +) (reg val) (reg x))


some-subroutine
  (assign x (op *) (reg inp1) (reg inp1))
  (assign val (op -) (reg inp1) (reg x))
  (goto (reg continue))
```

A Calling Convention for Subroutines

- Save any registers that will be needed later onto stack
  - Put label for continuation in the **`continue`** register
  - Goto subroutine entry point (label)
    - Do subroutine computations
    - Put result in identified registers (e.g. **`val`**)
    - Goto (return to) location specified by **`continue`** register
- Restore saved registers from the stack

```
  (assign x (op +) (reg x) (reg y))
  (assign inp1 (op *) (reg y) (const 5))
  (save x)
  (assign continue (label after-call))
  (goto (label some-subroutine))
after-call
  (restore x)
  (assign y (op +) (reg val) (reg x))


some-subroutine
  (assign x (op *) (reg inp1) (reg inp1))
  (assign val (op -) (reg inp1) (reg x))
  (goto (reg continue))
```

-

Stack Discipline - Inside a Subroutine

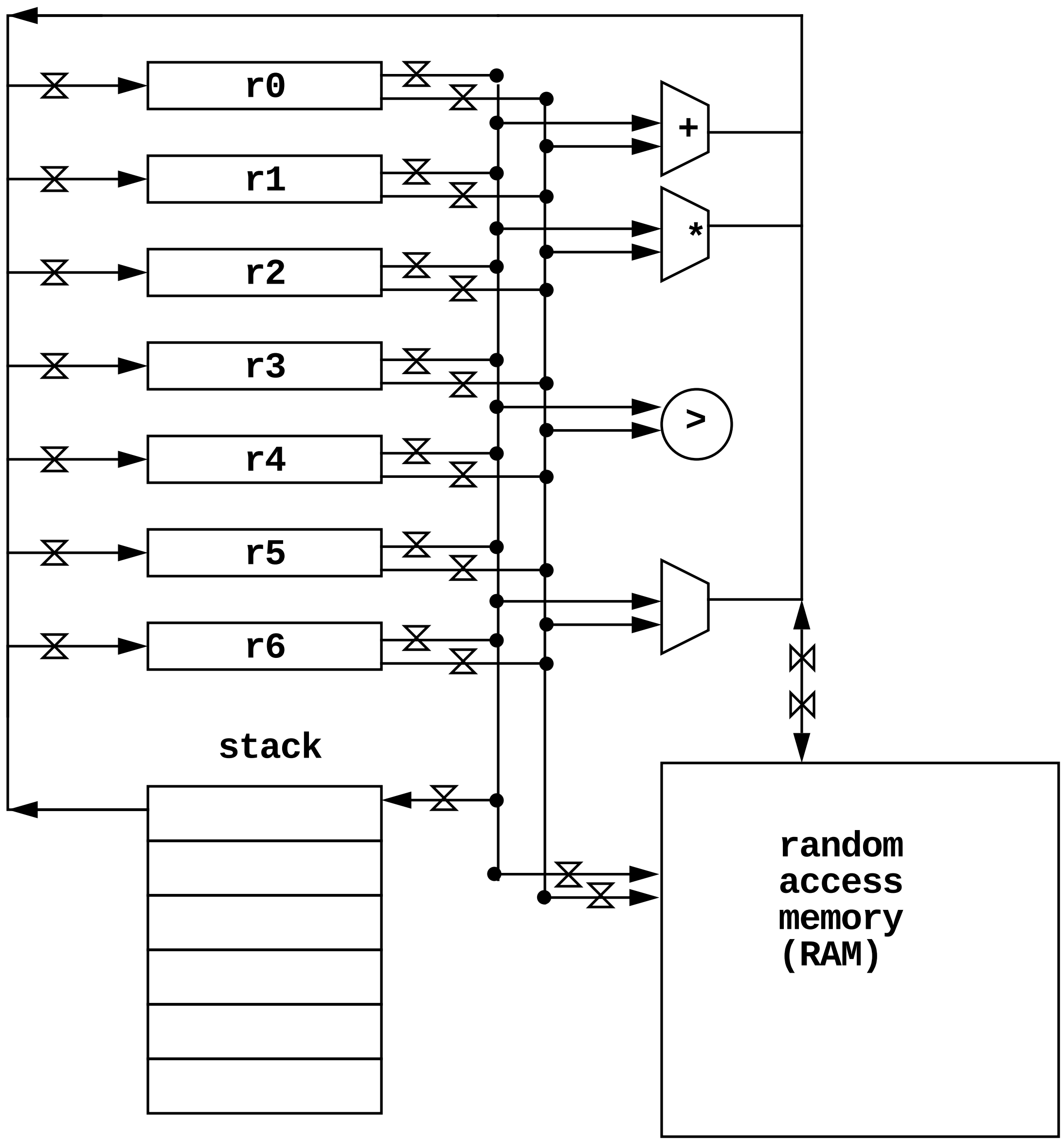
- A called subroutine can use the stack to perform its function

- However, that subroutine should put the stack back the way it was before returning

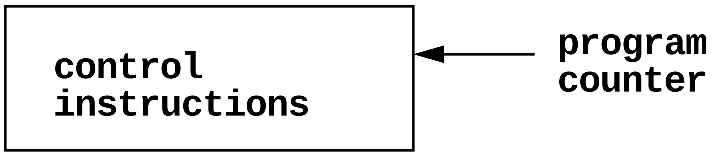
- Other special case contracts regarding stack use are possible -- but use with caution!

A General Purpose Register Machine

Data Flow:

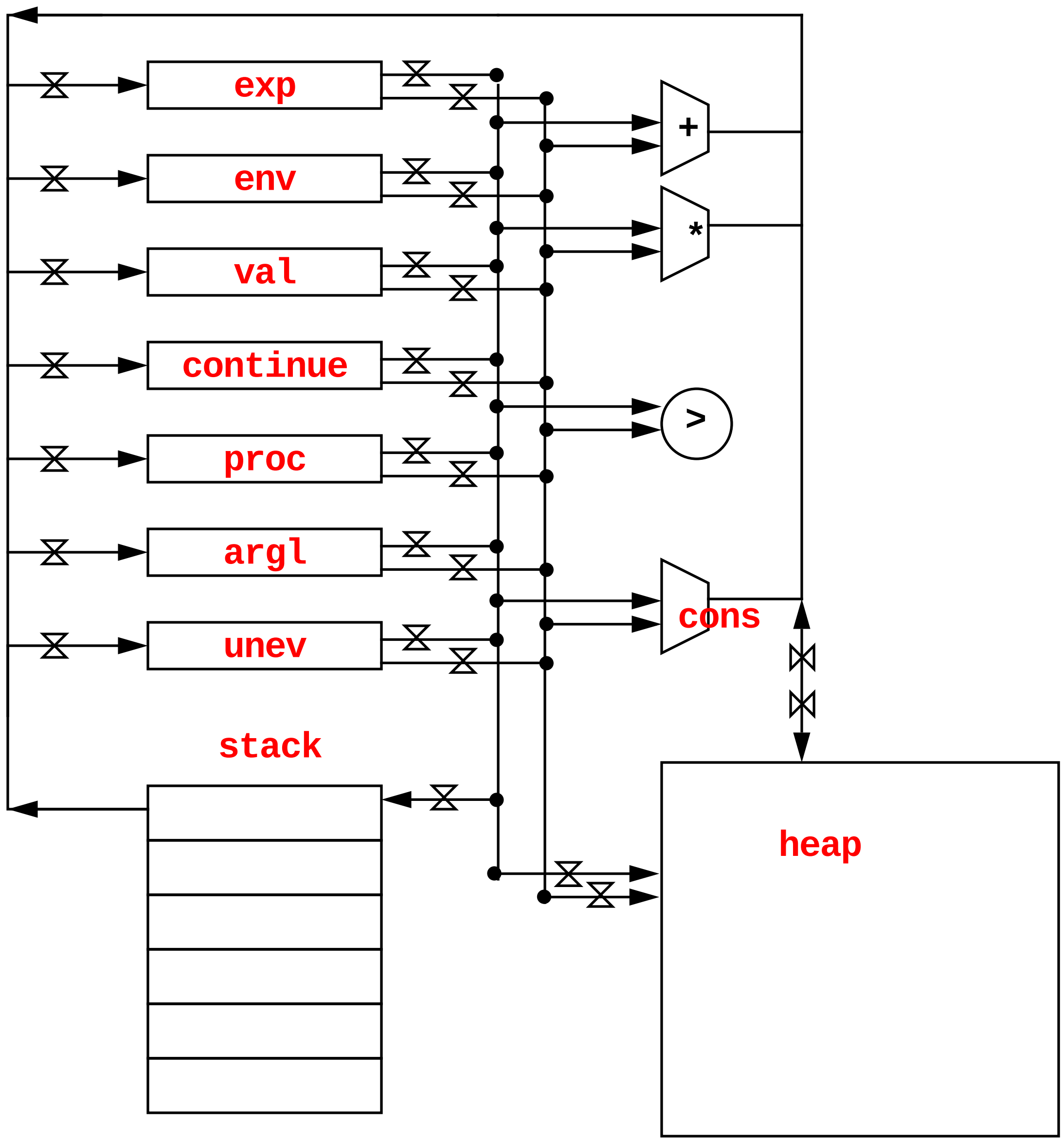


Control Flow:

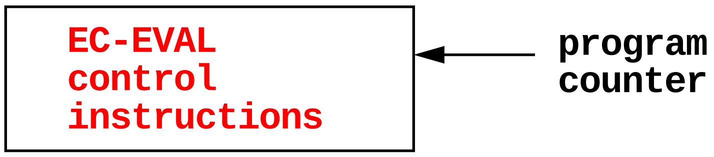


Scheme Interpreter - Register Machine

Data Flow:



Control Flow:



Implementing a Scheme Interpreter in Assembly Language

1. Registers

- **exp**	The expression to be evaluated
- **env**	The environment in which to find variable vals
- **val**	Where the value is stored when **eval** is done
- **continue**	The label to resume at when **eval** is done
- **argl**	The arguments to a procedure to be applied
- **proc**	The procedure that is to be applied
- **unev**	Either uneval'd subexpressions of a combination (which go into **proc** and **argl** after they are evaluated), or the subexpressions of a **begin** expression that is being evaluated

2. Primitive Operations:
   - Basic mathematical operations (e.g. **+, -, *, /**)
   - Predicates (e.g. **=, >, <**, etc.)
   - Compound data operations (e.g. **cons, car, cdr, null?**)
   - Environment manipulation (e.g. **lookup-variable, extend-environment**)
   - Expression syntax operations (e.g. **if-predicate**)

3. Stack

4. Heap:
   - random access memory for storage of **cons** cells and other objects in the environment

MC-EVAL

```
;; The Core Evaluator
(define (mc-eval exp env)
  (cond ((self-evaluating? exp) exp)
        ((variable? exp) (lookup-variable-value exp env))
        ((quoted? exp) (text-of-quotation exp))
        ((assignment? exp) (eval-assignment exp env))
        ((definition? exp) (eval-definition exp env))
        ((if? exp) (eval-if exp env))
        ((lambda? exp)
         (make-procedure (lambda-parameters exp)
                         (lambda-body exp) env))
        ((begin? exp)
         (eval-sequence (begin-actions exp) env))
        ((application? exp)
         (eval-application exp env))
        (else (error "Unknown expression" exp))))

(define (eval-if exp env)
  (if (true? (eval (if-predicate exp) env))
      (eval (if-consequent exp) env)
      (eval (if-alternative exp) env)))
```

Eval-dispatch Contract

1. **`exp`** has an expression to be evaluated
2. **`env`** has an environment to be used for the evaluation
3. **`continue`** has a label to be used to deliver the result
4. When the value has been computed, it will be placed in the **`val`** register and computing will continue at the label stored in the **`continue`** register
5. The stack will be returned to its state at the beginning of **`eval-dispatch`** (that is, anything added to the stack will have be restored back off the stack, and nothing originally on the stack will have been removed from the stack)
6. Any other registers may be obliterated!

Eval-dispatch

```
eval-dispatch
  (test (op self-evaluating?) (reg exp))
  (branch (label ev-self-eval))
  (test (op quoted?) (reg exp))
  (branch (label ev-quoted))
  (test (op variable?) (reg exp))
  (branch (label ev-variable))
  (test (op assignment?) (reg exp))
  (branch (label ev-assignment))
  (test (op definition?) (reg exp))
  (branch (label ev-definition))
  (test (op if?) (reg exp))
  (branch (label ev-if))
  (test (op lambda?) (reg exp))
  (branch (label ev-lambda))
  (test (op begin?) (reg exp))
  (branch (label ev-begin))
  (test (op cond?) (reg exp))
  (branch (label ev-cond))
  (test (op let?) (reg exp))
  (branch (label ev-let))
  (test (op application?) (reg exp))
  (branch (label ev-application))
  (goto (label unknown-expression-type-error))
```

Evaluation of Simple Expressions

```
ev-self-eval
  (assign val (reg exp))
  (goto (reg continue))

ev-quoted
  (assign val (op text-of-quotation) (reg exp))
  (goto (reg continue))

ev-variable
  (assign val (op lookup-variable-value)
              (reg exp) (reg env))
  (goto (reg continue))

ev-lambda
  (assign unev (op lambda-parameters) (reg exp))
  (assign exp (op lambda-body) (reg exp))
  (assign val (op make-procedure)
              (reg unev) (reg exp) (reg env))
  (goto (reg continue))
```

Details: Syntax, Memory Manipulation

In this discussion, we ignore the details of

- Syntax manipulation
- Memory management
  - Creation of list structured memory
  - Management of the environment

These can likewise be implemented in the register machine:

```
...
(test (op lambda?) (reg exp))
(branch (label ev-if))
...
```

Becomes

```
(assign val (op gettag) (reg exp))
(test (op eq?) (reg val) (const ’lambda))
(branch (label ev-lambda))
```

And

```
(assign unev (op lambda-parameters) (reg exp))
```

Becomes

```
(assign unev (op cdr) (reg exp))
(assign unev (op car) (reg unev))
```

Eval-if

Strategy:

1. Make a recursive call to evaluate the predicate
   -> Deferred operations: the consequent or the alternative

2. After return, turn control over to `eval-dispatch` to handle either the alternative or the consequent
   -> Do NOT make a recursive call -- no deferred ops!

```
ev-if
  (save exp)          ;save expression for later
  (save env)
  (save continue)
  (assign continue (label ev-if-decide))
  (assign exp (op if-predicate) (reg exp))
  (goto (label eval-dispatch)) ;evaluate the predicate

ev-if-decide
  (restore continue)
  (restore env)
  (restore exp)
  (test (op true?) (reg val))
  (branch (label ev-if-consequent))
ev-if-alternative
  (assign exp (op if-alternative) (reg exp))
  (goto (label eval-dispatch))
ev-if-consequent
  (assign exp (op if-consequent) (reg exp))
  (goto (label eval-dispatch))
```

MC-EVAL

```
;; The Core Evaluator
(define (mc-eval exp env)
  (cond ((self-evaluating? exp) exp)
        ((variable? exp) (lookup-variable-value exp env))
        ((quoted? exp) (text-of-quotation exp))
        ((assignment? exp) (eval-assignment exp env))
        ((definition? exp) (eval-definition exp env))
        ((if? exp) (eval-if exp env))
        ((lambda? exp)
         (make-procedure (lambda-parameters exp)
                         (lambda-body exp) env))
        ((begin? exp)
         (eval-sequence (begin-actions exp) env))
        ((application? exp)
         (eval-application exp env))
        (else (error "Unknown expression" exp))))

(define (eval-application exp env)
  (apply (eval (operator exp) env)
         (list-of-values (operands exp) env)))

(define (list-of-values exps env)
  (cond ((no-operands? exps) '())
        (else
          (cons (eval (first-operand exps) env)
                (list-of-values
                  (rest-operands exps)
                  env)))))
```

MC-APPLY

```
(define (mc-apply procedure arguments)
  (cond ((primitive-procedure? procedure)
         (apply-primitive-procedure procedure arguments))
        ((compound-procedure? procedure)
         (eval-sequence
          (procedure-body procedure)
          (extend-environment
            (procedure-parameters procedure)
            arguments
            (procedure-environment procedure))))
        (else (error "Unknown proc  -- APPLY"
                     procedure))))
```

Apply-dispatch Contract

1. **proc** contains a procedure (primitive or compound) that is to be applied
2. **argl** contains the arguments to the procedure
3. The top of the stack contains a label to be used to deliver the result
4. When the value has been computed, it will be placed in the **val** register, and computation will continue at the location originally stored at the top of the stack
5. The stack will have had one item (the **continue** label) removed from it. Nothing else on the stack when **apply-dispatch** started will have been changed
6. Any other registers may be obliterated

Apply-dispatch

```
apply-dispatch  ;expects continuation to be on the stack
  (test (op primitive-procedure?) (reg proc))
  (branch (label primitive-apply))
  (test (op compound-procedure?) (reg proc))
  (branch (label compound-apply))
  (goto (label unknown-procedure-type-error))

primitive-apply
  (assign val (op apply-primitive-procedure)
              (reg proc) (reg argl))
  (restore continue)
  (goto (reg continue))

compound-apply
  (assign unev (op procedure-parameters) (reg proc))
  (assign env (op procedure-environment) (reg proc))
  (assign env (op extend-environment)
              (reg unev) (reg argl) (reg env))
  (assign unev (op procedure-body) (reg proc))
  (goto (label ev-sequence))
```

MC-EVAL

```
;; The Core Evaluator
(define (mc-eval exp env)
  (cond ((self-evaluating? exp) exp)
        ((variable? exp) (lookup-variable-value exp env))
        ((quoted? exp) (text-of-quotation exp))
        ((assignment? exp) (eval-assignment exp env))
        ((definition? exp) (eval-definition exp env))
        ((if? exp) (eval-if exp env))
        ((lambda? exp)
         (make-procedure (lambda-parameters exp)
                         (lambda-body exp) env))
        ((begin? exp)
         (eval-sequence (begin-actions exp) env))
        ((application? exp)
         (eval-application exp env))
        (else (error "Unknown expression" exp))))

(define (eval-application exp env)
  (apply (eval (operator exp) env)
         (list-of-values (operands exp) env)))

(define (list-of-values exps env)
  (cond ((no-operands? exps) '())
        (else
          (cons (eval (first-operand exps) env)
                (list-of-values
                  (rest-operands exps)
                  env)))))
```

Evaluating an Application

Strategy: "Evaluate all subexpressions, then apply the value of the first to the values of the rest."

1. Evaluate the operator (using a subroutine call to **eval-dispatch**). Remember our calling convention & **eval-dispatch** contract!

```
ev-application
  (save continue)      ;dest for after application
  (save env)
  (assign unev (op operands) (reg exp))
  (save unev)          ;the operands
  (assign exp (op operator) (reg exp))
  (assign continue (label ev-appl-did-operator))
  (goto (label eval-dispatch)) ;eval the operator
```

2. Once we have the operator, we will save it away (in **proc**) and start working on the operands. Notice that the operands (in **unev**) and the environment are restored, but not the continuation - which remains on the stack.

```
ev-appl-did-operator   ;deferred ops - handle operands
  (restore unev)                      ;the operands
  (restore env)
  (assign argl (op empty-arglist))     ;init argl
  (assign proc (reg val))              ;the operator
  (test (op no-operands?) (reg unev))
  (branch (label apply-dispatch))    ;ready to apply!
  (save proc)          ;else we need to eval operands
```

3. Save the arguments that have been computed so far (and are in **argl**) so we can add on to them when we have the value of the next operand. See if this is the last operand. If so, handle it specially (because after the last one we don't need to save **env** or **unev** any more).

```
ev-appl-operand-loop
  (save argl)
  (assign exp (op first-operand) (reg unev))
  (test (op last-operand?) (reg unev))
  (branch (label ev-appl-last-arg))
  (save env)  ;prepare for subroutine call to compute
  (save unev) ; the next operand value
  (assign continue (label ev-appl-accumulate-arg))
  (goto (label eval-dispatch))
```

4. We have one more argument value, so get back the list of arguments remaining to evaluate (**unev**), the environment for the next argument (**env**), and the list of argument values already computed (**argl**). Add the value just computed to the list of computed arguments, remove one argument from the list remaining to compute, and return to step 3.

```
ev-appl-accumulate-arg
  (restore unev)
  (restore env)
  (restore argl)
  (assign argl (op adjoin-arg) (reg val) (reg argl))
  (assign unev (op rest-operands) (reg unev))
  (goto (label ev-appl-operand-loop))
```

5. Special case for computing the value of the last argument: don't save anything, but use a different continuation label. Remember that the original continuation for the combination is still on the stack from step 1!

```
ev-appl-last-arg
  (assign continue (label ev-appl-accum-last-arg))
  (goto (label eval-dispatch))
```

6. We've got the value of the last argument now. So get back all of the computed argument values (`argl`), add this last one to the list, get back the procedure to call (`proc`), and go do the application. Remember that the original continuation for the combination is still on the stack from step 1 - so we conform to the contract for apply-dispatch!

```
ev-appl-accum-last-arg
  (restore argl)
  (assign argl (op adjoin-arg) (reg val) (reg argl))
  (restore proc)
  (goto (label apply-dispatch))
```

Eval-sequence

```
(define (eval-sequence exps env)
  (cond ((last-exp? exps) (eval (first-exp exps) env))
        (else (eval (first-exp exps) env)
              (eval-sequence (rest-exps exps) env))))
```

BECOMES

```
ev-sequence
  (assign exp (op first-exp) (reg unev))
  (test (op last-exp?) (reg unev))
  (branch (label ev-sequence-last-exp))
  (save unev)
  (save env)
  (assign continue (label ev-sequence-continue))
  (goto (label eval-dispatch))
ev-sequence-continue
  (restore env)
  (restore unev)
  (assign unev (op rest-exps) (reg unev))
  (goto (label ev-sequence))
ev-sequence-last-exp
  (restore continue)
  (goto (label eval-dispatch))
```

Ev-sequence - With tail recursion broken

```
ev-sequence
  (test (op no-more-exps?) (reg unev))
  (branch (label ev-sequence-end))
  (assign exp (op first-exp) (reg unev))
  (save unev)
  (save env)
  (assign continue (label ev-sequence-continue))
  (goto (label eval-dispatch))
ev-sequence-continue
  (restore env)
  (restore unev)
  (assign unev (op rest-exps) (reg unev))
  (goto (label ev-sequence))
ev-sequence-end
  (restore continue)
  (goto (reg continue))
```