SSA in Scheme

Static single assignment (SSA) :
assignment conversion (“boxing”),
alpha-renaming/alphatization,
and administrative normal form (ANF)

Roadmap

- Our compiler projects will target the LLVM backend.
- This will take us two more assignments:
  - Assignment 3: Fundamental simplifications, and implementation of continuations (& call/cc).
  - Assignment 4: Implementation of closures (closure conversion) and final code emission (LLVM IR).
- Assignment 5 focuses on top-level, matching, defines, etc

LLVM

- Major compiler framework: Clang (C/C++ on OSX), GHC, …
- LLVM IR: Assembly for a idealized virtual machine.
- IR allows an unbounded number of virtual registers:
  - Performs register allocation for various target platforms.
  - ***But,*** no register may shadow another or be mutated!
- Supports a variety of calling conventions (e.g., C, GHC, Swift, …).
- Uses low-level types (with flexible bit widths, e.g. i1, i32, i64, …).

```
x = a+1;
y = b*2;
y = (3*x) + (y*y);
```

Clang (C -> LLVM IR)

```
%x0 = add i64 %a0, 1
%y0 = mul i64 %b0, 2
%t0 = mul i64 3, %x0
%t1 = mul i64 %y0, %y0
%y1 = add i64 %t0, %t1
```

Static single assignment (SSA)?

- Significant added complexity in program analysis, optimization, and final code emission, arises from the fact that a single variable can be assigned in many places.

- This occurs both due to shadowing and direct mutation (`set!`).

- Thus each use of a variable X may hold a value assigned at one of several distinct points in the code.

- E.g., Constant propagation, common sub-expression elimination, type-recovery, control-flow analysis, *etc*.

SSA

- All variables are static, or `const` (in C/C++ terms).
- No variable name is reused (at least in an overlapping scope).
- Instead of a variable X with multiple assignment points, SSA requires these points to be explicit syntactically as distinct variables X_0, X_1, … X_i.
- When control diverges and then joins back together, join points are made explicit using a special phi form, e.g.,

$$X_5 \leftarrow \phi(X_2, X_4)$$

C-like IR

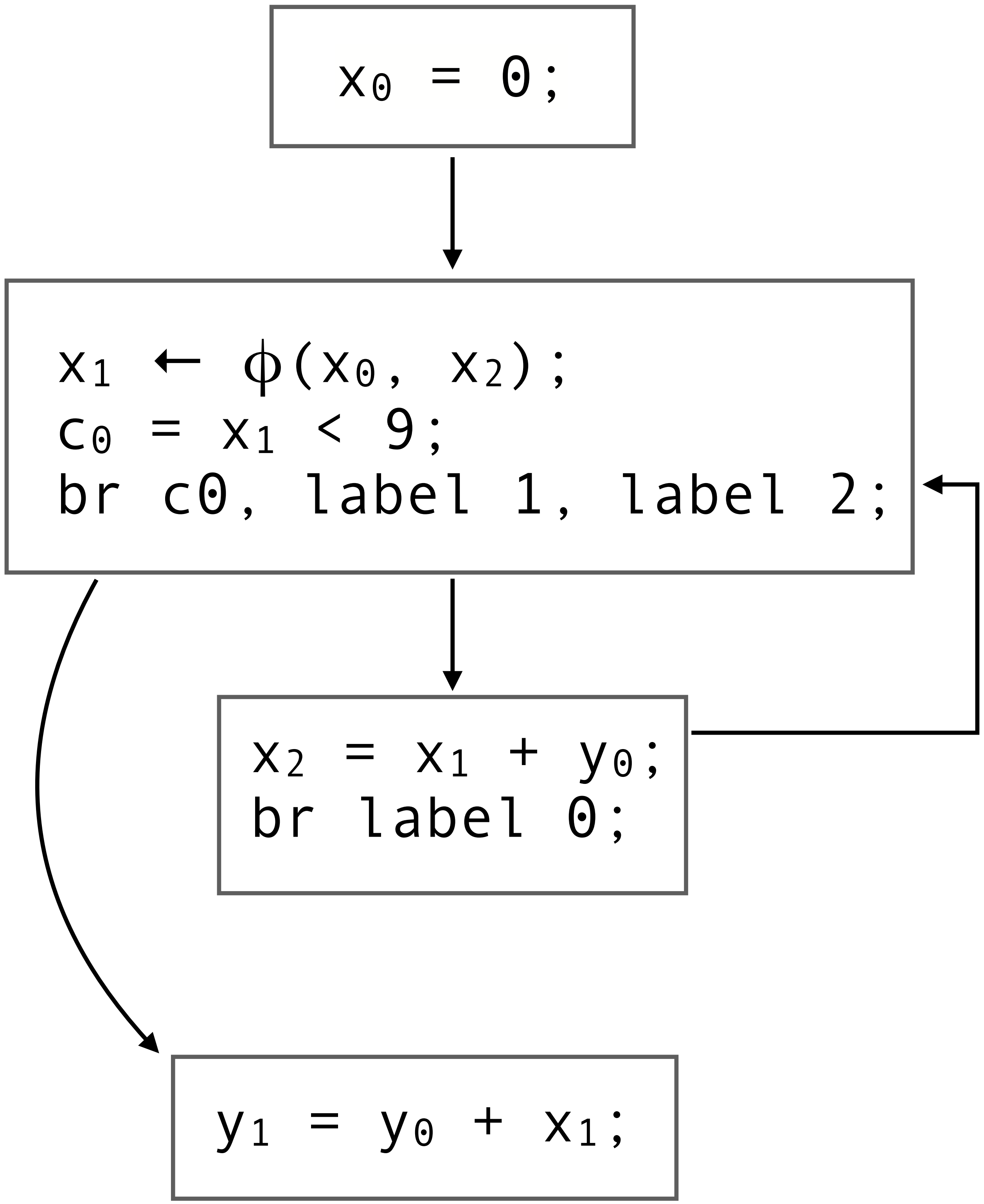
```
x = f(x);

if (x > y)
    x = 0;
else
{
    x += y;
    x *= x;
}

return x;
```

In SSA form

```
x_1 = f(x_0);

if (x_1 > y_0)
    x_2 = 0;
else
{
    x_3 = x_1 + y_0;
    x_4 = x_3 * x_3;
}
x_5 ← φ(x_2, x_4);

return x_5;
```

```
x = 0;

while (x < 9)
    x = x + y;

y += x;
```

```
x₀ = 0;

label 0:
 x₁ ← φ(x₀, x₂);
 c₀ = x₁ < 9;
 br c0, label 1, label 2;

label 1:
 x₂ = x₁ + y₀;
 br label 0;

label 2:
 y₁ = y₀ + x₁;
```



$x_0 = 0;$

label 0:

$x_1 \leftarrow \phi(x_0,\ x_2);$

$c_0 = x_1 < 9;$

br c0, label 1, label 2;

label 1:

$x_2 = x_1 + y_0;$

br label 0;

label 2:

$y_1 = y_0 + x_1;$

SSA in a Scheme IR?

- Assignment conversion
  - Eliminates `set!` by heap-allocating mutable values.
  - Replaces `(set! x y)` with `(prim vector-set! x 0 y)`.
- Alpha-renaming
  - Eliminates shadowing issues via alpha-conversion.
- Administrative normal form (ANF) conversion
  - Uses `let` to administratively bind all subexpressions.
  - Assigns subexpressions to a temporary intermediate variable.

Assignment conversion

- “Boxes” all mutable values, placing them on the heap.
- A box is a (heap-allocated) length-1 mutable vector.
- Mutable variables, when initialized, are placed in a box.
- When assigned, a mutable variable’s box is updated.
- When referenced, its value is retrieved from this box.

```
(lambda (x y)
  (set! x y)
  x)
```

⟶

```
(lambda (x y)
  (let ([x (make-vector 1 x)])
    (vector-set! x 0 y)
    (vector-ref x 0)))
```

α-renaming ("alphatization")

- Assign every binding point (e.g., at let- or lambda-forms) a unique variable name and rename all its references in a capture-avoiding manner.
- Can be done with a recursive AST walk and substitution env!

```
(define (alphatize e env)
  (match e
    [`(lambda (,x) ,e0)
     (define x+ (gensym x))
     `(lambda (,x+)
        ,(alphatize e0 (hash-set env x x+)))]
    [(? symbol? x)
     (hash-ref env x)]
    ...))
```

Administrative normal form (ANF)

- Partitions the grammar into complex expressions (e) and atomic expressions (ae)—variables, datums, etc.
- Expressions cannot contain sub-expressions, except possibly in tail position, and therefore must be `let`-bound.
- ANF-conversion syntactically enforces an evaluation order as an explicit stack of let forms binding each expression in turn.
- Replaces a multitude of different continuations with a single type of continuation: the `let`-continuation.

```
((f g) (+ a 1) (* b b))
```

ANF conversion

```
(let ([t0 (f g)])
  (let ([t1 (+ a 1)])
    (let ([t2 (* b b)])
      (t0 t1 t2))))
```

```
x = a+1;
y = b*2;
y = (3*x) + (y*y);
```

```
(let ([x (+ a 1)])
  (let ([y (* b 2)])
    (let ([y (+ (* 3 x) (* y y))])
      ...)))
```

ANF conversion & alpha-renaming

```
(let ([x0 (+ a0 1)])
  (let ([y0 (* b0 2)])
    (let ([t0 (* 3 x0)])
      (let ([t1 (* y0 y0)])
        (let ([y1 (+ t0 t1)])
          ...)))))
```

What about join points?

```
x₁ = f(x₀);

if (x₁ > y₀)
    x₂ = 0;
else
{
    x₃ = x₁ + y₀;
    x₄ = x₃ * x₃;
}
X₅ ← φ(x₂, x₄);

return x₅;
```

```
(let ([x1 (f x0)])
  (let ([x5
         (if (> x1 y0)
           (let ([x2 0]) x2)
           (let ([x3 (+ x1 y0)])
             (let ([x4 (* x3 x3)]))
               x4))])
    x5))
```

What about join points?

```
x₀ = 0;

label 0:
 x₁ ← ϕ(x₀, x₂);
 c₀ = x₁ < 9;
 br c0, label 1, label 2;

label 1:
 x₂ = x₁ + y₀;
 br label 0;

label 2:
 x₃ ← ϕ(x₁, x₂);
 y₁ = y₀ + x₃;
```

```
(let ([x0 0])
  (let ([x3
         (let loop0 ([x1 x0])
           (if (< x1 9)
             (let ([x2 (+ x1 y0)])
               (loop0 x2))
             x1))])
    (let ([y1 (+ y0 x3)])
      ...)))
```

They're just calls/returns!

```
(let ([x0 0])
  (let ([x3
         (letrec* ([loop0
                    (lambda (x1)
                      (if (< x1 9)
                        (let ([x2 (+ x1 y0)])
                          (loop0 x2))
                        x1))])
           (loop0 x0))])
    (let ([y1 (+ y0 x3)])
      ...)))
```

```
(let ([x0 0])
  (let ([x3
         (letrec* ([loop0
                    (lambda (x1)
                      (if (< x1 9)
                        (let ([x2 (+ x1 y0)])
                          (loop0 x2))
                        x1))])
           (loop0 x0))])
    (let ([y1 (+ y0 x3)])
      ...)))
```

```
(let ([x0 0])
  (let ([x3
         (let ([loop0 ‘()])
           (set! loop0
                 (lambda (x1)
                   (if (< x1 9)
                       (let ([x2 (+ x1 y0)])
                         (loop0 x2))
                       x1)))
           (loop0 x0))])
    (let ([y1 (+ y0 x3)])
      ...)))
```

```
(let ([x0 0])
  (let ([x3
         (let ([loop0 ‘()])
           (set! loop0
                 (lambda (x1)
                   (if (< x1 9)
                       (let ([x2 (+ x1 y0)])
                         (loop0 x2))
                       x1)))
           (loop0 x0))])
    (let ([y1 (+ y0 x3)])
      ...)))
```

```
(let ([x0 0])
  (let ([x3
         (let ([loop0 (make-vector 1 '())])
           (vector-set! loop0 0
             (lambda (x1)
               (if (< x1 9)
                   (let ([x2 (+ x1 y0)])
                     (let ([loop2
                            (vector-ref loop0 0)])
                       (loop2 x2)))
                   x1)))
           (let ([loop1 (vector-ref loop0 0)])
             (loop1 x0))))])
    (let ([y1 (+ y0 x3)])
      ...)))
```