CSE401: Code Generation

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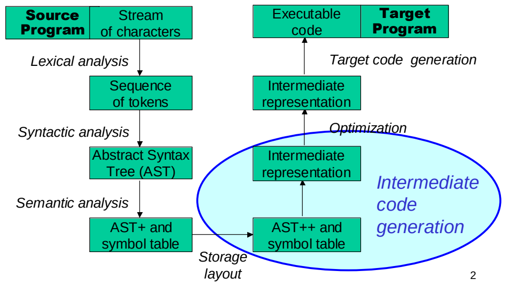
Slides by Chambers, Eggers, Notkin, Ruzzo, Snyder and others

Prototype compiler structure



Intermediate code generation

- Purpose: translate ASTs into linear sequence of simple statements called *intermediate code*
  - Can optimize intermediate code in place
  - A later pass translates intermediate code into *target code*
- Intermediate code is machine-independent
  - Don't worry about details of the target machine (e.g., number of registers, kinds of instruction formats)
  - Intermediate code generator and optimizer are portable across target machines
- Intermediate code is simple and explicit
  - Decomposes code generation problem into simpler pieces
  - Constructs implicit in the AST become explicit in the intermediate code

PL/0

- Our PL/0 compiler merges intermediate and target code generation for simplicity of coding

Three-address code:
a simple intermediate language

- Each statement has at most one operation in its right-hand side
  - Introduce extra temporary variables if needed
- Control structures are broken down into (conditional) branch statements
- Pointer and address calculations are made explicit

Examples

A.
```
x := y * z + q / r
```

A.
```
t1 := y * z
t2 := q / r
x := t1 + t2
```

B.
```
for i := 0 to 10 do …
end
```

B.
```
i := 0
loop:
  if i < 10 goto done;
  …
  i := i + 1
  goto loop;
done:
```

C.
```
x := a[i]
```

C.
```
t1 := i * 4
x  := *(a + t1)
```

Available operations

```
var := constant
var := var
var := unop var
var := var binop var
var := proc(var, …)
var := &var
var := *(var + constant)
*(var + constant) := var
if var goto label
goto label
label:
return var
return
```

generally *one* operation per statement, not arbitrary expressions, etc.

ICG (Intermediate code generation) from ASTs

- Once again (like type checking), we'll do a tree traversal
- Cases
  - expressions
  - assignment statements
  - control statements
  - declarations are already done

ICG for expressions

- How: tree walk, bottom-up, left-right, (largely postorder) assigning a new temporary for each result
- Pseudo-code

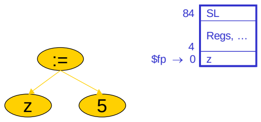
```
Name IntegerLiteral::codegen(STS* s) {
  result := new Name;
  emit(result := _value);
  return result;
}
```

Temps: just suppose we had infinitely many registers

Another pseudo-example

```
Name BinOp::codegen(SymTabScope* s) {
  Name e1 = _left->codegen(s);
  Name e2 = _right->codegen(s);
  result = new Name;
  emit(result := e1 _op e2);
  return result;
}
```

Example

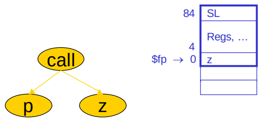


```
module main;
  var z:int;
  procedure p(var q:int);
    var a:array[5] of
          array[10] of int;
    var b:int;
  begin
    b := 1 + 2;
    b := b + z;
    q := q + 1;
    b := a[4][8];
    if b>1 then b:=0 end
  end p;
begin
  z := 5;
  p(z);
end main.
```

t1 := 5

$*(fp+z_{offset})$:= t1

Example



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  var z:int;
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    var a:array[5] of
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  begin
    b := 1 + 2;
    b := b + z;
    q := q + 1;
    b := a[4][8];
    if b>1 then b:=0 end
  end p;
begin
  z := 5;
  p(z);
end main.
```

t1 := z_{offset}

t2 := fp+t1

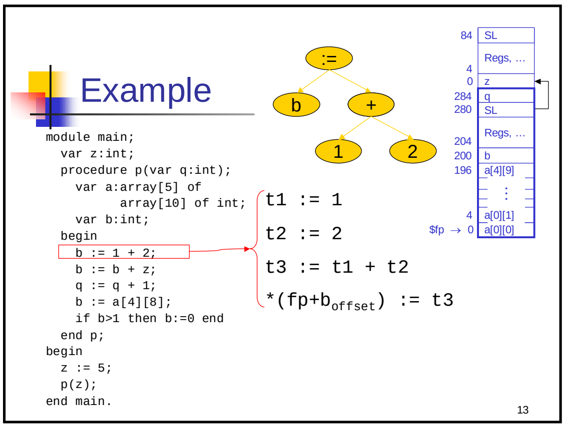
*(sp) := t2

sp := sp-4

*(sp) := fp

sp := sp-4

call p



Example

```
module main;
  var z:int;
  procedure p(var q:int);
    var a:array[5] of
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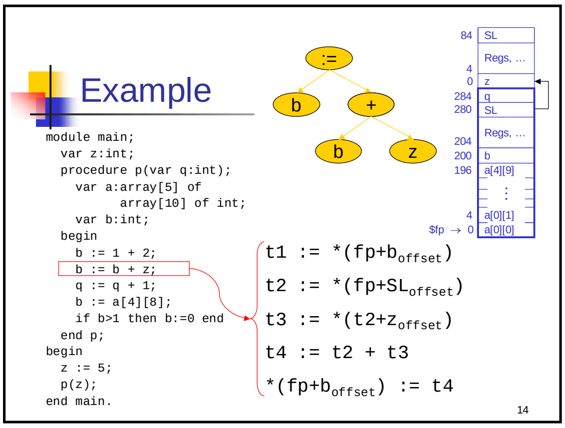
  begin
    b := 1 + 2;
    b := b + z;
    q := q + 1;
    b := a[4][8];
    if b>1 then b:=0 end
  end p;
begin
  z := 5;
  p(z);
end main.
```

t1 := 1

t2 := 2

t3 := t1 + t2

*(fp+b_{offset}) := t3



Example

```
module main;
  var z:int;
  procedure p(var q:int);
    var a:array[5] of
          array[10] of int;
    var b:int;
  begin
    b := 1 + 2;
    b := b + z;
    q := q + 1;
    b := a[4][8];
    if b>1 then b:=0 end
  end p;
begin
  z := 5;
  p(z);
end main.
```

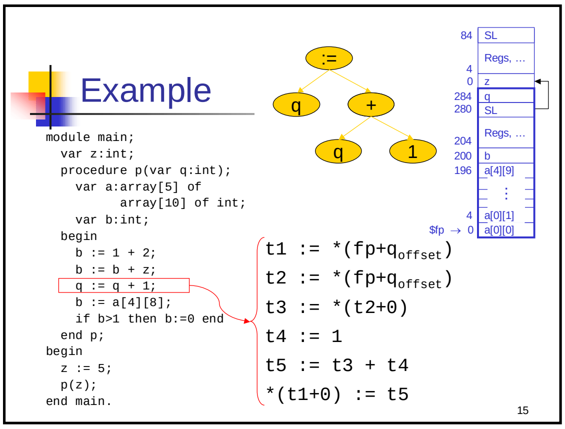
t1 := *(fp+b_{offset})

t2 := *(fp+SL_{offset})

t3 := *(t2+z_{offset})

t4 := t2 + t3

*(fp+b_{offset}) := t4



Example

```
module main;
  var z:int;
  procedure p(var q:int);
    var a:array[5] of
          array[10] of int;
    var b:int;
  begin
    b := 1 + 2;
    b := b + z;
    q := q + 1;
    b := a[4][8];
    if b>1 then b:=0 end
  end p;
begin
  z := 5;
  p(z);
end main.
```

t1 := *(fp+q_{offset})

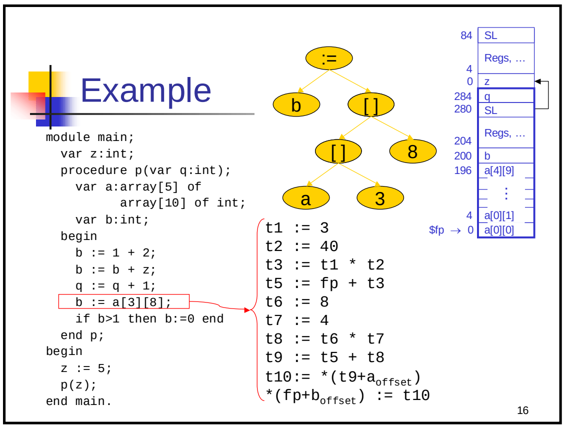
t2 := *(fp+q_{offset})

t3 := *(t2+0)

t4 := 1

t5 := t3 + t4

*(t1+0) := t5



Example

```
module main;
  var z:int;
  procedure p(var q:int);
    var a:array[5] of
          array[10] of int;
    var b:int;
  begin
    b := 1 + 2;
    b := b + z;
    q := q + 1;
    b := a[3][8];
    if b>1 then b:=0 end
  end p;
begin
  z := 5;
  p(z);
end main.
```

t1 := 3

t2 := 40

t3 := t1 * t2

t5 := fp + t3

t6 := 8

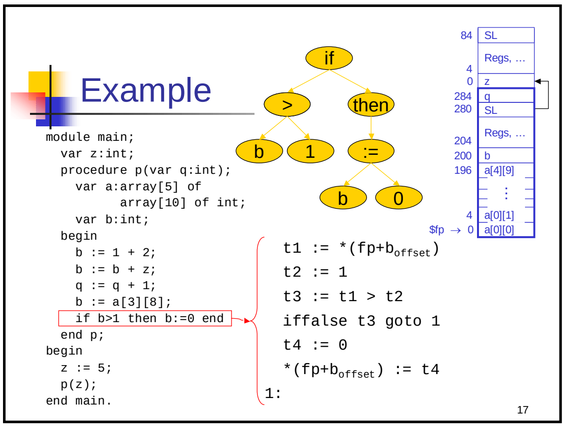
t7 := 4

t8 := t6 * t7

t9 := t5 + t8

t10:= *(t9+a_{offset})

*(fp+b_{offset}) := t10



Example

```
module main;
  var z:int;
  procedure p(var q:int);
    var a:array[5] of
          array[10] of int;
    var b:int;
  begin
    b := 1 + 2;
    b := b + z;
    q := q + 1;
    b := a[3][8];
    if b>1 then b:=0 end
  end p;
begin
  z := 5;
  p(z);
end main.
```

t1 := *(fp+b_{offset})

t2 := 1

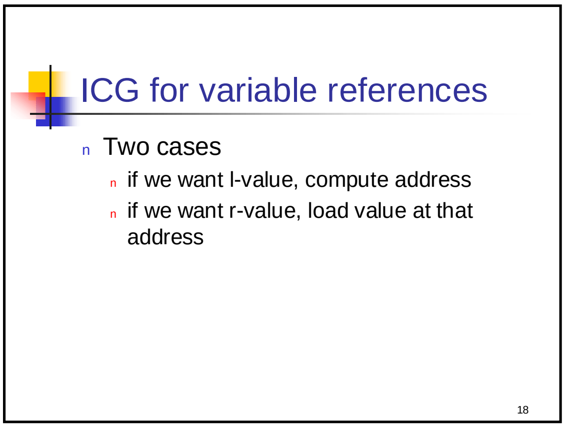
t3 := t1 > t2

iffalse t3 goto 1

t4 := 0

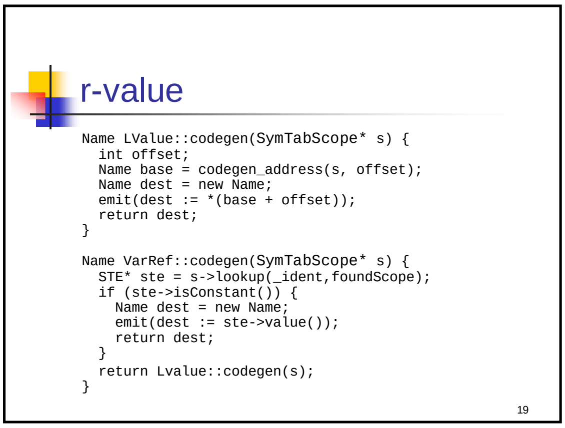
*(fp+b_{offset}) := t4

1:



ICG for variable references

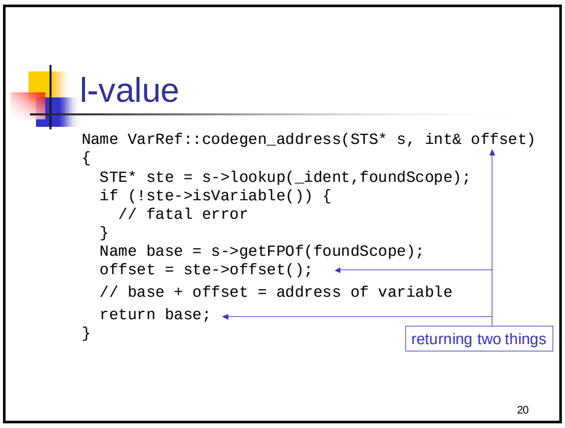
- Two cases
  - if we want l-value, compute address
  - if we want r-value, load value at that address



r-value

```
Name LValue::codegen(SymTabScope* s) {
  int offset;
  Name base = codegen_address(s, offset);
  Name dest = new Name;
  emit(dest := *(base + offset));
  return dest;
}

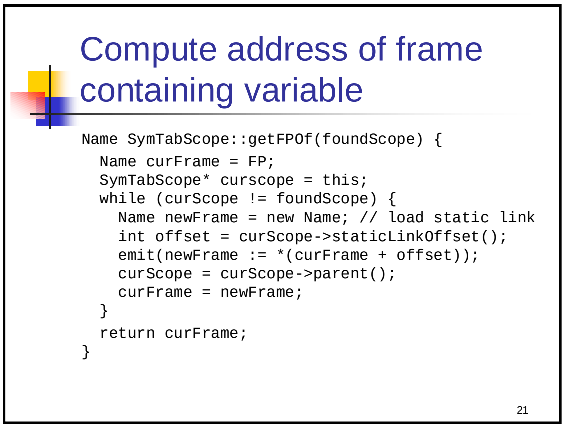
Name VarRef::codegen(SymTabScope* s) {
  STE* ste = s->lookup(_ident,foundScope);
  if (ste->isConstant()) {
    Name dest = new Name;
    emit(dest := ste->value());
    return dest;
  }
  return Lvalue::codegen(s);
}
```



l-value

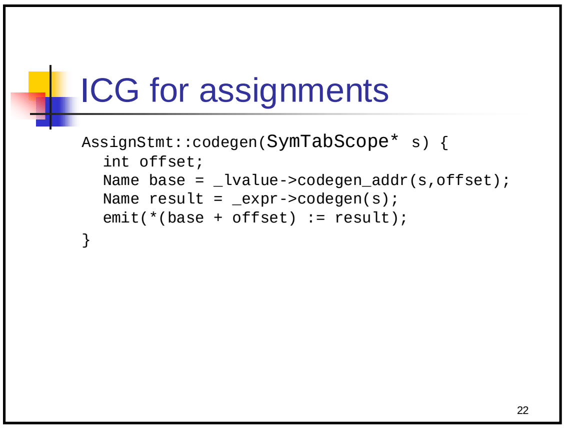
```
Name VarRef::codegen_address(STS* s, int& offset)
{
  STE* ste = s->lookup(_ident,foundScope);
  if (!ste->isVariable()) {
    // fatal error
  }
  Name base = s->getFPOf(foundScope);
  offset = ste->offset();
  // base + offset = address of variable
  return base;
}
```

returning two things



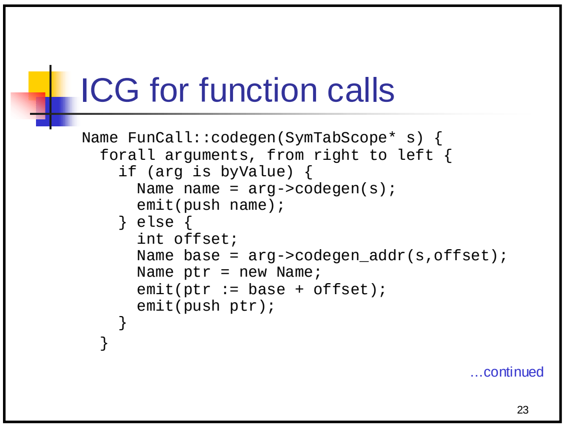
Compute address of frame containing variable

```
Name SymTabScope::getFPOf(foundScope) {
  Name curFrame = FP;
  SymTabScope* curscope = this;
  while (curScope != foundScope) {
    Name newFrame = new Name; // load static link
    int offset = curScope->staticLinkOffset();
    emit(newFrame := *(curFrame + offset));
    curScope = curScope->parent();
    curFrame = newFrame;
  }
  return curFrame;
}
```



ICG for assignments

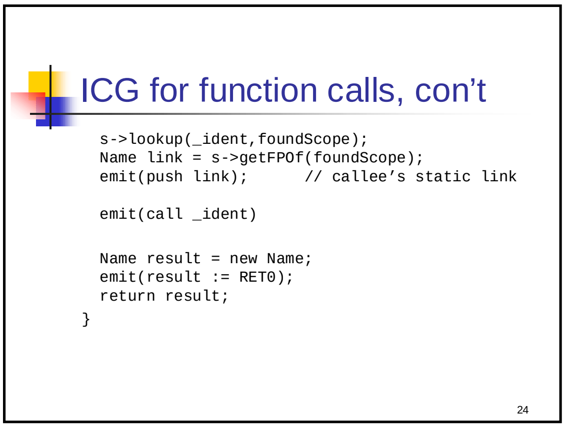
```
AssignStmt::codegen(SymTabScope* s) {
  int offset;
  Name base = _lvalue->codegen_addr(s,offset);
  Name result = _expr->codegen(s);
  emit(*(base + offset) := result);
}
```



ICG for function calls

```
Name FunCall::codegen(SymTabScope* s) {
  forall arguments, from right to left {
    if (arg is byValue) {
      Name name = arg->codegen(s);
      emit(push name);
    } else {
      int offset;
      Name base = arg->codegen_addr(s,offset);
      Name ptr = new Name;
      emit(ptr := base + offset);
      emit(push ptr);
    }
  }
```

…continued



ICG for function calls, con’t

```
  s->lookup(_ident,foundScope);
  Name link = s->getFPOf(foundScope);
  emit(push link);      // callee’s static link

  emit(call _ident)

  Name result = new Name;
  emit(result := RET0);
  return result;
}
```

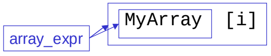
Accessing call-by-ref params

- Formal parameter is address of actual, not the value, so we need an extra load statement

-
  ```
  Name VarRef::codegen_address(STS* s, int& offset){
    ste = s->lookup(_ident,foundScope);
    Name base = s->getFPOf(foundScope);
    offset = ste->offset();
    if (ste->isFormalByRef()) {
      Name ptr = new Name;
      emit(ptr := *(base + offset));
      offset = 0;
      return ptr;
    }
    return base;
  }
  ```

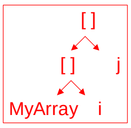
ICG for array accesses

- AST:
  `array_expr[index_expr]`
- Code generated:
  ```
  (array_b,array_o):=<base,offset of array_expr>
  i := <value of index_expr>
  delta := i * <size of element type>
  (elmt_b, elmt_o) := (array_b + delta, array_o)
  ```
- 2D Arrays? Not really:
  ```
  var MyArray array[10] of
                array[5] of int;
  ```



```
MyArray  [i]  [j];
```

array_expr



ICG for if statement

```
void IfStmt::codegen(SymTabScope* s) {
  Name t = _test->codegen(s);
  Label else_lab = new Label;
  emit(if t = 0 goto else_lab);
  _then_stmts->codegen(s);
  Label done_lab = new Label;
  emit(goto done_lab);
  emit(else_lab:);
  _else_stmts->codegen(s);
  emit(done_lab:);
}
```

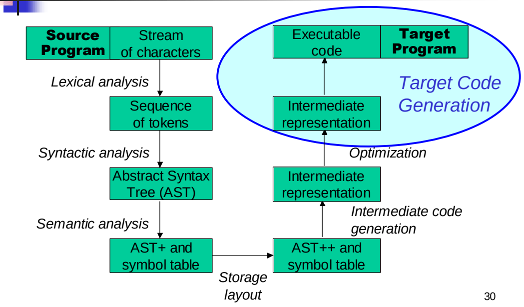
ICG for while statement

Short-circuiting of and & or

- Example

  -
    ```
    if x <> 0 and y / x > 5 then
      b := y < x;
    end;
    ```
- Treat as control structure, not operator:
  - `e1 and e2` →
    ```
       t0 := 0
       t1 := e1
       iffalse t1 goto 1
       t0 := e2
    1: //value in t0
    ```

Prototype compiler structure



Source Program

Stream of characters

Lexical analysis

Sequence of tokens

Syntactic analysis

Abstract Syntax Tree (AST)

Semantic analysis

AST+ and symbol table

Storage layout

AST++ and symbol table

Intermediate code generation

Intermediate representation

Optimization

Intermediate representation

Executable code

Target Program

Target Code Generation

Target Code Generation

- Input: intermediate representations (IR)
  - Ex: three-address code
- Output: target language program
  - Absolute binary code
  - Relocatable binary code
  - Assembly code
  - C

Task of code generator

- Bridge the gap between intermediate code and target code
  - Intermediate code: machine independent
  - Target code: machine dependent
- Two jobs
  - Instruction selection:
    for each IR instruction (or sequence), select target language instruction (or sequence)
  - Register allocation: for each IR variable, select target language register/stack location

Instruction selection

- Given one or more IR instructions, pick the "best" sequence of target machine instructions with the same semantics
  - "best" = fastest, shortest
- Correctness is a big issue, especially if the code generator (codegen) is complex

Difficulty depends on instruction set

- RISC: easy
  - Usually only one way to do something
  - Closely resembles IR instructions
- CISC: hard
  - Lots of alternative instructions with similar semantics
  - Lots of tradeoffs among speed, size
  - Simple RISC-like translation may be inefficient
- C: easy, as long as C is appropriate for desired semantics
  - Can leave optimizations to the C compiler

Example

- IR code
  - `t3 := t1 + t2`
- Target code for MIPS
  - `add $3,$1,$2`
- Target code for SPARC
  - `add %1,%2,%3`
- Target code for 68k
  - `mov.l d1,d3`
    `add.l d2,d3`
- Note that a single IR instruction may expand to several target instructions

Example

- IR code
  - `t1 := t1 + 1`
- Target code for MIPS
  - `add $1,$1,1`
- Target code for SPARC
  - `add %1,1,%1`
- Target code for 68k
  - `add.l #1,d1` **or**
  - `inc.l d1`
- Can have choices
- This is a pain, since choices imply you must make decisions

Example

- IR code (push x onto stack)

  -
    ```
    sp := sp – 4
    *sp := t1
    ```
- Target code for MIPS

  -
    ```
    sub $sp,$sp,4
    sw  $1,0($sp)
    ```
- Target code for SPARC

  -
    ```
    sub %sp,4,%sp
    st  %1,[%sp+0]
    ```
- Target code for 68k
  - `mov.l d1,-(sp)`
- Note that several IR instructions may combine to a single target instruction
- This is hard!

Instruction selection in PL/0

- Very simple instruction selection
  - As part of generating code for an AST node
  - Merged with intermediate code generation, because it's so simple
- Interface to target machine: `assembler` class
  - Function for each kind of target instruction
  - Hides details of assembly format, etc.
  - Two assembler classes (MIPS and x86), but you only need to extend MIPS

Resource constraints

- Intermediate language uses unlimited temporary variables
  - This makes intermediate code generation easy
- Target machine, however, has fixed resources for representing "locals"
  - MIPS, SPARC: 31 registers minus SP, FP, RetAddr, Arg1-4, …
  - 68k: 16 registers, divided into data and address registers
  - x86: 4(?) general-purpose registers, plus several special-purpose registers

Register allocation

- Using registers is
  - Necessary: in load/store RISC machines
  - Desirable: since *much* faster than memory
- So…
  - Should try to keep values in registers if possible
  - Must reuse registers for many temp variables, so we must free registers when no longer needed
  - Must be able to handle out-of-registers condition, so we must *spill* some variables to stack locations
  - Interacts with instructions selection, which is a pain, especially on CISCs

Classes of registers

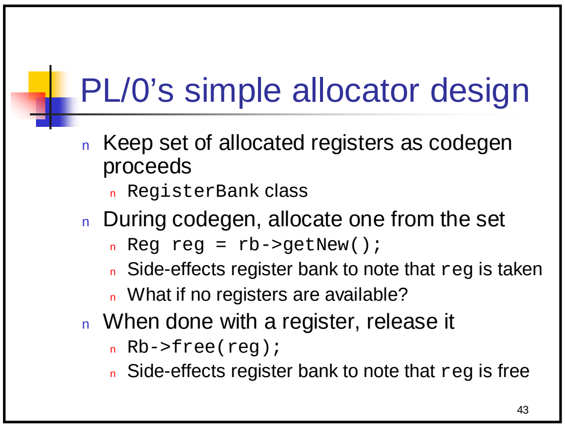
- What registers can the allocator use?
- Fixed/dedicated registers
  - SP, FP, return address, …
  - Claimed by machine architecture, calling convention, or internal convention for special purpose
  - Not easily available for storing locals
- Scratch registers
  - A couple of registers are kept around for temp values
    - E.g., loading a spilled value from memory to operate upon it
- Allocatable registers
  - Remaining registers are free for the allocator to allocate (PL/0 on MIPS: $8-$25)

Which variables go in registers?

- Temporary variables: easy to allocate
  - Defined and used exactly once, during expression eval
    - So the allocator can free the register after use easily
  - Usually not too many in use at one time
    - So less likely to run out of registers

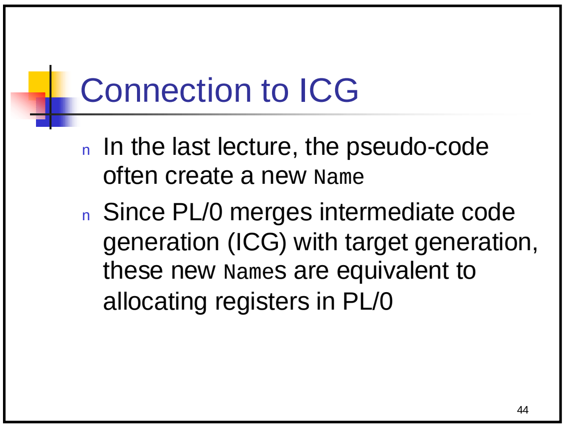
PL/0

- Local variables: hard, but doable
  - Need to determine last use of variable to free register
  - Can easily run out of registers, so need to make decisions
  - What about load/store to a local through a pointer?
  - What about the debugger?
- Global variables, procedure params, across calls, …:
  - Really hard. A research project?



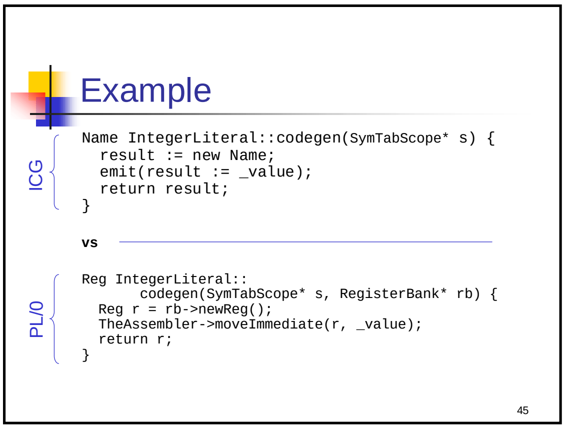
PL/0's simple allocator design

- Keep set of allocated registers as codegen proceeds
  - `RegisterBank` class
- During codegen, allocate one from the set
  - `Reg reg = rb->getNew();`
  - Side-effects register bank to note that `reg` is taken
  - What if no registers are available?
- When done with a register, release it
  - `Rb->free(reg);`
  - Side-effects register bank to note that `reg` is free



Connection to ICG

- In the last lecture, the pseudo-code often create a new `Name`
- Since PL/0 merges intermediate code generation (ICG) with target generation, these new `Names` are equivalent to allocating registers in PL/0



Example

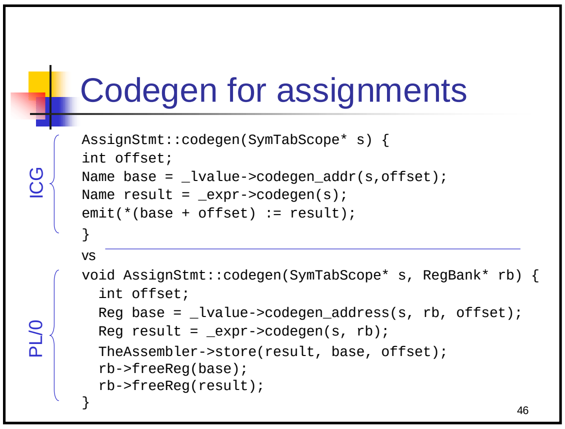
ICG

```
Name IntegerLiteral::codegen(SymTabScope* s) {
  result := new Name;
  emit(result := _value);
  return result;
}
```

vs

PL/0

```
Reg IntegerLiteral::
       codegen(SymTabScope* s, RegisterBank* rb) {
  Reg r = rb->newReg();
  TheAssembler->moveImmediate(r, _value);
  return r;
}
```



Codegen for assignments

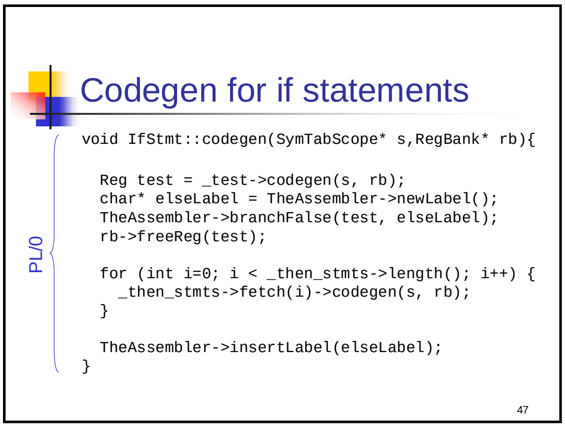
ICG

```
AssignStmt::codegen(SymTabScope* s) {
int offset;
Name base = _lvalue->codegen_addr(s,offset);
Name result = _expr->codegen(s);
emit(*(base + offset) := result);
}
```

vs

PL/0

```
void AssignStmt::codegen(SymTabScope* s, RegBank* rb) {
  int offset;
  Reg base = _lvalue->codegen_address(s, rb, offset);
  Reg result = _expr->codegen(s, rb);
  TheAssembler->store(result, base, offset);
  rb->freeReg(base);
  rb->freeReg(result);
}
```



Codegen for if statements

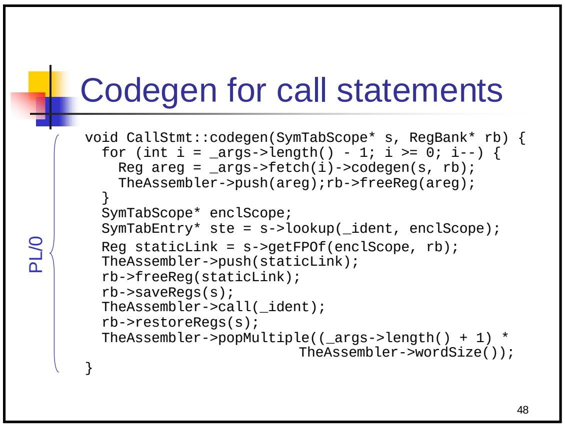
PL/0

```
void IfStmt::codegen(SymTabScope* s,RegBank* rb){

  Reg test = _test->codegen(s, rb);
  char* elseLabel = TheAssembler->newLabel();
  TheAssembler->branchFalse(test, elseLabel);
  rb->freeReg(test);

  for (int i=0; i < _then_stmts->length(); i++) {
    _then_stmts->fetch(i)->codegen(s, rb);
  }

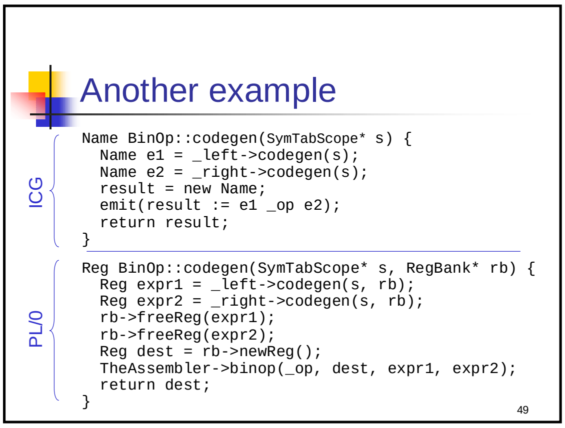
  TheAssembler->insertLabel(elseLabel);
}
```



Codegen for call statements

PL/0

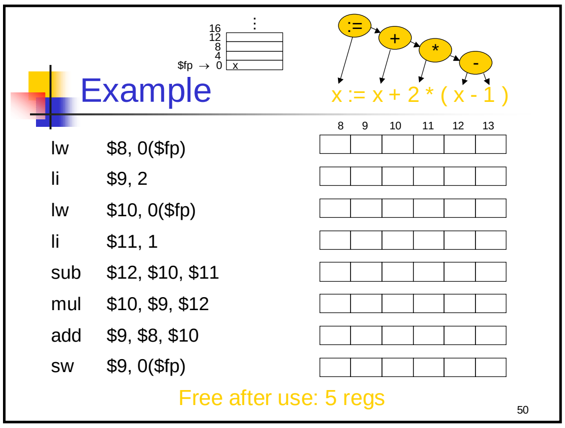
```
void CallStmt::codegen(SymTabScope* s, RegBank* rb) {
  for (int i = _args->length() - 1; i >= 0; i--) {
    Reg areg = _args->fetch(i)->codegen(s, rb);
    TheAssembler->push(areg);rb->freeReg(areg);
  }
  SymTabScope* enclScope;
  SymTabEntry* ste = s->lookup(_ident, enclScope);
  Reg staticLink = s->getFPOf(enclScope, rb);
  TheAssembler->push(staticLink);
  rb->freeReg(staticLink);
  rb->saveRegs(s);
  TheAssembler->call(_ident);
  rb->restoreRegs(s);
  TheAssembler->popMultiple((_args->length() + 1) *
                              TheAssembler->wordSize());
}
```



Another example

```
Name BinOp::codegen(SymTabScope* s) {
  Name e1 = _left->codegen(s);
  Name e2 = _right->codegen(s);
  result = new Name;
  emit(result := e1 _op e2);
  return result;
}
```

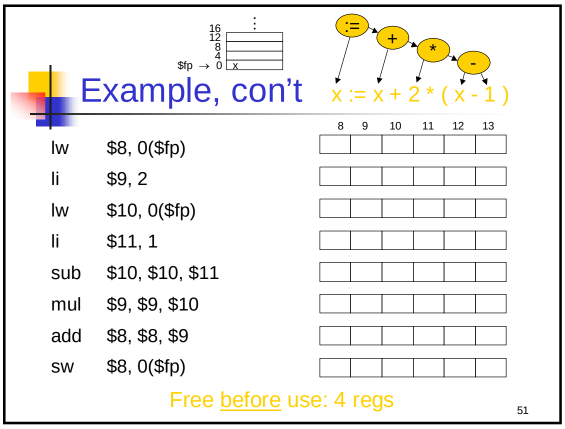
```
Reg BinOp::codegen(SymTabScope* s, RegBank* rb) {
  Reg expr1 = _left->codegen(s, rb);
  Reg expr2 = _right->codegen(s, rb);
  rb->freeReg(expr1);
  rb->freeReg(expr2);
  Reg dest = rb->newReg();
  TheAssembler->binop(_op, dest, expr1, expr2);
  return dest;
}
```



Example

```
lw    $8, 0($fp)
li    $9, 2
lw    $10, 0($fp)
li    $11, 1
sub   $12, $10, $11
mul   $10, $9, $12
add   $9, $8, $10
sw    $9, 0($fp)
```

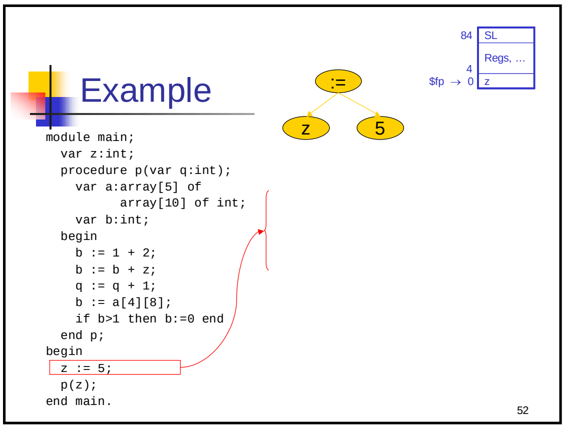
Free after use: 5 regs



Example, con't

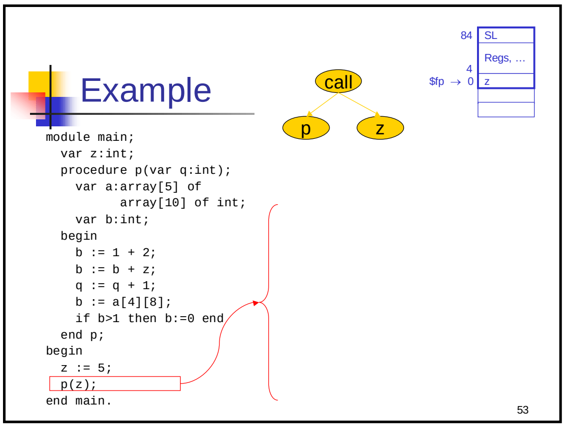
```
lw    $8, 0($fp)
li    $9, 2
lw    $10, 0($fp)
li    $11, 1
sub   $10, $10, $11
mul   $9, $9, $10
add   $8, $8, $9
sw    $8, 0($fp)
```

Free before use: 4 regs



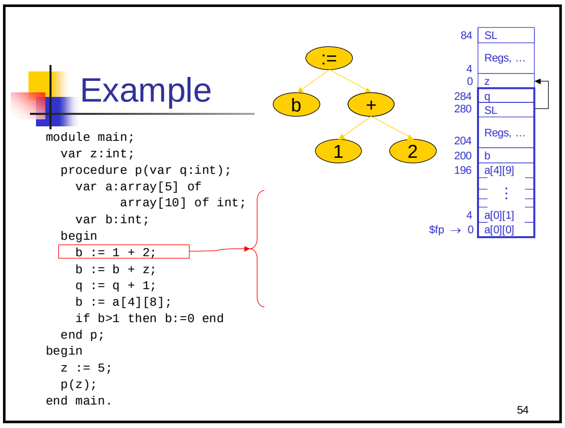
Example

```
module main;
  var z:int;
  procedure p(var q:int);
    var a:array[5] of
          array[10] of int;
    var b:int;
  begin
    b := 1 + 2;
    b := b + z;
    q := q + 1;
    b := a[4][8];
    if b>1 then b:=0 end
  end p;
begin
  z := 5;
  p(z);
end main.
```



Example

```
module main;
  var z:int;
  procedure p(var q:int);
    var a:array[5] of
          array[10] of int;
    var b:int;
  begin
    b := 1 + 2;
    b := b + z;
    q := q + 1;
    b := a[4][8];
    if b>1 then b:=0 end
  end p;
begin
  z := 5;
  p(z);
end main.
```



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    var a:array[5] of
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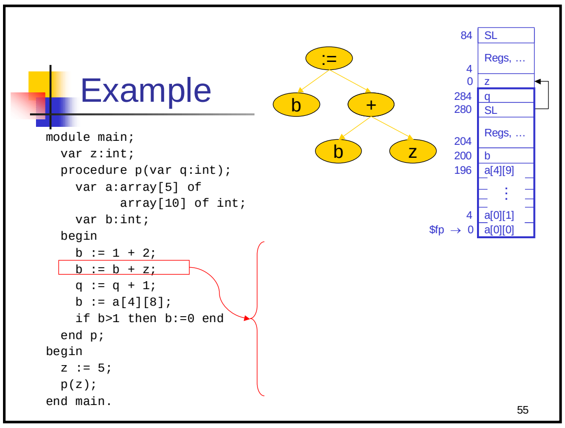

Example

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  var z:int;
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    var a:array[5] of
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  z := 5;
  p(z);
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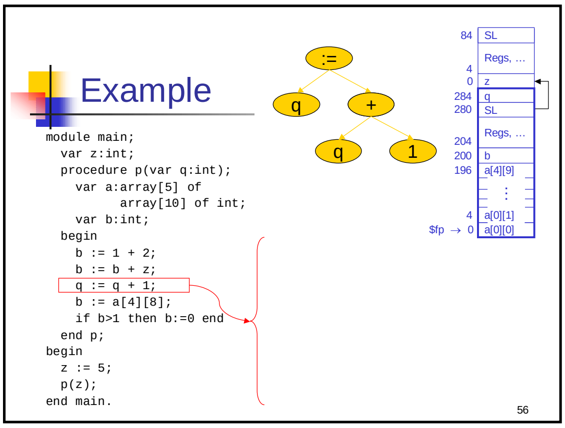

Example

```
module main;
  var z:int;
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    var a:array[5] of
          array[10] of int;
    var b:int;
  begin
    b := 1 + 2;
    b := b + z;
    q := q + 1;
    b := a[4][8];
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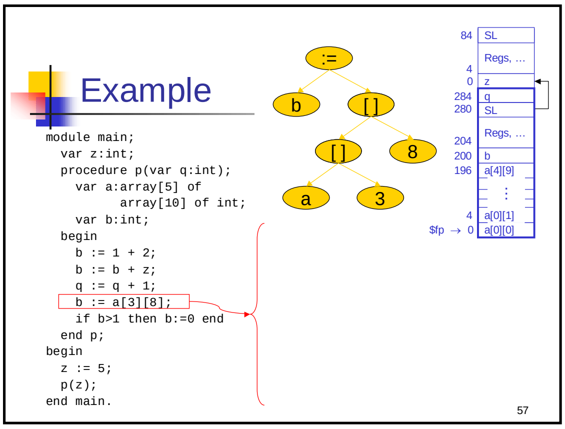
  end p;
begin
  z := 5;
  p(z);
end main.
```



Example

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module main;
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    var a:array[5] of
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  end p;
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  z := 5;
  p(z);
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```

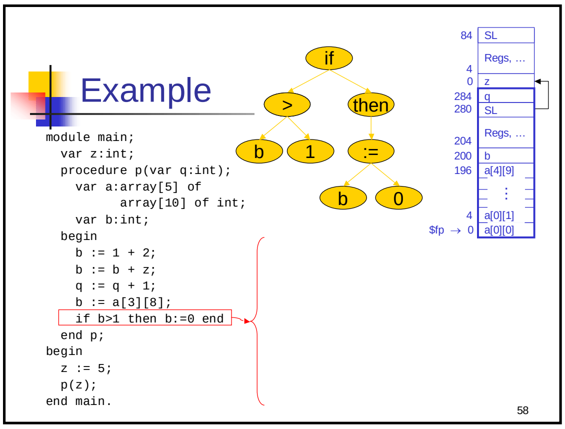

Example

```
module main;
  var z:int;
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    var a:array[5] of
          array[10] of int;
    var b:int;
  begin
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    b := b + z;
    q := q + 1;
    b := a[3][8];
    if b>1 then b:=0 end
  end p;
begin
  z := 5;
  p(z);
end main.
```