

Intermediate Representations

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Intermediate Representations

- 1 Intermediate Representations
- 2 Memory Management
- 3 Translation to Intermediate Language
- 4 The Case of the Tiger Compiler

Intermediate Representations

- 1 Intermediate Representations
 - Compilers Structure
 - Intermediate Representations
 - Tree
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So many ends...

Ends:

`front end` analysis

`middle end` generic synthesis

`back end` specific synthesis

The gcc team suggests

`front end` name (“a front end”).

`front-end` adjective (“the front-end interface”).

The front end is dedicated to analysis:

- lexical analysis (scanning)
- syntactic analysis (parsing)
- ast generation
- static semantic analysis (type checking, context sensitive checks)
- source language specific optimizations
- hir generation

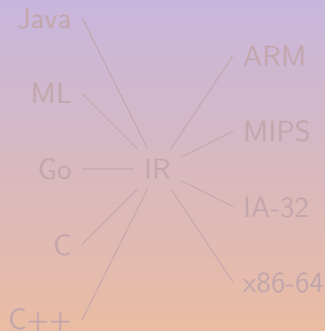
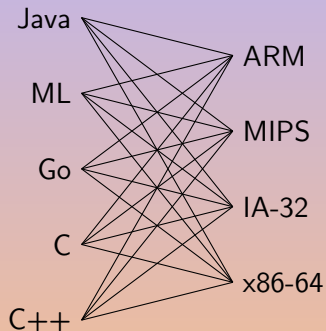
The back end is dedicated to specific synthesis:

- instruction selection (mir to lir)
- register allocation
- assembly specific optimizations
- assembly code emission

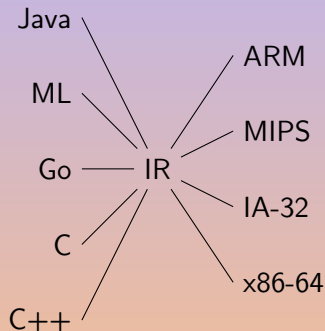
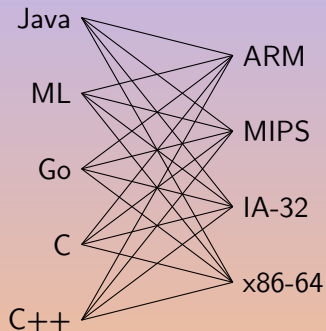
The middle end is dedicated to generic synthesis:

- stepwise refinement of hir to mir
- generic optimizations

Retargetable Compilers



Retargetable Compilers



Other Compiling Strategies

- Intermediate language-based strategy: SmartEiffel, GHC
- Bytecode strategy: Java bytecode (JVM), CIL (.NET)
- Hybrid approaches: GCJ (Java bytecode or native code)
- Retargetable optimizing back ends: MLRISC, VPO (Very Portable Optimizer), and somehow C- - (Quick C- -).
- Modular systems: LLVM (compiler as a library, centered on a typed IR). Contains the LLVM core libraries, Clang, LLDB, etc. Also:
 - VMKit: a substrate for virtual machines (JVM, etc.).
 - Emscripten: an LLVM-to-JavaScript compiler. Enables C/C++ to JS compilation.

Intermediate Representations (IR) are fundamental.

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Intermediate representation:

- a faithful model of the source program
- “written” in an abstract language, the *intermediate language*
- may have an external syntax
- may be interpreted/compiled (havam, byte code)
- may have different levels (gcc’s Tree is very much like C).

What Language Flavor?

- Imperative?
 - Stack Based? (Java Byte-code)
 - Register Based? (gcc's rtl, tc's Tree)
- Functional?

Most functional languages are compiled into a lower level language, eventually a simple λ -calculus.
- Other?

What Level?

A whole range of expressivities, typically aiming at making some optimizations easier:

- Keep array expressions?

Yes: adequate for dependency analysis and related optimizations,

No: Good for constant folding, strength reduction, loop invariant code motion, etc.

- Keep loop constructs?

What level of machine independence?

- Explicit register names?

Designing an Intermediate Representation

“ *Intermediate-language design is largely an art, not a science.*

— [Muchnick, 1997]

Different Levels [Muchnick, 1997]

```
float a[20][10];  
...  
a[i][j+2];
```

```
t1 <- a[i,j+2]
```

```
t1 <- j + 2
```

```
r1 <- [fp - 4]
```

```
t2 <- i * 20
```

```
r2 <- r1 + 2
```

```
t3 <- t1 + t2
```

```
r3 <- [fp - 8]
```

```
t4 <- 4 * t3
```

```
r4 <- r3 * 20
```

```
t5 <- addr a
```

```
r5 <- r4 + r2
```

```
t6 <- t5 + t4
```

```
r6 <- 4 * r5
```

```
t7 <- *t6
```

```
r7 <- fp - 216
```

```
f1 <- [r7 + r6]
```

Different Levels [Muchnick, 1997]

```
float a[20][10];  
...  
a[i][j+2];
```

```
t1 <- a[i,j+2]
```

```
t1 <- j + 2  
t2 <- i * 20  
t3 <- t1 + t2  
t4 <- 4 * t3  
t5 <- addr a  
t6 <- t5 + t4  
t7 <- *t6
```

```
r1 <- [fp - 4]  
r2 <- r1 + 2  
r3 <- [fp - 8]  
r4 <- r3 * 20  
r5 <- r4 + r2  
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r7 <- fp - 216  
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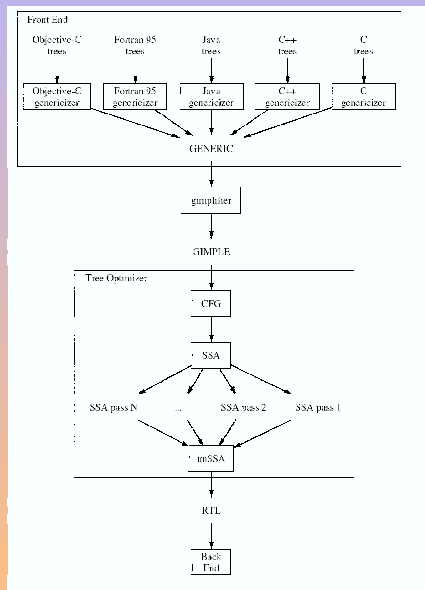
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r6 <- 4 * r5
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t7 <- *t6
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r7 <- fp - 216
```

```
f1 <- [r7 + r6]
```

Different Levels: The GCC Structure



Stack Based: Java Byte-Code [Edwards, 2003]

```
class Gcd
{
    static public int gcd(int a, int b)
    {
        while (a != b)
        {
            if (a > b)
                a -= b;
            else
                b -= a;
        }
        return a;
    }

    static public int main(String[] arg)
    {
        return gcd(12, 34);
    }
}
```

Stack Based: Java Byte-Code

```
% gcj-3.3 -c gcd.java
% jcf-dump-3.3 -c gcd
...
Method name:"gcd" public static
Signature: 5=(int,int)int
Attribute "Code", length:66,
max_stack:2, max_locals:2,
code_length:26
  0: iload_0
  1: iload_1
  2: if_icmpeq 24
  5: iload_0
  6: iload_1
  7: if_icmple 17
10: iload_0
11: iload_1
12: isub
13: istore_0
17: iload_1
18: iload_0
19: isub
20: istore_1
21: goto 0
24: iload_0
25: ireturn
Attribute "LineNumberTable",
      length:22, count: 5
      line: 5 at pc: 0
      line: 7 at pc: 5
      line: 8 at pc: 10
      line: 10 at pc: 17
      line: 12 at pc: 24
...
```

Advantages

- Trivial translation of expressions
- Trivial interpreters
- No pressure on registers
- Often compact

Disadvantages

- Does not fit with today's architectures
- Hard to analyze
- Hard to optimize

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Stack Based: Examples

ucode, used in hp pa-risk, and mips, was designed for stack evaluation (HP 3000 is stack based).

Today it is less adequate.

mips translates it back and forth to triples for optimization.

hp converts it into sllic (Spectrum Low Level ir) [Muchnick, 1997].

Register Based: tc's Tree

```
let function gcd(a: int, b: int) : int =  
  (  
    while a <> b  
      do if a > b then a := a - b  
          else b := b - a;  
    a  
  )  
in  
  print_int(gcd(42, 51))  
end
```

Register Based: tc's Tree (1/4)

```
/* == High Level Intermediate representation. == */  
# Routine: gcd  
label 10  
# Prologue  
move temp t0 temp fp  
move temp fp temp sp  
move  
    temp sp  
    binop sub temp sp const 12  
move  
mem temp fp  
    temp i0  
move  
    mem binop add temp fp const -4  
    temp i1  
move  
    mem binop add temp fp const -8  
    temp i2
```

Register Based: tc's Tree (2/4)

Body

```
move temp rv
  eseq
  seq
  label l2
  cjump ne mem binop add temp fp const -4
        mem binop add temp fp const -8
        name l3 name l1
  label l3
  seq
  cjump gt mem binop add temp fp const -4
        mem binop add temp fp const -8
        name l4 name l5
  label l4
  move mem binop add temp fp const -4
        binop sub mem binop add temp fp const -4
        mem binop add temp fp const -8
  jump name l6
```

Register Based: tc's Tree (3/4)

```
label 15
  move mem binop add temp fp const -8
      binop sub mem binop add temp fp const -8
          mem binop add temp fp const -4

label 16
seq end
jump name 12
label 11
seq end
mem binop add temp fp const -4
```

Epilogue

```
move temp sp temp fp
move temp fp temp t0
label end
```

Register Based: tc's Tree (4/4)

```
# Routine: _main
label main
# Prologue
# Body
seq
  sxp
    call
      name print_int
      call name 10 temp fp const 42 const 51
      call end
    call end
  sxp
    const 0
seq end
# Epilogue
label end
```

Register Based: What Structure?

How is the structure coded?

Addresses Expressions and instructions have names, or (absolute) addresses. (Stack based is a bit like a relative address).

- 2 address instructions? (*triples*)
- 3 address instructions? (*quadruples*)

Tree Expressions and instructions are unnamed, related to each other as nodes of trees

dag Compact, good for local value numbering, but that's all.

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Quadruples vs. Triples [Muchnick, 1997]

L1: i <- i + 1	(1) i + 1
	(2) i sto (1)
t1 <- i + 1	(3) i + 1
t2 <- p + 4	(4) p + 4
t3 <- *t2	(5) *(4)
p <- t2	(6) p sto (4)
t4 <- t1 < 10	(7) (3) < 10
*r <- t3	(8) *r sto (5)
if t4 goto L1	(9) if (7), (1)

Quadruples vs. Triples [Muchnick, 1997]

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p <- t2	(6) p sto (4)
t4 <- t1 < 10	(7) (3) < 10
*r <- t3	(8) *r sto (5)
if t4 goto L1	(9) if (7), (1)

Register Based: gcc's rtl

```
int
gcd(int a, int b)
{
    while (a != b)
    {
        if (a > b)
            a -= b;
        else
            b -= a;
    }
    return a;
}
```

Register Based: gcc's rtl

```
;; Function gcd
(note 1 0 2 ("gcd.c") 3)
(note 2 1 3 NOTE_INSN_DELETED)
(note 3 2 4 NOTE_INSN_FUNCTION_BEG)
(note 4 3 5 NOTE_INSN_DELETED)
(note 5 4 6 NOTE_INSN_DELETED)
(note 6 5 7 NOTE_INSN_DELETED)
(insn 7 6 8 (const_int 0 [0x0]) -1 (nil)
  (nil))
```


Register Based: gcc's rtl cont'd

```
(note 8 7 9 ("gcd.c") 4)
(note 9 8 40 NOTE_INSN_LOOP_BEG)
(note 40 9 10 NOTE_INSN_LOOP_CONT)
(code_label 10 40 13 2 "" "" [0 uses])
(insn 13 10 14 (set (reg:SI 59)
  (mem/f:SI (reg/f:SI 53 virtual-incoming-args) [0 a+0 S4 A32]))
  -1 (nil) (nil))
(insn 14 13 15 (set (reg:CCZ 17 flags)
  (compare:CCZ (reg:SI 59)
    (mem/f:SI (plus:SI (reg/f:SI 53 virtual-incoming-args)
      (const_int 4 [0x4])) [0 b+0 S4 A32]))) -1 (nil)
  (nil))
```

Register Based: gcc's rtl cont'd

```
(jump_insn 15 14 16 (set (pc)
  (if_then_else (ne (reg:CCZ 17 flags)
    (const_int 0 [0x0]))
    (label_ref 18)
    (pc))) -1 (nil)
  (nil))
(jump_insn 16 15 17 (set (pc)
  (label_ref 44)) -1 (nil)
  (nil))
(barrier 17 16 18)
(code_label 18 17 19 4 "" "" [0 uses])
(note 19 18 20 NOTE_INSN_LOOP_END_TOP_COND)
(note 20 19 21 NOTE_INSN_DELETED)
(note 21 20 22 NOTE_INSN_DELETED)
```

Register Based: gcc's rtl cont'd

```
(note 22 21 25 ("gcd.c") 6)
(insn 25 22 26 (set (reg:SI 60)
  (mem/f:SI (reg/f:SI 53 virtual-incoming-args) [0 a+0 S4 A32])))
-1 (nil) (nil))
(insn 26 25 27 (set (reg:CCGC 17 flags)
  (compare:CCGC (reg:SI 60)
    (mem/f:SI (plus:SI (reg/f:SI 53 virtual-incoming-args)
      (const_int 4 [0x4])) [0 b+0 S4 A32]))) -1 (nil)
  (nil))
(jump_insn 27 26 28 (set (pc)
  (if_then_else (le (reg:CCGC 17 flags)
    (const_int 0 [0x0]))
    (label_ref 34)
    (pc))) -1 (nil)
  (nil))
```

Register Based: gcc's rtl cont'd

```
(note 28 27 30 ("gcd.c") 7)
(insn 30 28 31 (set (reg:SI 61)
  (mem/f:SI (plus:SI (reg/f:SI 53 virtual-incoming-args)
    (const_int 4 [0x4]))) [0 b+0 S4 A32])) -1 (nil)
  (nil))
(insn 31 30 32 (parallel[
  (set (mem/f:SI (reg/f:SI 53 virtual-incoming-args)
    [0 a+0 S4 A32])
    (minus:SI (mem/f:SI (reg/f:SI 53 virtual-incoming-args)
      [0 a+0 S4 A32])
      (reg:SI 61)))
  (clobber (reg:CC 17 flags))
] ) -1 (nil)
  (expr_list:REG_EQUAL (minus:SI (mem/f:SI (reg/f:SI 53
    virtual-incoming-args) [0 a+0 S4 A32])
    (mem/f:SI (plus:SI (reg/f:SI 53 virtual-incoming-args)
      (const_int 4 [0x4]))) [0 b+0 S4 A32])))
  (nil)))
(jump_insn 32 31 33 (set (pc)
  (label_ref 39)) -1 (nil)
  (nil))
(barrier 33 32 34)
(code_label 34 33 35 5 "" "" [0 uses])
```

Register Based: gcc's rtl cont'd

```
(note 35 34 37 ("gcd.c") 9)
(insn 37 35 38 (set (reg:SI 62)
  (mem/f:SI (reg/f:SI 53 virtual-incoming-args) [0 a+0 S4 A32]))
  -1 (nil) (nil))
(insn 38 37 39 (parallel[
  (set (mem/f:SI (plus:SI (reg/f:SI 53 virtual-incoming-args)
    (const_int 4 [0x4])) [0 b+0 S4 A32])
    (minus:SI (mem/f:SI (plus:SI (reg/f:SI 53
      virtual-incoming-args)
      (const_int 4 [0x4])) [0 b+0 S4 A32])
      (reg:SI 62)))
  (clobber (reg:CC 17 flags))
] ) -1 (nil)
(expr_list:REG_EQUAL (minus:SI (mem/f:SI (plus:SI (reg/f:SI
  53 virtual-incoming-args)
  (const_int 4 [0x4])) [0 b+0 S4 A32])
  (mem/f:SI (reg/f:SI 53 virtual-incoming-args) [0 a+0 S4 A32]))
  (nil)))
(code_label 39 38 41 6 "" "" [0 uses])
(jump_insn 41 39 42 (set (pc)
  (label_ref 10)) -1 (nil)
  (nil))
(barrier 42 41 43)
(note 43 42 44 NOTE_INSN_LOOP_END)
```

Register Based: gcc's rtl cont'd

```
(note 45 44 46 ("gcd.c") 11)
(note 46 45 47 NOTE_INSN_DELETED)
(note 47 46 49 NOTE_INSN_DELETED)
(insn 49 47 51 (set (reg:SI 64)
  (mem/f:SI (reg/f:SI 53 virtual-incoming-args) [0 a+0 S4 A32])) -1 (nil)
  (nil))
(insn 51 49 52 (set (reg:SI 58)
  (reg:SI 64)) -1 (nil)
  (nil))
(jump_insn 52 51 53 (set (pc)
  (label_ref 56)) -1 (nil)
  (nil))
(barrier 53 52 54)
(note 54 53 55 NOTE_INSN_FUNCTION_END)
(note 55 54 59 ("gcd.c") 12)
(insn 59 55 60 (clobber (reg/i:SI 0 eax)) -1 (nil)
  (nil))
(insn 60 59 56 (clobber (reg:SI 58)) -1 (nil)
  (nil))
(code_label 56 60 58 1 "" "" [0 uses])
(insn 58 56 61 (set (reg/i:SI 0 eax)
  (reg:SI 58)) -1 (nil)
  (nil))
(insn 61 58 0 (use (reg/i:SI 0 eax)) -1 (nil)
  (nil))
```

Advantages

- Suits today's architectures
- Clearer data flow

Disadvantages

- Harder to synthesize
- Less compact
- Harder to interpret

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Tree [Appel, 1998]

A simple intermediate language:

- Tree structure (no kidding...)
- Unbounded number of registers (temporaries)
- Two way conditional jump

Tree: Grammar

```
<Exp> ::= "const" int
        | "name" <Label>
        | "temp" <Temp>
        | "binop" <Oper> <Exp> <Exp>
        | "mem" <Exp>
        | "call" <Exp> [{<Exp>}] "call end"
        | "eseq" <Stm> <Exp>
```

```
<Stm> ::= "move" <Exp> <Exp>
        | "sxp" <Exp>
        | "jump" <Exp> [{<Label>}]
        | "cjump" <Relop> <Exp> <Exp> <Label> <Label>
        | "seq" [{<Stm>}] "seq end"
        | "label" <Label>
```

```
<Oper> ::= "add" | "sub" | "mul" | "div" | "mod"
```

```
<Relop> ::= "eq" | "ne" | "lt" | "gt" | "le" | "ge"
```

Tree Samples

```
% echo '1 + 2 * 3' | tc -H -  
/* == High Level Intermediate representation. == */  
# Routine: Main Program  
label Main  
# Prologue  
# Body  
sxp  
    binop add  
        const 1  
        binop mul  
            const 2  
            const 3  
# Epilogue  
label end
```

Tree Samples

```
% echo 'if 1 then print_int (1)' | tc -H -  
# Routine: Main Program  
label Main  
# Prologue  
# Body  
seq  
  cjump ne, const 1, const 0, name 11, name 12  
  label 11  
  sxp call name print_int, const 1  
  jump name 13  
  label 12  
  sxp const 0  
  label 13  
seq end  
# Epilogue  
label end
```

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 - Activation Blocks
 - Nonlocal Variables
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Memory Management

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Memory Hierarchy [Appel, 1998]

Different kinds of memory in a computer, with different performances:

Registers Small memory units built on the cpu (bytes, 1 cycle)

L1 Cache Last main memory access results (kB, 2-3 cycles)

L2 Cache (MB, 10 cycles)

Memory The usual ram (GB, 100 cycles)

Storage Disks (100GB, TB, > 1Mcycles)

Use the registers as much as possible.

Register Overflow

What if there are not enough registers? Use the main memory, but how?
Recursion:

Without Each name is bound once. It can be statically allocated a single unit of main memory. (Cobol, Concurrent Pascal, Fortran (unless recursive)).

With A single name can be part of several concurrent bindings. Memory allocation must be dynamic.

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Memory allocation must be dynamic.

Dynamic Memory Allocation

Depending on the persistence, several models:

Global Global objects, whose liveness is equal to that of the program, are statically allocated (e.g., `static` variables in C)

Automatic Liveness is bound to that of the host function (e.g., `auto` variables in C)

Heap Liveness is independent of function liveness:

User Controlled

`malloc/free` (C), `new/dispose` (Pascal),
`new/delete` (C++) etc.

Garbage Collected

With or without `new`

(`lisp`, `Smalltalk`, `ML`, `Haskell`, `Tiger`, `Perl` etc.).

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Depending on the persistence, several models:

Global Global objects, whose liveness is equal to that of the program, are statically allocated
(e.g., `static` variables in C)

Automatic Liveness is bound to that of the host function
(e.g., `auto` variables in C)

Heap Liveness is independent of function liveness:

User Controlled

`malloc/free` (C), `new/dispose` (Pascal),
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With or without `new`

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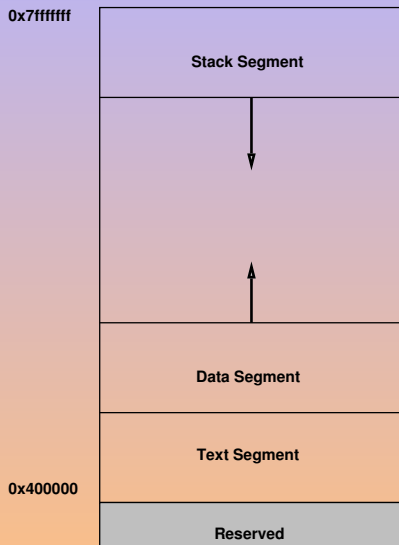
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spim Memory Model [Larus, 1990]



Stack Management

Function calls is a last-in first-out process, hence, it is properly represented by a stack.

Or...

“Call tree”: the complete history of calls.

The execution of the program is its depth first traversal.

Depth-first walk requires a stack.

Activation Blocks

- 1 Intermediate Representations
- 2 Memory Management
 - Memory Management
 - **Activation Blocks**
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Activation Blocks

- In recursive languages, a single routine can be “opened” several times concurrently.
- An *activation* designates one single instance of execution.
- Automatic variables are bound to the liveness of the activation.
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Activation Blocks Contents

Data to store on the stack:

arguments incoming

local variables user automatic variables

return address where to **return**

saved registers the caller's environment to restore

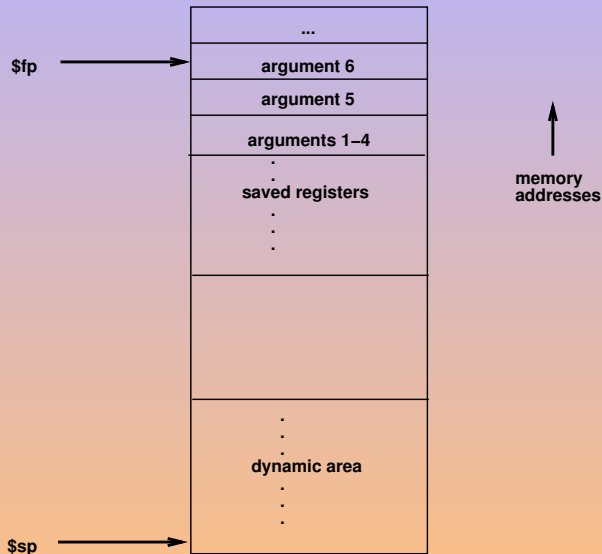
temp compiler automatic variables, spills

static link when needed

Activation Blocks Layout

The layout is suggested by the constructor.
Usually the layout is from earliest known, to latest.

Activation Blocks Layout on mips [Larus, 1990]



Frame & Stack Pointers

The stack of activation blocks is implemented as an array with

frame pointer the inner frontier of the activation block

stack pointer the outer frontier

Usually the stack is represented growing towards the bottom.

Flexible Automatic Memory

`auto` Static size, automatic memory.

`malloc` Dynamic size, persistent memory.

Automatic memory is extremely convenient...

```
int
open2(char* str1, char* str2, int flags, int mode)
{
    char name[strlen(str1) + strlen(str2) + 1];
    stpcpy(stpcpy(name, str1), str2);
    return open(name, flags, mode);
}
```

Flexible Automatic Memory

malloc is a poor replacement.

```
int
open2(char* str1, char* str2, int flags, int mode)
{
    char* name
        = (char*) malloc(strlen(str1) + strlen(str2) + 1);
    if (name == 0)
        fatal("virtual memory exceeded");
    stpcpy(stpcpy(name, str1), str2);
    int fd = open(name, flags, mode);
    free(name);
    return fd;
}
```

Flexible Automatic Memory

alloca is a good replacement.

```
int
open2(char *str1, char *str2, int flags, int mode)
{
    char *name
        = (char *) alloca(strlen(str1) + strlen(str2) + 1);
    strcpy(stpcpy(name, str1), str2);
    return open(name, flags, mode);
}
```

Advantages of `alloca` [Loosemore et al., 2003]

- Using `alloca` wastes very little space and is very fast. (It is open-coded by the GNU C compiler.)
- `alloca` does not cause memory fragmentation.
Since `alloca` does not have separate pools for different sizes of block, space used for any size block can be reused for any other size.
- Automatically freed.
Nonlocal exits done with `longjmp` automatically free the space allocated with `alloca` when they exit through the function that called `alloca`. This is the most important reason to use `alloca`.

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Arrays vs. Alloca [Loosemore et al., 2003]

- A variable size array's space is freed at the end of the scope of the name of the array.
The space allocated with `alloca` remains until the end of the function.
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Implementing Dynamic Arrays & Alloca

- Playing with `$sp` which makes `$fp` mandatory.
- An additional stack (as with the C emulation of `alloca`).

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escapes-n-recursion

```
let function trace(fn: string, val: int) =
  (print(fn); print("("); print_int(val); print(") "))

function one(input : int) =
let function two() =
  (trace("two", input); one(input - 1))
in
  if input > 0 then
    (two(); trace("one", input))
  end
in
  one(3); print("\n")
end
```

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```
% tc -H escapes-n-recursion.tig > f.hir && havm f.hir
```

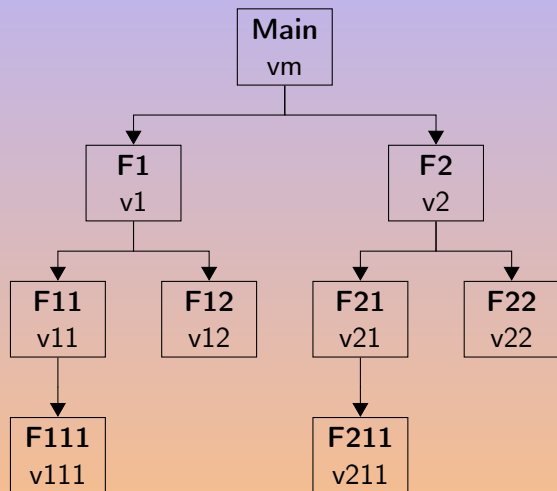

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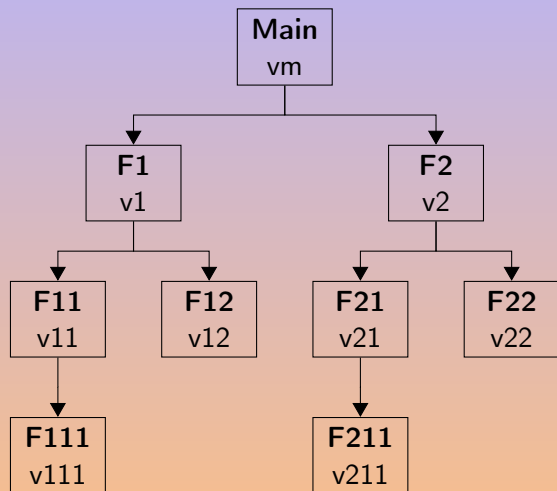
Deep Static Function Hierarchies



What if:

- Main uses vm
- Main calls F1
- F1 uses v1
- F1 uses vm, non-
local
- F1 calls F11
- F11 uses v11
- F11 uses v1
- F11 uses vm
- F11 calls F12
- F12 calls F1

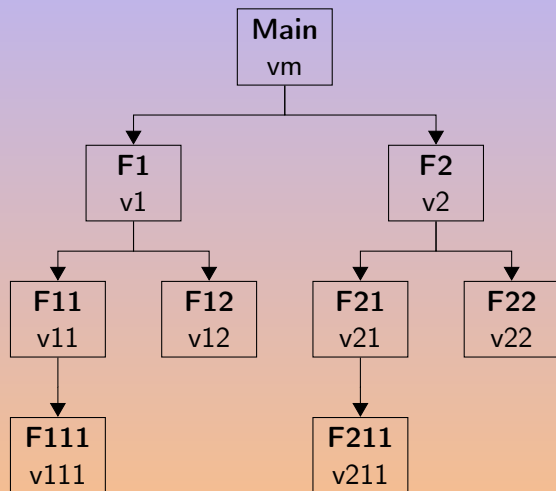
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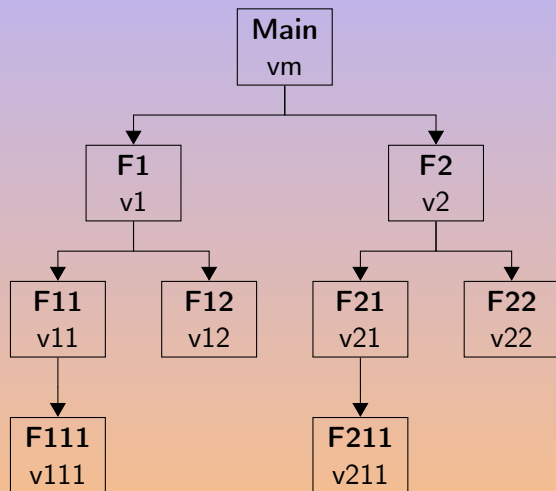
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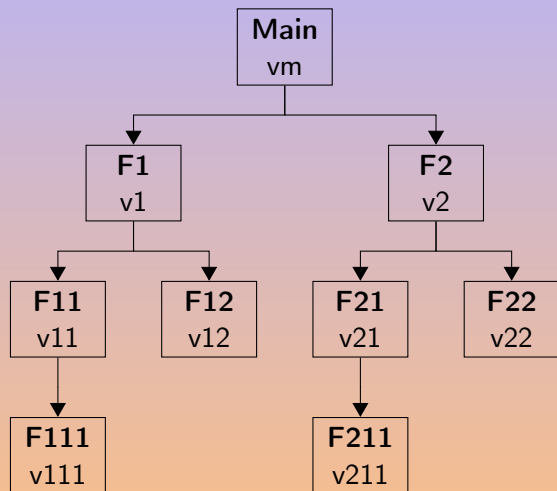
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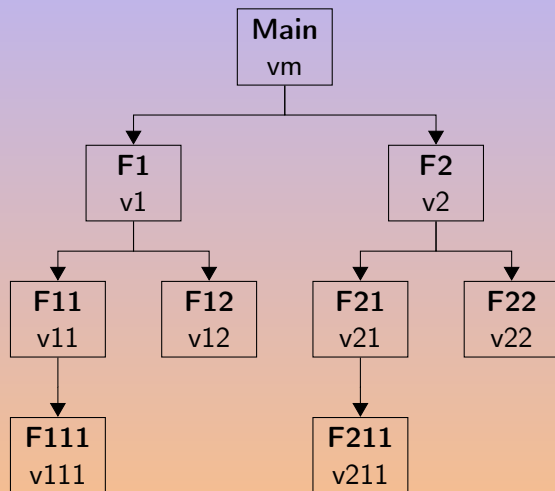
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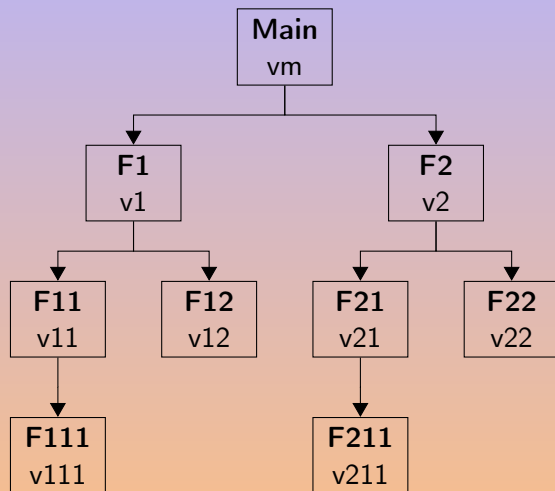
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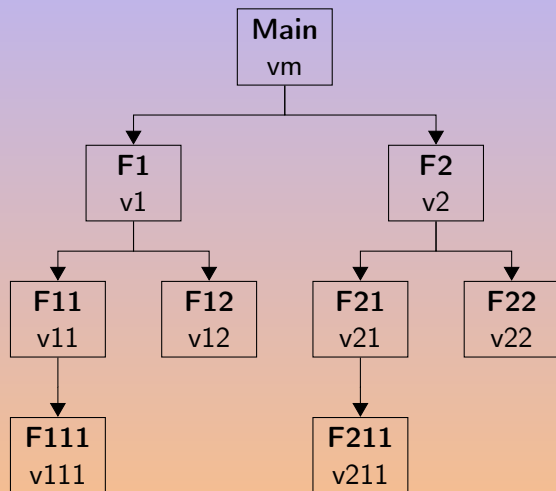
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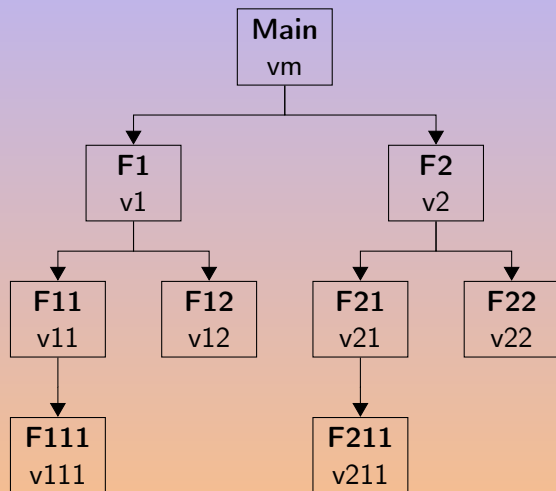
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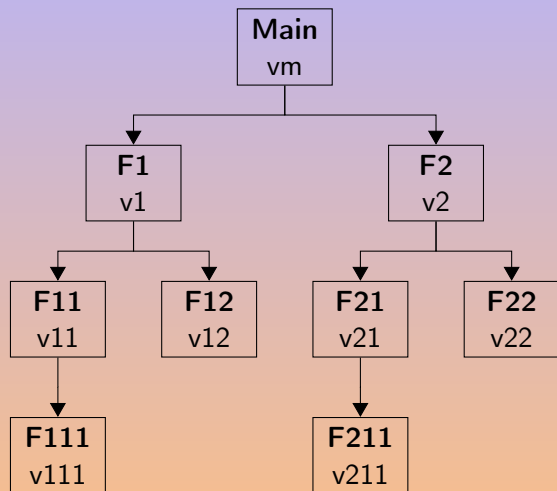
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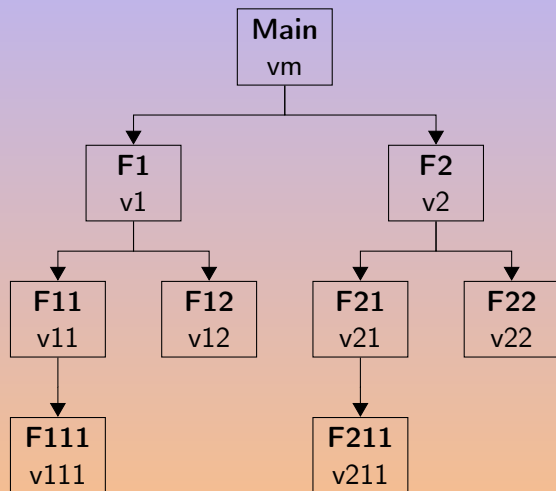
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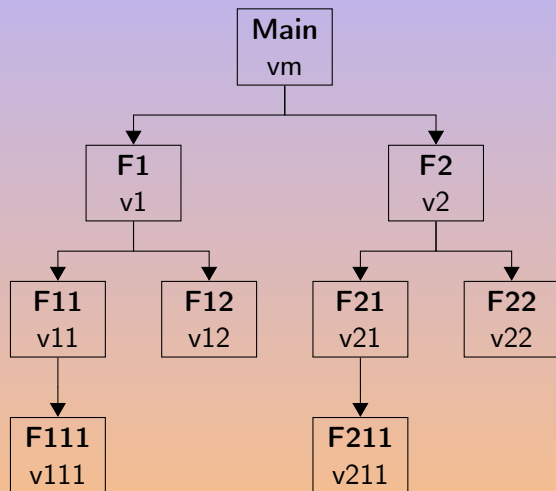
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Deep Static Function Hierarchies

The caller must provide the callee with its static link.

Caller	Callee	Static Link
Main	F1	$fp_{Main} = fp$
F1	F11	$fp_{F1} = fp$
F11	F12	$fp_{F1} = sl_{F11} = *fp_{F11} = *fp$
F12	F2	$fp_{Main} = sl_{F1} = *sl_{F12} = **fp_{F12} = **fp$
F2	F22	$fp_{F2} = fp$
F22	F11	$fp_{F1} = ???$

Assuming that the static link is stored at fp .

Higher Order Functions

```
let
  function addgen (a: int) : int -> int =
    let
      function res (b: int) : int =
        a + b
    in
      res
    end
  var add50 := addgen (50)
in
  add50 (1)
end
```

Translation to Intermediate Language

- 1 Intermediate Representations
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 - Calling Conventions
 - Clever Translations
 - Complex Expressions
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Calling Conventions

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Calling Conventions at hir Level

You must:

- Preserve *some* registers (`fp`, `sp`)
- Allocate the frame
- Handle the static link (`i0`)
- Receive the (other) arguments (`i1`, `i2...`)

You don't:

- Save temporaries (`havam` has magic for recursion)
- Jump to the `ra` (this is not nice feature from `havam`)

havr Calling Conventions

```
let function gcd (a: int, b: int) : int = (...)  
in print_int (gcd (42, 51)) end
```

Routine: gcd

label 10

Prologue

```
move temp t2, temp fp  
move temp fp, temp sp  
move temp sp, temp sp - const 4  
move mem temp fp, temp i0  
move temp t0, temp i1  
move temp t1, temp i2
```

Body

```
move temp rv  
  eseq  
  ...  
  temp t0
```

Epilogue

```
move temp sp, temp fp  
move temp fp, temp t2  
label end
```

Routine: Main Program

label Main

```
sxp call name print_int  
      call name 10 temp fp  
      const 42 const 51
```

label end

Clever Translations

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Translating Conditions

What is the right translation for $\alpha < \beta$, with α and β two arbitrary expressions?

- 1 `cjump ($\alpha < \beta$, ltrue, lfalse)`
- 2

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eseq (seq (cjump ( $\alpha < \beta$ , ltrue, lfalse),
              label ltrue
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```
seq (sxp ( $\alpha$ )
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This is context sensitive!
- How to implement this?
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- Eek.

Context Sensitive Translation

- The right translation depends upon the *use*.
This is context sensitive!
- How to implement this?
 - When entering an IfExp, warn “I want a condition”,
 - then, depending whether it is an expression or a statement, warn “I want an expression” or “I want a statement”.
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Prototranslation, Expression Shells

Rather, delay the translation until the use is known (`translate::Exp`):

Ex Expression shell, encapsulation of a proto value,

Nx Statement shell, encapsulating a wannabe statement,

Cx Condition shell, encapsulating a wannabe condition.

Then, ask them to finish their translation according to the use:

Exp	un_nx	un_ex	un_cx (t, f)
Ex(e)			
Cx(a < b)			
Nx(s)			

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Exp	un_nx	un_ex	un_cx (t, f)
Ex(e)	sxp(e)	e	cjump($e \neq 0$, t, f)
Cx(a < b)	seq(sxp(a), sxp(b))		
Nx(s)			

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Cx(a < b)	seq(sxp(a), sxp(b))	eseq(t \leftarrow (a < b), t)	cjump(a < b, t, f)
Nx(s)	s	???	???

```
if 11 < 22 | 22 < 33 then print_int(1) else print_int(0)
```

```
cjump ne
  eseq seq cjump 11 < 22 name 10 name 11
    label 10 move temp t0 const 1
      jump name 12
    label 11 move temp t0
      eseq seq move temp t1 const 1
        cjump 22 < 33 name 13 name 14
          label 14
            move temp t1 const 0
            label 13
          seq end
        temp t1
      jump name 12
    label 12
  seq end
temp t0
const 0
name 15
name 16
label 15  sxp call name print_int const 1
          jump name 17
label 16  sxp call name print_int const 0
          jump name 17
label 17
```

A Better Translation: Ix

```
seq
  cjump 11 < 22 name 13 name 14
  label 13
    cjump 1 <> 0 name 10 name 11
  label 14
    cjump 22 < 33 name 10 name 11
seq end
label 10
  sxp call name print_int const 1
  jump name 12
label 11
  sxp call name print_int const 0
label 12
```

Complex Expressions

- 1 Intermediate Representations
- 2 Memory Management
- 3 Translation to Intermediate Language**
 - Calling Conventions
 - Clever Translations
 - Complex Expressions**
- 4 The Case of the Tiger Compiler

Complex Expressions

- Array creation
- Record creation
- String comparison
- While loops
- For loops

While Loops

```
while condition  
  do body
```

While Loops

```
while condition  
  do body
```

```
test:  
  if not (condition)  
    goto done  
  body  
  goto test  
done:
```

For Loops

```
for i := min to max  
do body
```

```
let i := min  
    limit := max  
in  
    while i <= limit  
    do  
        (body; ++i)  
    end
```

For Loops

```
for i := min to max
  do body
```

```
let i := min
    limit := max
in
  if (i > limit)
    goto end
loop:
  body
  if (i >= limit)
    goto end
  ++i
  goto loop
end:
```

Additional Features

- Bounds checking
- Nil checking
- ...

The Case of the Tiger Compiler

- 1 Intermediate Representations
- 2 Memory Management
- 3 Translation to Intermediate Language
- 4 The Case of the Tiger Compiler
 - Translation in the Tiger Compiler
 - lir: Low Level Intermediate Representation

Translation in the Tiger Compiler

- 1 Intermediate Representations
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 - lir: Low Level Intermediate Representation

Actors: The temp Module

`temp::Temp` *temporaries* are pseudo-registers.
Generation of fresh temporaries.

`temp::Label` Pseudo addresses, both for data and code.
Generation of fresh labels.

`misc::endo_map<T>` Mapping from T to T.
Used during register allocation.

Actors: The tree Module

Implementation of hir and lir.

```
/Tree/  /Exp/  Const (int)
        Name  (temp::Label)
        Temp  (temp::Temp)
        Binop (Oper, Exp, Exp)
        Mem   (Exp)
        Call  (Exp, list<Exp*>)
        Eseq  (Stm, Exp)
/Stm/   Move  (Exp, Exp)
        Sxp   (Exp)
        Jump  (Exp, list<temp::Label>)
        CJump (Relop, Exp, Exp, Label, Label)
        Seq   (list<Stm *>)
        Label (temp::Label)
```

- `temp::Temp` is not `tree::Temp`.
The latter aggregates one of the former.
Similarly with `Label`.
- n-ary seq.
(Unlike [Appel, 1998]).
- `Sxp` instead of `Exp`.

Actors: The frame Module

Access How to reach a “variable”.

Abstract class with two concrete subclasses.

```
frame::In_Register
```

```
frame::In_Frame
```

Frame What “variables” a frame contains.

```
local_alloc(bool escapes_p) -> Access
```

Frames and (`frame::`) accesses are not aware of static links.

Actors: The translate Module

- Access** Static link aware version of `frame::Access`:
how to reach a variable, including non local: a `frame::Access`
and a `translate::Level`.
`exp(Level use) -> Exp` Tree expression
The location of `this` `Access`, from the use point of view.
- Level** Static link aware version of `frame::Frame`:
what variables a frame contains, and *where is its parent level*.
`fp(Level use) -> Exp` Tree expression
The frame pointer of `this` `Level`, from the use point of view.
Used for calls, and reaching frame resident temporaries.

Actors: The translate Module

`translate::Exp`

Prototranslation wrappers (Ex, Nx, Cx, Ix).

`translate/translation.hh`

Auxiliary functions used by the Translator.

`translate::Translator`

The translator.

lir: Low Level Intermediate Representation

- 1 Intermediate Representations
- 2 Memory Management
- 3 Translation to Intermediate Language
- 4 The Case of the Tiger Compiler
 - Translation in the Tiger Compiler
 - **lir: Low Level Intermediate Representation**

hir constructs not supported in assembly complicate the back end:

- Structure
 - No nested sequences.
- Expressions
 - Assembly is imperative: there is no “expression”.
- Calling Conventions
 - A (high-level) call is a delicate operation, not a simple instruction.
- Two Way Conditional Jumps
 - Machines provide “jump or continue” instructions.
- Limited Number of Registers
 - From temps to actual registers.

Inadequacy of hir

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Linearization: Principle

- `eseq` and `seq` must be eliminated (except the outermost `seq`).
- Similar to cut-elimination: permute inner `eseq` and `seq` to lift them higher, until they vanish.
- A simple rewriting system.

$$\begin{aligned} \text{eseq } (s1, \text{eseq } (s2, e)) &\rightsquigarrow \text{eseq } (\text{seq } (s1, s2), e) \\ \text{sxp } (\text{eseq } (s, e)) &\rightsquigarrow \text{seq } (s, \text{sxp } (e)) \end{aligned}$$

Linearization: More Rules

`seq (ss1, seq (ss2), ss3)`

Linearization: More Rules

$\text{seq}(\text{ss1}, \text{seq}(\text{ss2}), \text{ss3}) \rightsquigarrow \text{seq}(\text{ss1}, \text{ss2}, \text{ss3})$

Linearization: More Rules

```
seq (ss1, seq (ss2), ss3)  $\rightsquigarrow$  seq (ss1, ss2, ss3)  
call (f, eseq (s, e), es)
```

Linearization: More Rules

$\text{seq} (ss1, \text{seq} (ss2), ss3) \rightsquigarrow \text{seq} (ss1, ss2, ss3)$
 $\text{call} (f, \text{eseq} (s, e), es) \rightsquigarrow \text{eseq} (s, \text{call} (f, e, es))$

Linearization: More Rules

`seq (ss1, seq (ss2), ss3) \rightsquigarrow seq (ss1, ss2, ss3)`

`call (f, eseq (s, e), es) \rightsquigarrow eseq (s, call (f, e, es))`

`binop (+, eseq (s, e1), e2)`

Linearization: More Rules

`seq (ss1, seq (ss2), ss3) \rightsquigarrow seq (ss1, ss2, ss3)`

`call (f, eseq (s, e), es) \rightsquigarrow eseq (s, call (f, e, es))`

`binop (+, eseq (s, e1), e2) \rightsquigarrow eseq (s, binop (+, e1, e2))`

Linearization: More Rules

`seq (ss1, seq (ss2), ss3) \rightsquigarrow seq (ss1, ss2, ss3)`

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`binop (+, e1, eseq (s, e2))`

Linearization: More Rules

$\text{seq} (\text{ss1}, \text{seq} (\text{ss2}), \text{ss3}) \rightsquigarrow \text{seq} (\text{ss1}, \text{ss2}, \text{ss3})$

$\text{call} (\text{f}, \text{eseq} (\text{s}, \text{e}), \text{es}) \rightsquigarrow \text{eseq} (\text{s}, \text{call} (\text{f}, \text{e}, \text{es}))$

$\text{binop} (+, \text{eseq} (\text{s}, \text{e1}), \text{e2}) \rightsquigarrow \text{eseq} (\text{s}, \text{binop} (+, \text{e1}, \text{e2}))$

$\text{binop} (+, \text{e1}, \text{eseq} (\text{s}, \text{e2})) \rightsquigarrow \text{eseq} (\text{s}, \text{binop} (+, \text{e1}, \text{e2}))$

Linearization: Incorrect Changes

`binop (+, e1, eseq (s, e2)) \rightsquigarrow eseq (s, binop (+, e1, e2))`

- But what if `s` modifies the value of `e1`?

```
binop (+, temp t,  
      eseq (move (temp t, const 42),  
            const 0))
```

```
 $\rightsquigarrow$  eseq (move (temp t, const 42),  
          binop (+, temp t, const 0))
```

- This transformation is *invalid*: it changes the semantics.
- How can it be solved?

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Linearization: Incorrect Changes

```
t + (t := 42, 0)
```

```
binop (+,  
      temp t,  
      eseq (move (temp t, const 42),  
            const 0))
```

Wrong

```
eseq (move (temp t,  
           const 42),  
      binop (+,  
            temp t,  
            const 0))
```


Linearization: Incorrect Changes

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t + (t := 42, 0)
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```
binop (+,  
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      eseq (move (temp t, const 42),  
            const 0))
```

Wrong

```
eseq (move (temp t,  
           const 42),  
      binop (+,  
            temp t,  
            const 0))
```

Right

```
eseq (seq (move (temp t0, temp t)  
          move (temp t, const 42)),  
      binop (+,  
            temp t0,  
            const 0))
```

Linearization: More Temporaries

- When “de-expressioning” fresh temporaries are needed

```
binop (+, e1, eseq (s, e2))  
  ~> eseq (seq (move (temp t, e1), s),  
           binop (+, temp t, e2))
```

- More generally

```
call (f, es1, eseq (s, e), es2)  
  ~> eseq (seq (move (temp t1, e1),  
               move (temp t2, e2),  
               move (temp t3, e3),  
               ...,  
               s),  
         call (f, ts, e, es2))
```

- This is extremely inefficient when not needed...

Linearization: Commutativity

- Save useless extra temporaries and moves.
- Problem: commutativity cannot be known statically.
E.g., `move (mem (t1), e)` and `mem (t2)`
commute iff $t1 \neq t2$.
- We need a *conservative* approximation,
i.e., never say “commute” when they don’t.
E.g., “if `e` is a `const` then `s` and `e` definitely commute”.

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E.g., “if `e` is a `const` then `s` and `e` definitely commute”.

Call Normalization

Normalization of a `call` depends on the kind of the routine:

`procedure` then its parent must be an `sxp`

`function` then its parent must be a `move` (`temp t, .`)

This normalization is performed simultaneously with linearization.

Two Way Jumps

Obviously, to enable the translation of a `cjump` into actual assembly instructions, the “false” label must follow the `cjump`.

How?

Two Way Jumps: Basic Blocks

Split the long outer seq into “basic blocks”:

- a single entry: the first instruction
- a single (maybe multi-) exit: the last instruction

It may require

- a new label as first instruction, to which the prologue jumps
- new labels after jumps or c jumps
- a new jump from the last instruction to the epilogue.

Two Way Jumps: Traces

Start from the initial block, and “sew” each remaining basic block to this growing “trace”.

- If the last instruction is a `jump`
 - if the “destination block” is available, add it
 - otherwise, fetch any other remaining block.
- If the last instruction is a `cjump`
 - If the false destination is available, push it
 - If the true destination is available, flip the `cjump` and push it,
 - otherwise, change the `cjump` to go to a fresh label, attach this label, and finally `jump` to the initial false destination.

Two Way Jumps: Optimizing Traces

Many jumps should be removable, but sometimes there are choices to make.

```
label prologue  
  Prologue.  
jump name test
```

```
label test  
cjump i <= N, body, done
```

```
label body  
  Body.  
jump name test
```

```
label done  
  Epilogue  
jump name end
```

Two Way Jumps: Optimizing Traces

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```



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