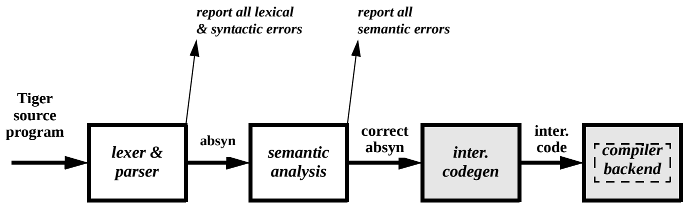
Intermediate Code Generation

- *Translating the **abstract syntax** into the **intermediate representation**.*



- *What should **Intermediate Representation** (**IR**) be like ?*

  not too low-level (machine independent) but also not too high-level (so that we can do optimizations)

- *How to convert **abstract syntax** into **IR** ?*

Intermediate Representations (IR)

- ***What makes a good IR ?*** *--- easy to convert from the absyn; easy to convert into the machine code; must be clear and simple; must support various machine-independent optimizing transformations;*

- *Some modern compilers use **several** IRs (e.g., k=3 in SML/NJ) --- each IR in later phase is a little closer (to the machine code) than the previous phase.*

  Absyn ==> IR_1 ==> IR_2 ... ==> IR_k ==> machine code

  pros : make the compiler cleaner, simpler, and easier to maintain

  cons : multiple passes of code-traversal --- compilation may be slow

- *The **Tiger** compiler uses one IR only --- the **Intermediate Tree (itree)***

  Absyn => **itree** *frags* => **assembly** => **machine code**

  How to design itree ? stay in the middle of absyn and assembly!

Case Study : itree

- *Here is one example, defined using ML datatype definition:*

```
structure Tree : TREE =
struct

  type label = string
  type size = int
  type temp = int

  datatype stm = SEQ of stm * stm | ......
       and exp = BINOP of binop * exp * exp | ......

       and test = TEST of relop * exp * exp

       and binop = FPLUS | FMINUS | FDIV | FMUL
                 | PLUS | MINUS | MUL | DIV
                 | AND | OR | LSHIFT | RSHIFT | ARSHIFT | XOR
       and relop = EQ | NE | LT | GT | LE | GE
                 | ULT | ULE | UGT | UGE
                 | FEQ | FNE | FLT | FLE | FGT | FGE
       and cvtop = CVTSU | CVTSS | CVTSF | CVTUU
                 | CVTUS | CVTFS | CVTFF
end
```


itree Statements and Expressions

- *Here is the detail of itree statements* **stm** *and itree expressions* **exp**

```
datatype stm = SEQ of stm * stm
             | LABEL of label
             | JUMP of exp
             | CJUMP of test * label * label
             | MOVE of exp * exp
             | EXP of exp

     and exp = BINOP of binop * exp * exp
             | CVTOP of cvtop * exp * size * size
             | MEM of exp * size
             | TEMP of temp
             | ESEQ of stm * exp
             | NAME of label
             | CONST of int
             | CONSTF of real
             | CALL of exp * exp list
```

itree Expressions

- ***itree** expressions stand for the computation of some value, possiblly with side-effects:*

CONST(*i*) the integer constant *i*

CONSTF(*x*) the real constant *x*

NAME(*n*) the symbolic constant *n* (i.e., the assembly lang. label)

TEMP(*t*) content of temporary *t* ; like registers (unlimited number)

BINOP(o,e_1,e_2) apply binary operator o to operands e_1 and e_2 , here e_1 must be evaluated before e_2

itree Expressions (cont'd)

- *more **itree** expressions:*

CVTOP(o,e,j,k) converting j-byte operand e to a k-byte value using operator o.

MEM(e,k) the contents of k bytes of memory starting at address e. if used as the left child of a **MOVE**, it means "store"; otherwise, it means "fetch". (k is often a word)

CALL(f,l) a procedure call: the application of function f : the expression f is evaluated first, then the expression list (for arguments) l are evaluated from left to right.

ESEQ(s,e) the statement s is evaluated for side effects, then e is evaluated for a result.

itree Statements

- ***itree** statements performs side-effects and control flow - no return value!*

SEQ(s_1,s_2) statement s_1 followed by s_2
EXP(e) evaluate expression e and discard the result
LABEL(n) define n as the current code address (just like a label definition in the assembly language)

MOVE(TEMP `t`, e**)** evaluate e and move it into temporary `t`

MOVE(MEM(e_1,k), e_2**)** evaluate e_1 to address `adr`, then evaluate e_2, and store its result into `MEM[adr]`

JUMP(e) jump to the address e; the common case is jumping to a known label `l` **JUMP(NAME(l))**

CJUMP(TEST(o,e_1,e_2),t,f) conditional jump, first evaluate e_1 and then e_2, do comparison o, if the result is true, jump to label t, otherwise jump the label f

itree Fragments

- *How to represent Tiger **function declarations** inside the **itree** ?*

representing it as a **itree PROC** *fragment* :

```
datatype frag
  = PROC of {name : Tree.label,        function name
             body : Tree.stm,          function body itree
             frame : Frame.frame}      static frame layout
  | DATA of string
```

each **itree PROC** *fragment* will be translated into a function definition in the final "*assembly code*"

- *The* **itree DATA** *fragment* is used to denote Tiger string literal. It will be placed as string constants in the final "assembly code".

- *Our job is to convert **Absyn** into a list of **itree** Fragments*

Example: Absyn => itree Frags

```
function tigermain () : resType =       (* added for uniformity !*)

let type intArray = array of int
   var a := intArray [9] of 0
   function readarray () = ...
   function writearray () = ...
   function exchange(x : int, y : int) =
      let var z := a[x] in a[x] := a[y]; a[y] := z end
   function quicksort(m : int, n : int) =
      let function partition(y : int, z : int) : int =
             let var i := y          var j := z + 1
              in (while (i < j) do
                    (i := i+1; while a[i] < a[y] do i := i+1;
                     j := j-1; while a[j] > a[y] do j := j-1;
                     if i < j then exchange(i,j));
                  exchange(y,j); j)
             end
       in if n > m then (let var i := partition(m,n)
                          in quicksort(m, i-1);
                             quicksort(i+1, n)
                         end)
      end
 in readarray(); quicksort(0,8); writearray()
end
```


Example: Absyn => itree frags

- *The **quicksort** program (in absyn) is translated to a list of **itree** frags :*

PROC(*label* `Tigermain`, ***itree** code for* `Tigermain`*'s body*,
`Tigermain`*'s frame layout info*)

PROC(*label* `readarray`, ***itree** code for* `readarray`*'s body*,
`readarray`*'s frame layout info*)

PROC(*label* `writearray`, ***itree** code for* `writearray`*'s body*,
`writearray`*'s frame layout info*)

PROC(*label* `exchange`, ***itree** code for* `exchange`*'s body*,
`exchange`*'s frame layout info*)

PROC(*label* `partition`, ***itree** code for* `partition`*'s body*,
`partition`*'s frame layout info*)

PROC(*label* `quicksort`, ***itree** code for* `quicksort`*'s body*,
`quicksort`*'s frame layout info*)

DATA("... assembly code for string literal #1 ...")
DATA("... assembly code for string literal #2 ...")
....

Summary: Absyn => itree Frags

- *Each absyn **function** declaration is translated into an **itree*** **`PROC`** *frag*

TODO:
1. functions are no longer nested -- must figure out the stack frame layout information and the runtime access information for local and non-local variables !
2. must convert function body (**Absyn.exp**) into **itree** ***`stm`***
3. calling conventions for **Tiger** functions and external **C** functions (which uses *standard* convention...)

- *Each **string** literal or **real** constant is translated into an **itree*** **`DATA`** *frag, associated with a **assembly code label** ---- To reference the constant, just use this **label.***

- ***Future work:** translate **itree-Frags** into the assembly code of your favourite machine (PowerPC, or SPARC)*

Review: Tiger Abstract Syntax

```
exp = VarExp of var
    | NilExp
    | IntExp of int
    | StringExp of string * pos
    | AppExp of {func: Symbol.symbol, args: exp list, pos: pos}
    | OpExp of {left: exp, oper: oper, right: exp, pos: pos}
    | RecordExp of {typ: Symbol.symbol, pos: pos,
                    fields: (Symbol.symbol * exp * pos) list}
    | SeqExp of (exp * pos) list
    | AssignExp of {var: var, exp: exp, pos: pos}
    | IfExp of {test: exp, then’: exp, else’: exp option, pos: pos}
    | WhileExp of {test: exp, body: exp, pos: pos}
    | ForExp of {var: Symbol.symbol, lo: exp, hi: exp,
                 body: exp, pos: pos}
    | BreakExp of pos
    | LetExp of {decs: dec list, body: exp, pos: pos}
    | ArrayExp of {typ: Symbol.symbol, size: exp,
                   init: exp, pos: pos}

dec = VarDec of {var: Symbol.symbol,init: exp, pos : pos,
                 typ: (Symbol.symbol * pos) option}
    | FunctionDec of fundec list
    | TypeDec of {name: Symbol.symbol, ty: ty, pos: pos} list
```

Mapping Absyn Exp into itree

- *We define the following new* ***generic*** *expression type* `gexp`

```
datatype gexp
  = Ex of Tree.exp
  | Nx of Tree.stm
  | Cx of Tree.label * Tree.label -> Tree.stm
```

this introduce three new constructors:

```
  Ex : Tree.exp -> gexp
  Nx : Tree.stm -> gexp
  Cx : (Tree.label * Tree.label -> Tree.stm) -> gexp
```

- *Each* ***Absyn.exp*** *that computes a value is translated into* `Tree.exp` *Each* ***Absyn.exp*** *that returns no value is translated into* `Tree.stm`
- *Each "condititional"* ***Absyn.exp*** *(which computes a boolean value) is translated into a function* `Tree.label * Tree.label -> Tree.stm`

Tiger Expression: `a>b | c<d` *would be translated into*

```
  Cx(fn (t,f) => SEQ(CJUMP(TEST(GT,a,b),t,z),
                     SEQ(LABEL z, CJUMP(TEST(LT,c,d),t,f))))
```


Mapping Absyn Exp into itree

- ***Utility*** *functions for convertion among* `Ex`*,* `Nx`*, and* `Cx` *expressions:*

```
unEx : gexp -> Tree.exp
unNx : gexp -> Tree.stm
unCx : gexp -> (Tree.label * Tree.label -> Tree.stm)

Examples:
fun seq [] = error "..."
  | seq [a] = a
  | seq(a::r) = SEQ(a,seq r)

fun unEx(Ex e) = e
  | unEx(Nx s) = T.ESEQ(s, T.CONST 0)
  | unEx(Cx genstm) =
      let val r = T.newtemp()
          val t = T.newlabel and f = T.newlabel()
       in T.ESEQ(seq[T.MOVE(T.TEMP r, T.CONST 1),
                     genstm(t,f),
                     T.LABEL f,
                     T.MOVE(T.TEMP r, T.CONST 0)
                     T.LABEL t],
                 T.TEMP r)
      end
```


Simple Variables

- *Define the* ***frame*** *and* ***level*** *type for each function definition:*

```
type frame = {formals: int, offlst : int list,
              locals : int ref, maxargs : int ref}

datatype level = LEVEL of {frame : frame,
                           slink_offset : offset,
                           parent : level} * unit ref
               | TOP

type access = level * offset
```

- *The* ***access information*** *for a variable* ***v*** *is a pair* `(l,k)` *where* `l` *is the level in which* ***v*** *is defined and* `k` *is the frame offset.*
- *The* ***frame offset*** *can be calculated by the* `allocLocal` *function in the* `Frame` *structure (which is architecture-dependant). The* ***access*** *information will be put in the* ***env*** *in the typechecking phase.*

Simple Variables (cont'd)

- *To access a* ***local variable v*** *at offset* `k`*, assuming the frame pointer is* `fp`*, just do* `MEM(BINOP(PLUS, TEMP fp, CONST k),`*w*`)`
- *To access a* ***non-local variable v*** *inside function* ***f*** *at level* l_f*, assuming* ***v****'s access is* (l_g, k)*; we do the following:*

`MEM(+(CONST` k_n`,MEM(+(CONST` k_{n-1}`,...MEM(+(CONST` k_1`,TEMP fp))..))`

Strip levels from l_f*, we use the static link offsets* k_1*,* k_2*, ... from these levels to construct the tree. When we reach* l_g*, we stop.*

```
datatype level = LEVEL of {frame : frame,
                           slink_offset : offset,
                           parent : level} * unit ref
               | TOP
```

use "`unit ref`*" to test if two levels are the same one.*

Array and Record Variables

- *In **Pascal**, an array variable stands for the contents of the array --- the assignment will do the copying :*

```
var a, b : array [1..12] of integer;
begin
     a := b
end;
```

- *In **Tiger** and **ML**, an array or record variable just stands for the pointer to the object, not the actual object. The assignment just assigns the pointer.*

```
let type intArray = array of int
    var a := intArray[12] of 0
    var b := intArray[12] of 7
 in a := b
end
```

- *In **C**, assignment on array variables are illegal !*

`int a[12], b[12], *c;`   `a = b;` ***is illegal!***   `c = a;` ***is legal!***

Array Subscription

- *If* `a` *is an array variable represented as* `MEM(e)`, *then **array subscription*** `a[i]` *would be (*`ws` *is the word size)*

  MEM(**BINOP**(PLUS,MEM(e),**BINOP**(MUL,i,CONST ws)))

- *To ensure **safety**, we must do the **array-bounds-checking**: if the array bounds are **L..H**, and the subscript is **i**; then report runtime **errors** when either **i < L** or **i > H** happens.*

- *Array subscription can be either **l-values** or **r-values** --- use it properly.*

- ***Record field selection** can be translated in the same way. We calculate the offset of each field at compile time.*

  `type point intlist = {hd : int, tl : intlist}`

  the offset for “hd” *and* “tl” *is* 0 *and* 4

Record and Array Creation

- *Tiger **record creation**:* var z = **foo** {f_1 = e_1, ..., f_n = e_n}

  we can implement this by calling the C `malloc` *function, and then **move** each* e_i *to the corresponding field of* `foo`*. (see Appel pp164)*

  ***In real compilers**, calling* `malloc` *is expensive; we often inline the* `malloc` *code.*

- *Tiger **array creation**:* var z = **foo** n **of** initv

  by calling a C `initArray(size,initv)` *function, which allocates an array of size* `size` *with initial value* `initv`.

  *to support array-bounds-checking, we can put the array **length** in the **0-th field**.* `z[i]` *is accessed at offset* `(i+1)*word_sz`

- *Requirement: a way to call external C functions inside Tiger.*

Integer and String

- ***Integer** : absyn* `IntExp(i)` => *itree* `CONST(i)`

- ***Arithmetic**: absyn* `OpExp(i)` => *itree* `BINOP(i)`

- ***Strings**: every string literal in Tiger or C is the constant address of a segment of memory initialized to the proper characters.*

  *During translation from **Absyn** to **itree**, we associate a label* `l` *for each string literal **s**:*

  *to refer to **s**, just use* `NAME l`

  Later, we'll generate assembly instructions that define and initialize this label `l` *and string literal **s**.*

  String representations:

  1. a word containing the length followed by characters (in Tiger)

  2. a pointer to a sequence of characters followed by `\000` *(in C)*

  3. a fixed length array of characters (in Pascal)

Conditionals

- *Each **comparison** expression* `a < b` *will be translated to a **Cx** generic expression* **fn** (*t*,*f*) **=>** (TEST(LT,a,b),*t*,*f*)
- *Given a conditional expression (in absyn)* ***if*** e_1 ***then*** e_2 ***else*** e_3

  1. translate e_1, e_2, e_3 into itree generic expressions e_1, e_2, e_3
  2. apply **unCx** to e_1, and **unEx** to e_2 and e_3
  3. make three labels, **then** case: *t* and **else** case: *f* and **join** : *j*
  4. allocate a temporary *r*, after label *t*, move e_2 to *r*, then jump to *j*; after label *f*, move e_3 to *r*, then jump to *j*
  5. apply ***unCx-ed*** version of e_1 to label *t* and *f*

- *Need to recognize certain **special case**:* `(x < 5) & (a > b)` *it is converted to "**if** x < 5 **then** a > b **else** 0" in absyn -------- too many labels if using the above algorithm --- **inefficient**. (read Appel page 162)*

Loops

- *Translating **while** loops:*

```
test:
  if not (condition) goto done
    ... the loop body ...
  goto test
done:
```

each round executes one conditional branch plus one jump

```
    goto test
top:
    ... the loop body ...
test:
    if (condition) goto top
done:
```

each round executes one conditional branch only

- *Translating **break** statements:* *just* **JUMP** *to* `done`

  need to pass down the label `done` *when translating the loop body!*

- *Translating **For** loops: (exercise, or see Appel pp 166)*

  for i := *lo* **to** *hi* **do** *body*

Function Calls

- *Inside a function **g**, the function call* $f(e_1, e_2, \ldots, e_n)$ *is translated into* **CALL**(**NAME** l_f, [sl, e_1, e_2, ..., e_n])

  *sl is the static link --- it is just a pointer to **f**'s **parent level**, but how can we find it when we are inside **g** ?*

  *striping the **level** of **g** one by one, generate the code that follow **g**'s chains of static links until we reach **f**'s **parent level**.*

- *When calling external C functions, what kind of static link do we pass ?*

- *In the future, we need to decide what is the **calling convention** ----- where the callee is expecting the formal parameters and the static link?*

Declarations

- ***Variable** declaration: need to figure out the **offset** in the frame, then* **move** *the expression on the r.h.s. to the proper **slot** in the **frame**.*
- ***Type** declaration: no need to generate any **itree** code !*
- ***Function** declaration: build the* **PROC** ***itree*** *fragment*

  Later we translate **PROC(**name **: label,** body **: stm,** frame**)**

  to assembly:

```
         _global name
name:    ......                 prologue
         assembly code for body
         ......                 epilogue
```

  *The **prologue** and **epilogue** captures the **calling sequence**, and can be figured out from the frame layout information in* `frame.` ***Prologue** and **epilogue** are often machine-dependant.*

Function Declarations

- *Generating **prologue** :*

    1. *psuedo-instructions to announce the beginning of a function*
    2. *a label definiton fo the function name*
    3. *an instruction to adjust the stack pointer (allocating a new frame)*
    4. ***store** instructions to save callee-save registers and return address*
    5. ***store** instructions to save arguments and static links*

- *Generating **epilogue** :*

    1. *an instruction to move the return result to a special register*
    2. ***load** instructions to restore callee-save registers*
    3. *an instruction to reset the stack pointer (pop the frame)*
    4. *a **return** instruction (jump to the return address)*
    5. *psuedo-instructions to announce the end of a function*