

Review Type Judgments

```
int program(int argc, string[] argv) {  
    if (true) {  
        return 0;  
    } else {  
        return 1;  
    }  
}
```

$$G; L_0 \vdash vdecls \Rightarrow L_i$$

$$G; L_1; retty \vdash stmt \Rightarrow L_2$$

$$G; L_0; t \vdash stmt_1 .. stmt_i \Rightarrow L_i$$

$$G; L_1 \vdash vdecl \Rightarrow L_2$$

$$G \vdash decl$$

$$\vdash prog$$

$$G_0 \vdash decl \Rightarrow G_1$$

$$G; L; t \vdash block$$

Review Type Judgments

```
int program(int argc, string[] argv) {  
    while (1 > 0) {  
        return 3;  
    }  
    return 0;  
}
```

Review Type Judgments

```
struct A { int x }  
struct B { int x; int y }
```

```
int f(A x) {  
    return 3;  
}
```

```
int g(B x) {  
    return 3;  
}
```

```
int l() {  
    var x = g;  
    x = f;  
    return 3;  
}
```

CS 516: COMPILERS

Lecture 16

Topics

- Review Type Derivations
- Compilation as translating Judgments



COMPILATION AS TRANSLATING JUDGMENTS

Why Inference Rules?

- They are a compact, precise way of specifying language properties.
- Correspond closely to recursive AST traversal
- Strong mathematical foundations
- Type checking - search backward through the rules
- It works for **compiling**, too!
- **Compiling in a context** is
 - Compilation follows the typechecking judgment
 - nothing more an “interpretation” of the inference rules that specify typechecking*: $\llbracket C \vdash e : t \rrbracket$

Compilation As Translating Judgments

- Consider the source typing judgment for source expressions:

$$C \vdash e : t$$

- How do we interpret this information in the target language?

$$\llbracket C \vdash e : t \rrbracket = ?$$

- $\llbracket C \rrbracket$ translates contexts
- $\llbracket t \rrbracket$ is a target type

Compilation As Translating Judgments

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$$\llbracket C \vdash e : t \rrbracket = ?$$

- $\llbracket C \rrbracket$ translates contexts
- $\llbracket t \rrbracket$ is a target type
- $\llbracket e \rrbracket$ translates to a (potentially empty) stream of instructions, that, when run, computes the result into some operand
- Invariant:** if $\llbracket C \vdash e : t \rrbracket = \text{ty, operand, stream}$
then the type (at the target level) of the operand is $\text{ty} = \llbracket t \rrbracket$

Example

- $C \vdash 516 + 5 : \text{int}$ what is $\llbracket C \vdash 516 + 5 : \text{int} \rrbracket$?

$\vdash 516 : \text{int}$

$\vdash 5 : \text{int}$

$C \vdash 516 : \text{int}$

$C \vdash 5 : \text{int}$

$C \vdash 516 + 5 : \text{int}$

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Invariant: $\llbracket C \vdash e : t \rrbracket = \text{ty, operand, stream}$

$\llbracket \vdash 516 : \text{int} \rrbracket = ???$

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Invariant: $\llbracket C \vdash e : t \rrbracket = \text{ty, operand, stream}$

$\llbracket \vdash 516 : \text{int} \rrbracket = (\text{i64}, \text{Const } 516, [])$

$\llbracket \vdash 5 : \text{int} \rrbracket = ???$

$\llbracket C \vdash 516 : \text{int} \rrbracket = ???$

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$\llbracket C \vdash 516 : \text{int} \rrbracket = (\text{i64}, \text{Const } 516, [])$

$\llbracket C \vdash 5 : \text{int} \rrbracket = (\text{i64}, \text{Const } 5, [])$

$\llbracket C \vdash 516 + 5 : \text{int} \rrbracket = (\text{i64}, \%tmp, [\%tmp = \text{add i64 (Const } 516) (\text{Const } 5)])$

What about the Context?

Question: What is $\llbracket C \rrbracket$?

- Source level C has bindings like: $x:\text{int}, y:\text{bool}$
 - We think of it as a finite map from identifiers to types
- What is the interpretation of C at the target level?
- $\llbracket C \rrbracket$ maps *source identifiers*, “ x ” to source types and $\llbracket x \rrbracket$

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**As exprs
(Values)**

$$\frac{x : t \in L}{G; L \vdash x : t} \text{ TYP_VAR}$$

**As addr
(Can be
assigned)**

$$\frac{x : t \in L \quad G; L \vdash \text{exp} : t}{G; L; rt \vdash x = \text{exp}; \Rightarrow L} \text{ TYP_ASSN}$$

Interpretation of Contexts

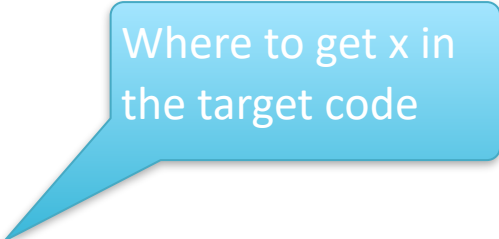
- **How to interpret contexts:**

$\llbracket C \rrbracket$ = a map from source identifiers to types and target identifiers

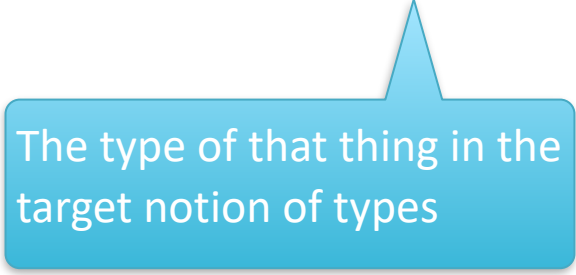
- **Invariant:**

$x : t \in C$ means that

- (1) lookup $\llbracket C \rrbracket x = (t, \%id_x)$
- (2) the (target) type of $\%id_x$ is $\llbracket t \rrbracket^*$ (a pointer to $\llbracket t \rrbracket$)



Where to get x in the target code



The type of that thing in the target notion of types

Interpretation of Variables

- **Expressions:** Invariant has the following form:

$$\left[\frac{x : t \in L}{G; L \vdash x : t} \text{ TYP_VAR} \right]$$

as expressions
(which denote values)

= (%tmp, [%tmp = load i64* %id_x])

where (i64, %id_x) = lookup $\llbracket L \rrbracket$ x

Translation tells you
the target type...

... and where it's stored

Translation of the **expression** x

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as addresses
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= stream @
[store $\llbracket t \rrbracket$ opn, $\llbracket t \rrbracket^*$ %id_x]

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= stream @
[store $\llbracket t \rrbracket$ opn, $\llbracket t \rrbracket^*$ %id_x]

where (t, %id_x) = lookup $\llbracket L \rrbracket$ x
and $\llbracket G; L \vdash exp : t \rrbracket = (\llbracket t \rrbracket, \text{opn}, \text{stream})$

1. First recursively translate *exp* to find out where to store

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2. Then create a new store instruction:

= stream @
[store $\llbracket t \rrbracket$ opn, $\llbracket t \rrbracket^*$ %id_x]

where (t, %id_x) = lookup $\llbracket L \rrbracket$ x
and $\llbracket G; L \vdash exp : t \rrbracket = (\llbracket t \rrbracket, \text{opn}, \text{stream})$

1. First recursively translate *exp* to find out where to store

Other Judgments?

- **Statement:** How to compile *stmt* typing rules

$$\llbracket C; rt \vdash stmt \Rightarrow C' \rrbracket = \llbracket C' \rrbracket, \text{stream}$$

stmt may
alter context

may need **C'** to get
values from **stream**

- **Declaration:** How to compile *decl* rules

-

$$\llbracket G; L \vdash t \ x = exp \Rightarrow G; L, x : t \rrbracket = \llbracket G; L, x : t \rrbracket, \text{stream}$$

INVARIANT: stream is of the form:

```
stream' @  
[ %id_x = alloca  $\llbracket t \rrbracket$ ;  
  store  $\llbracket t \rrbracket$  opn,  $\llbracket t \rrbracket^*$  %id_x ]
```

and $\llbracket G; L \vdash exp : t \rrbracket = (\llbracket t \rrbracket, \text{opn}, \text{stream}')$

- Rest follow similarly

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extended context
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INVARIANT: stream is of the form:

stream' @

[%id_x = alloca $\llbracket t \rrbracket$;

store $\llbracket t \rrbracket$ opn, $\llbracket t \rrbracket^*$ %id_x]

allocate space

store initial value

and $\llbracket G; L \vdash exp : t \rrbracket = (\llbracket t \rrbracket, \text{opn}, \text{stream}')$

- Rest follow similarly

Homework 5

```
let rec cmp_exp (tc : TypeCtxt.t) (c:Ctxt.t) (exp:Ast.exp node) :  
Ll.ty * Ll.operand * stream =
```

```
match exp.elc with
```

```
| Ast.CInt i  -> I64, Const i, []
```

```
| Ast.CNull r -> cmp_ty tc (TNullRef r), Null, []
```

```
| Ast.CStr s ->
```

```
  let gid = gensym "str_arr" in
```

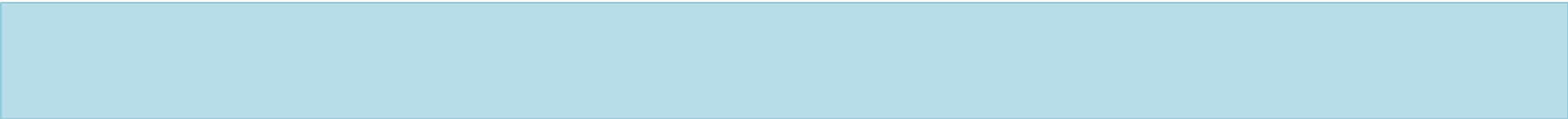
```
  let str_typ = str_arr_ty s in
```

```
  let uid = gensym "str" in
```

```
    Ptr I8, Id uid, []
```

```
>:: G(gid, (str_typ, GString s))
```

```
>:: I(uid, Gep(Ptr str_typ, Gid gid, [Const 0L; Const 0L;]))
```



COMPILING CONTROL

Translating while

- Consider translating “while(*e*) *s*”:
 - Test the conditional, if true jump to the body, else jump to the label after the body.

$\llbracket C; rt \vdash \text{while}(e) \ s \Rightarrow C' \rrbracket = \llbracket C' \rrbracket,$

```
lpre:
    opn =  $\llbracket C \vdash e : \text{bool} \rrbracket$ 
    %test = icmp eq i1 opn, 0
    br %test, label %lpost, label %lbody
lbody:
     $\llbracket C; rt \vdash s \Rightarrow C' \rrbracket$ 
    br %lpre
lpost:
```

- Note: writing `opn =  $\llbracket C \vdash e : \text{bool} \rrbracket$` is pun
 - translating $\llbracket C \vdash e : \text{bool} \rrbracket$ generates *code* that puts the result into `opn`
 - In this notation there is implicit collection of the code

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lpost:
```

- Note: writing $\text{opn} = \llbracket C \vdash e : \text{bool} \rrbracket$ is pun
 - translating $\llbracket C \vdash e : \text{bool} \rrbracket$ generates code that puts the result into *opn*
 - In this notation

$$\frac{H; G; L \vdash \text{exp} : \text{bool} \quad H; G; L; rt \vdash \text{block}; r}{H; G; L; rt \vdash \text{while}(\text{exp}) \text{ block} \Rightarrow L; \perp}$$

Translating if-then-else

- Similar to while except that code is slightly more complicated because if-then-else must reach a merge and the else branch is optional.

$$\llbracket C; rt \vdash \text{if } (e) \ s_1 \ \text{else} \ s_2 \Rightarrow C' \rrbracket = \llbracket C' \rrbracket$$

```
    opn =  $\llbracket C \vdash e : \text{bool} \rrbracket$ 
    %test = icmp eq i1 opn, 0
    br %test, label %else, label %then
then:
     $\llbracket C; rt \vdash s_1 \Rightarrow C' \rrbracket$ 
    br %merge
else:
     $\llbracket C; rt \vdash s_2 \Rightarrow C' \rrbracket$ 
    br %merge
merge:
```

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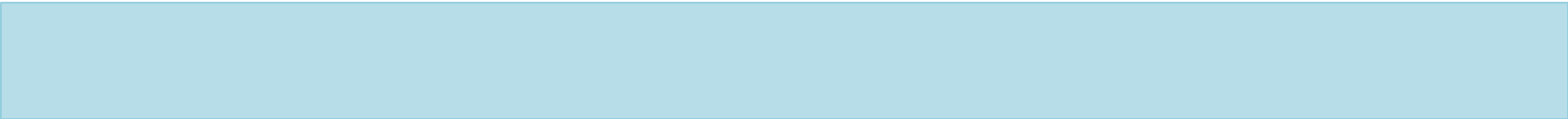
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else:
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merge:
```

$$H; G; L \vdash \text{exp} : \text{bool}$$
$$H; G; L; rt \vdash \text{block}_1; r_1$$
$$H; G; L; rt \vdash \text{block}_2; r_2$$
$$\frac{}{H; G; L; rt \vdash \text{if}(\text{exp}) \ \text{block}_1 \ \text{else} \ \text{block}_2 \Rightarrow L; r_1 \wedge r_2}$$

Connecting this to Code

- Instruction streams:
 - Must include labels, terminators, and “hoisted” global constants
- Must post-process the stream into a control-flow-graph
- See frontend.ml from HW4,
for example, function `cmp_stmt` case `If(g, st1, st2)`



OPTIMIZING CONTROL

Standard Evaluation

- Consider compiling the following program fragment:

```
if (x & !y | !w)
    z = 3;
else
    z = 4;
return z;
```



```
%tmp1 = icmp Eq [[y]], 0      ; !y
%tmp2 = and [[x]] [[tmp1]]
%tmp3 = icmp Eq [[w]], 0
%tmp4 = or %tmp2, %tmp3
%tmp5 = icmp Eq %tmp4, 0
br %tmp4, label %else, label %then

then:
    store [[z]], 3
    br %merge

else:
    store [[z]], 4
    br %merge

merge:
    %tmp5 = load [[z]]
    ret %tmp5
```

Observation

- Usually, we want the translation $\llbracket e \rrbracket$ to produce a value
 - $\llbracket C \vdash e : t \rrbracket = (\text{ty}, \text{operand}, \text{stream})$
 - e.g. $\llbracket C \vdash e_1 + e_2 : \text{int} \rrbracket = (\text{i64}, \%tmp, [\%tmp = \text{add } \llbracket e_1 \rrbracket \llbracket e_2 \rrbracket])$
- But when the expression we're compiling appears in a test, the program jumps to one label or another after the comparison but otherwise never uses the value.
- In many cases, we can avoid “materializing” the value (i.e. storing it in a temporary) and thus produce better code.
 - This idea also lets us implement different functionality too:
e.g. short-circuiting boolean expressions

Idea: Use a different translation for tests

Usual Expression translation:

$\llbracket C \vdash e : t \rrbracket = (\text{ty}, \text{operand}, \text{stream})$

Conditional branch translation:

Translate booleans, without materializing the value:

$\llbracket C \vdash e : \text{bool}@ \rrbracket \text{ ltrue lfalse} = \text{stream}$

No ty or operand.
Instead a stream that
uses true and lfalse

$\llbracket C, rt \vdash \text{if } (e) \text{ then } s_1 \text{ else } s_2 \Rightarrow C' \rrbracket = \llbracket C' \rrbracket,$

Notes:

- takes two extra arguments:
a “true” branch label and a
“false” branch label.
- Doesn’t “return a value”
- Aside: this is a form of
continuation-passing
translation...

```
insns3
then:
   $\llbracket s_1 \rrbracket$ 
  br %merge
else:
   $\llbracket s_2 \rrbracket$ 
  br %merge
merge:
```

where

$\llbracket C, rt \vdash s_1 \Rightarrow C' \rrbracket = \llbracket C' \rrbracket, \text{ insns}_1$

$\llbracket C, rt \vdash s_2 \Rightarrow C'' \rrbracket = \llbracket C'' \rrbracket, \text{ insns}_2$

$\llbracket C \vdash e : \text{bool}@ \rrbracket \text{ then else} = \text{insns}_3$ ²³

Short Circuit Compilation: Expressions

- $\llbracket C \vdash e : \text{bool}@ \rrbracket \text{ ltrue lfalse} = \text{insns}$

$$\llbracket C \vdash \text{false} : \text{bool}@ \rrbracket \text{ ltrue lfalse} = [\text{br } \% \text{lfalse}] \quad \text{FALSE}$$

$$\llbracket C \vdash \text{true} : \text{bool}@ \rrbracket \text{ ltrue lfalse} = [\text{br } \% \text{ltrue}] \quad \text{TRUE}$$

$$\llbracket C \vdash e : \text{bool}@ \rrbracket \text{ lfalse ltrue} = \text{insns} \quad \text{NOT}$$

$$\llbracket C \vdash !e : \text{bool}@ \rrbracket \text{ ltrue lfalse} = \text{insns}$$

Short-Circuit Evaluation

Idea: build the logic into the translation

$$\llbracket C \vdash e1 : \text{bool@} \rrbracket \text{ ltrue right} = \text{insns}_1 \quad \llbracket C \vdash e2 : \text{bool@} \rrbracket \text{ ltrue lfalse} = \text{insns}_2$$
$$\llbracket C \vdash e1 \mid e2 : \text{bool@} \rrbracket \text{ ltrue lfalse} =$$

```
insns1
right:
  insn2
```

$$\llbracket C \vdash e1 : \text{bool@} \rrbracket \text{ right lfalse} = \text{insns}_1 \quad \llbracket C \vdash e2 : \text{bool@} \rrbracket \text{ ltrue lfalse} = \text{insns}_2$$
$$\llbracket C \vdash e1 \& e2 : \text{bool@} \rrbracket \text{ ltrue lfalse} =$$

```
insns1
right:
  insn2
```

where `right` is a fresh label

Short-Circuit Evaluation

- Consider compiling the following program fragment:

```
if (x & !y | !w)
    z = 3;
else
    z = 4;
return z;
```



```
%tmp1 = icmp Eq [[x]], 0
br %tmp1, label %right2, label %right1

right1:
    %tmp2 = icmp Eq [[y]], 0
    br %tmp2, label %then, label %right2

right2:
    %tmp3 = icmp Eq [[w]], 0
    br %tmp3, label %then, label %else

then:
    store [[z]], 3
    br %merge

else:
    store [[z]], 4
    br %merge

merge:
    %tmp5 = load [[z]]
    ret %tmp5
```