

Types and Type Checking

– lecture 7 –

Types

- Means of providing interpretation to the "bits".
- Two classes:
 - *Basic*: supported in hardware
 - *Aggregate*: hierarchical way of combining basic types
- In *strongly typed languages* (Ocaml, Haskell): means of detecting incorrect usage of functions

Basic Types

- Most languages have these types. We do a case study on C.
- `int` : 32 bits, signed (2's complement)
- `unsigned int` : 32 bits, unsigned
- `long long int` : 64 bits, signed
- `long long unsigned int` : 64 bits, unsigned
- `short int` : 16 bits, signed
- `unsigned short int` : 16 bits, unsigned
- `char` : 8 bits, signed
- `unsigned char` : 8 bits, unsigned
- `unsigned char` : 8 bits, unsigned
- `float` : 32 bit floating point reals
- `double` : 64 bit floating point reals
- `long double` : 80 bit floating point reals
- Operations on these types will be translated directly into the corresponding machine code instructions:
execution is very efficient


Datatype Conversions

- Usually called *casts*. Two main types:
 - A notion of *value* can be preserved
 - * *integral* \rightarrow *real* : preserve the value
 - * *real* \rightarrow *integral* : truncates away the fractional part
 - * small size integral \rightarrow large size integral : *sign extended*
 - Conversion may take the *floor* or the *ceiling*, depending on the language.
 - Bits can be copied over.
 - * Conversion between pointer types
 - * If sizes are not the same, the least significant bytes are usually preserved
- Implicit casts:
 - Compiler tries to perform conversions to match operators and declarations of functions.
 - When the result of an expression does not fit into 32 bits, it is cast to its address.
 - Exception: structures
 - Specific to C, most other languages do not perform this cast

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```
int a; float b;  
...  
x = a + b ;
```



a is converted to float, value is preserved

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```
char a; int b;  
...  
x = a + b ;
```




a is sign-extended to int, value is preserved

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```
float a;  
...  
int f(int x) ;  
...  
x = f(a);
```




a is truncated to int, value is preserved to utmost extent possible

Aggregate Types

- Arrays
- Most languages provide *records*
 - In C they are called *structures*
 - In object oriented programming they are extended to *objects*
- Unions: specific to C, help save space.
- High-level aggregate datatypes (Python, Ruby):
 - Lists
 - Tuples
 - Sets
 - Dictionaries
 - implemented in libraries for languages without these primitives

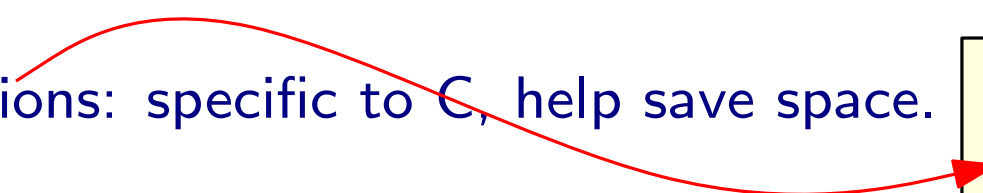
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```
struct struct_name {  
    type1 field1 ;  
    type2 field2, field3 ;  
    type3 field4[10] ;  
} var1, var2, * var3 ;
```

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```
union union_name {  
    type1 field1 ;  
    type2 field2, field3 ;  
    type3 field4[10] ;  
} var1, var2, * var3 ;
```

C Pointers

- Models the memory address of a datum.
- Memory is an array of bytes (unsigned characters) → pointer is an unsigned integer.
- At the type system level, the language distinguishes between pointers and integers for safety reasons.
 - This does not happen in VAL
- Declaration: `type * p`
- Operations:
 - `*p` : dereference
 - `p+k` : pointer arithmetic, points `k*sizeof(*p)` bytes away.
- The address of any *lvalue* can be captured into a pointer with the `&` (address-of) operator.

Pointers to Functions

```
type f() {  
    ...  
}  
  
...  
{  
    type (*p)() ; // pointer to a function that returns "type"  
    p = &f ; // assign p to address of f  
    ...  
    (*p)() ; // calls f  
    ...  
}
```

Pointers to Functions

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    ...  
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`p=f` would work too

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`f` would be implicitly cast to its address

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`p()` would work too

Pointers to Functions

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type f() {  
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```
...  
{
```

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    type (*p)() ; // pointer to a function that returns "type"  
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```

```
    ...  
    (*p)() ; // calls f  
    ...
```

```
}
```

`p()` would work too

`p` would be implicitly cast to its dereference

A Rich Type Language

```
#include <stdlib.h>

int * g(int a, int b) { // function that returns pointer to int
    return (int*)malloc(10) ;
}

typedef int * t(int,int) ;

int * (*f())(int,int) { // function that returns the address of g
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}

int main() {
    int (**a)[3][10] ;
    a = (int (**)[3][10])malloc(sizeof(int (**)[3][10])) ;
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f is

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int main() {
    int (**a)[3][10] ;
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f is a function that returns a pointer

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f is a function that returns a pointer to a function

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f is a function that returns a pointer to a function that returns a pointer

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Type operators have precedence: `()` and `[]` bind tighter than `*` ; we can use brackets to alter the precedence.

`int *a[10]` ; declares an array of pointers to int

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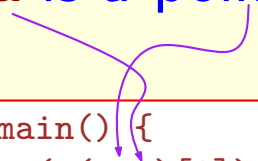
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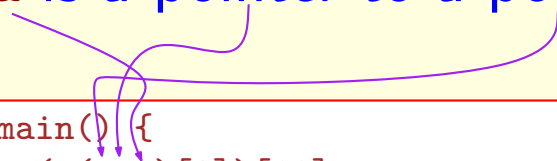
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```

Each layer of pointers must be initialized.

A Rich Type Language

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```

Drop the a to obtain the cast.

A Rich Type Language

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```

Move one * from right side to the left side

Continue on for each level of pointers

Type Checking for a Toy Language

Type constructors:

`int x ;` : declares `x` to be of base type integer

`T $ x ;` : `x` is a pointer to type `T`

`T x @ N ;` : `x` is an array of size `N`,
with elements of type `T`

`T x#(T1 arg1;
...;Tn argn) ;` : `x` is a function that takes `n` arguments,
of types `T1,...,Tn`. Arguments must be
separated by semicolon

`Str ~~~ { ... } ;` : declares the structure `Str`, having the
fields declared as normal 'variables'
within the curly braces.

`Str ~~~ x, y, z ;` : declare `x, y, z` to be of the structure
type `Str`. `Str` must have been declared
in advance.

Type-related Operators

`$` : pointer dereference -- `($p)` same as `(*p)` in C

`&` : address-of operator, similar to C

`_@N` : array indexing -- `a@2` same as `a[2]` in C

`_#_` : function application -- `f#(2;3)` same as `f(2,3)` in C

`_~~_` : field selector from a structure -- `s~~f` same as `s.f` in C

Code Sample

```
int x,           % x is an integer
    $y,          % y is a pointer to an integer
    z@10,        % z is an array of 10 integers
    $ $ $ zzz ;  % zzz is a pointer to pointer to pointer to integer
```

```
int ($fptr)#( int aa;          % fptr is a pointer to a function that
                        int bb;  % takes 3 arguments and returns an integer
                        int ($pp)#(int x)) ; % -- the third arg is a pointer to function too
```

```
s ~~~ { int f1,$ f2@10 ;      % s is a structure type, with 4 fields: an integer,
                        int e1,e3@10 } ; % an array of pointers to integers, a second integer,
                                           % and an array of integers.
```

```
s ~~~ p,q ;           % p and q are variables of type s
```

Code Sample

```
int proc # ( int a;          % proc is a procedure that takes 3 arguments
            int b;          % and returns an int. The third arg has a function type
            int ($p)#(int x)) :: {
    int c,d;                % two local integer variables
    int f # (int w) ::      % a local (nested) function, can only be called from inside proc
        {x = w ; return 1 } ;

    if a > 100 then {
        return a+1         % the type of the return expression will be checked against
    } ;                    % the type declared to be returned by the procedure

    ss ~~~ { int aa,bb } ;  % declarations can appear anywhere; another structure with 2 fields
    ss ~~~ sss ;           % sss is a structure of type ss

    sss ~~~ aa =            % assignment to the field 'aa' of structure 'sss'
        2 + c +
        f#d * proc#(x;$y;p) ; % calling f and then proc, recursively

    return ($pp)#(3) ;      % calling the pointer to function, and returning its value from proc
} ;
```

Code Sample

```
int qq#(int d) ::                                % another function
    { return d+1 } ;

fptr = & proc ;                                % assignment of the address of proc to a pointer to function

z@8 = ($fptr)#(6;20;&qq) ;                       % calling a pointer to function

x = 1 ; y = & x ; z@1 = $y ; % examples of assignments, some involving function calls
x = proc#(3;4;&qq) ;                             % -- all data transfers are int
$ y = proc#(z@2;$y;&qq) ;
p ~~ f1 = q ~~ e1 ;                             % assignment of and to structure fields

x = $ (z+2) ;                                    % pointer arithmetic, z+2 is a legal pointer

$ $ zzz = y ;                                    % multiple dereferencing, a pointer to int is assigned

y = (p~~f2)@2 ;                                  % access to an array element inside a structure

$ $ $ zzz = $((p~~f2)@2)                        % multiple dereferencing of pointers
```

Type Checking of Toy Language

```
/*
 * The main predicate computes the type of an
 * expression/statement. For expressions (i.e. syntactic constructs
 * that have value, the type is the type of the value. For type
 * declarations, the type returned is the atom 'type', and for all
 * other statements, the type is 'stmt'. The dummy types 'type' and
 * 'stmt' are important so as to allow us to check that structures
 * do not have any code in their definition.
 *
 * The arguments are as follows:
 *   arg1 (input)   : expression whose type is being calculated
 *   arg2 (output)  : the type returned for arg1
 *   arg3 (input)   : the input attributes
 *   arg4 (output)  : the output attributes
 *
```


Type Representation

* Types are encoded as an "inside-out" representation of
* the declaration. For instance, a declaration of the form

*

```
int ($fptr)#( int aa; int bb; int ($pp)#(int x)) ;
```

*

* associates the following type representation with variable fptr :

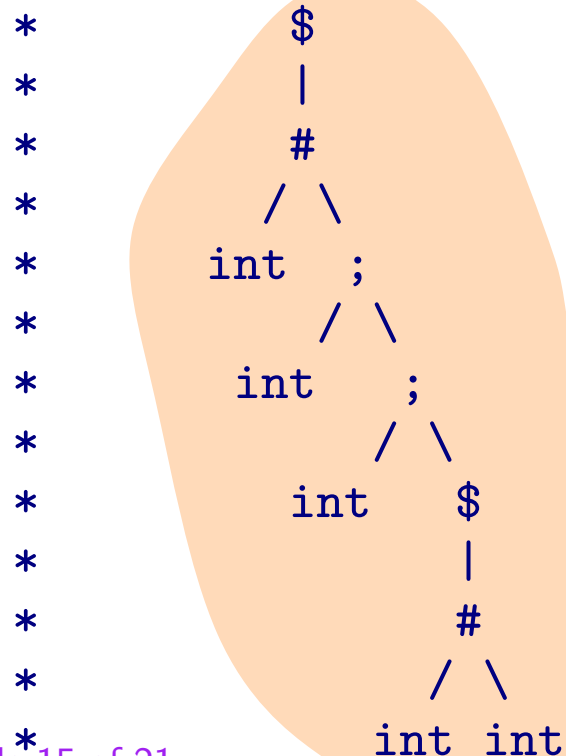
*

```
$(int#(int;int;$(int#int)))
```

*

* This representation has the syntactic tree

*



Variables, Constants, and Pointers

```
typecheck(X,T,A,A) :- atom(X), !, get_assoc(type_env,A,Local), member((X->T),Local),!.
```

```
    % if X is a variable, then it must have been declared, so its name  
    % and associated type must be stored in the type_env attribute
```

```
typecheck(N,int,A,A) :- integer(N), !.
```

```
    % an integer constant has type 'int'
```

```
typecheck(E,($T),A,A) :- E =.. [Op,E1,E2], member(Op,[+,-]),
```

```
    typecheck(E1,TE,A,_), % pointer arithmetic: if p is a pointer, then p+k and p-k are legal pointers  
    same_type(TE,$T), % same_type checks if a cast is possible, so that E1 is interpreted as ptr  
    typecheck(E2,int,A,_). % array names will be cast to pointers.
```

```
typecheck(E,int,A,A) :- E =.. [Op,E1,E2], % arithmetic expressions have integer operands and result
```

```
    member(Op,[+,-,*,/,rem,/\/,==,\=,<,>]),!, % binary operators are checked here  
    typecheck(E1,int,A,_), typecheck(E2,int,A,_).
```

```
typecheck(E,int,A,_) :- % arithmetic expressions have integer operands and result
```

```
    E =.. [Op,E1], member(Op,[\,-,+]), !, % unary operators are checked here  
    typecheck(E1,int,A,_).
```

```
typecheck(($E),T,A,A) :- !, % type of a dereferenced expression: the type of E must be
```

```
    typecheck(E,TE,A,_), % equivalent to that of pointer to some type T  
    same_type($T,TE). % and then the type of the result will be T.
```

Arrays, Addresses, Proc Calls, Struct Access

```
typecheck((E1@E2),T,A,A) :-!, % array subscript expression
    typecheck(E1,TE,A,_), % the type of E1 must be equivalent to that of array with
    same_type(TE,@(T)), % elements of some type T, and then the result will be
    typecheck(E2,int,A,_). % of type T. The subscript E2 must be of type int
```

```
typecheck((&E),($T),A,A) :-!, % address-of expression
    ( atom(E) ; E = _ @ _ % operator & can only be applied to a variable, an array element,
    ; E = _ ~~ _ ; E = $ _ ), % a structure field, or a dereferenced pointer
    typecheck(E,T,A,_).
```

```
typecheck((P#L),T,A,A) :- !, % function call expression
    typecheck(args(L),LT1,A,_), % compute the type of all args as a tuple LT1
    typecheck(P,(T#LT2),A,_), % the type of P recorded in type_env must be of the pattern
    same_type(LT1,LT2). % T#LT2, where T is some return type, and LT2 is some tuple type
    % Then, LT1 and LT2 must be cast-able to each other, and T will be
    % the type of the function call expression.
```

```
typecheck(args(L),TL,A,A) :- !, % tuple of arguments. 'args' is just a wrapper to avoid confusion
    ( L = (H;T), TL = (TH;TT) % with statement sequencing { S1 ; S2 }, because the ';' is used there too
    -> typecheck(H,TH,A,_), % if the tuple has more than 1 component, compute the types by
        typecheck(args(T),TT,A,_), % recursing through all components
    ; typecheck(L,TL,A,_)). % otherwise, just compute the type of the singleton argument
```

```
typecheck((S ~~ F),T,A,A) :- !, % structure field access; F must be an atom, and S must be
    atom(F), typecheck(S,~~~(TS),A,_), % a declared structure. 'check_struct_acc' will check if
    check_struct_acc(TS,F,T,A). % the field was declared, and retrieve its type.
```

Statements

```
% Type checking for statements. The returned type is either the atom  
% 'type', that represents the fact that the program fragment subjected  
% to type checking has only declarations (useful to check that the  
% inside of a structure does not have any executable code -- which would  
% not be syntactically acceptable); or the atom 'stmt', to represent  
% that it does contain some executable code.
```

```
typecheck((E1 = E2),stmt,A,A) :- !, % assignment  
    typecheck(E1,T1,A,_),           % the types of the two sides must be cast-able to each other  
    typecheck(E2,T2,A,_),  
    (    atom(E1) ;    E1 = _ @ _    % the LHS must be a l-value, i.e. a variable, array element,  
    ;    E1 = $ _ ;    E1 = _ ~~ _ ), % dereferenced expression, or structure field  
    same_type(T1,T2),  
    writeln( 'Assignment' : E1=E2 | T1 = T2 ). % We print all the assignments, to have some verification
```

```
% 'if' and 'while' statements are straightforward. The inner scopes may  
% have their own declarations, but these do not need to survive as we  
% return to the outer scope, thus we do not care about the output attrs
```

```
typecheck((if B then { S } ),stmt,A,A) :- !,  
    typecheck(B,int,A,_), typecheck(S,stmt,A,_).
```

```
typecheck((if B then { S1 } else { S2 } ), stmt, A, A) :-  
    typecheck(B,int,A,_), typecheck(S1,stmt,A,_), typecheck(S2,stmt,A,_).
```

```
typecheck((while B then { S } ),stmt,A,A) :- !, typecheck(B,int,A,_), typecheck(S,stmt,A,_).
```

Declarations and Misc

```
% Declarations must be stored in the type environment. All
% variable declarations start with 'int' or have ~~~ at the top level,
% so they are easy to identify
```

```
typecheck(int Decl, type, Ain, Aout) :- !,
    process_decl(int,Decl,Ain,Aout,0). % places the declared identifier in the type environment
```

```
typecheck( Str ~~~ { Fields } , type, Ain, Aout) :- !, % structure declaration
    get_assoc(type_env,Ain,Orig_env,A1,[]), % start with a fresh type environment, but preserve the old one
    typecheck(Fields,type,A1,A2), % the {...} block of the structure must not contain executable code
    % -- this is enforced by expected the atom 'type' as return type
    get_assoc(type_env,A2,StructFields,A3,Orig_env), % convert the computed type environment into a list of fields for the
    % structure and restore the original type environment
    get_assoc(structures,A3,Structures,Aout,[(Str->StructFields)|Structures]).
    % The output attributes are important here
```

```
typecheck(Str ~~~ Decls, type, Ain, Aout) :- !, % variable declaration, whose type is a previously defined structure
    get_assoc(structures,Ain,Structures), % check that the structure has been declared
    member(Str->,Structures),
    process_decl((~~~(Str)),Decls,Ain,Aout,0). % process the declaration, placing the declared variable in the type
    % environment
```

```
typecheck({S},T,A,A) :- !, typecheck(S,T,A,_). % handle local scope
```

```
typecheck((S;),T,A,A) :- !, typecheck(S,T,A,_). % handle statements terminated with ';' ;'
```

```
typecheck((S1 ; S2), T, Ain, Aout) :- !, % sequence of statements, attributes must be handled properly
    typecheck(S1,T1,Ain,Aaux),
    typecheck(S2,T2,Aaux,Aout),
    ( T1 = type, T2 = type, T = type, ! % compute the type of the statement; return 'type' only if both S1 and S2
    ; T = stmt ) . % have returned 'type' -- means there's no executable code in S1 and S2
```

Procedure Definition and Return

```
typecheck(Head::{Body},stmt,Ain,Aout) :- !, % procedure definition
    Head =.. [T,Rest],
    process_decl(T,Rest,Ain,A1,0),
    get_assoc(type_env,A1,[_->Type#_|_]),
    get_assoc(return_type,A1,OrigRetType,A2,Type),
    typecheck({Body},stmt,A2,A3),
    put_assoc(return_type,A3,OrigRetType,Aout).

typecheck(return Expr,stmt,A,A) :- !, % return statement
    typecheck(Expr,Type,A,_),
    get_assoc(return_type,A,T),
    same_type(Type,T).
```

% compute the type of the function id, and place it in the type env
% retrieve the return type of the function, and store it in the
% 'return_type' attribute; save the original value so it can be
% returned later

% type-check the body; return expressions will be matched against
% val of return_type

% restore the original return type, in case we're in a nested function

% type check the return expression, and match it against the return_type attribute

% The function's declared return type and the type of the return expression
% must be cast-able

Conclusion

- Types are trees, and type checking is pattern matching
- Multiple base types: implicit/explicit cast operators must be added to the language
- Cast-ability can be decided via pattern matching as well.