Script generated by TTT

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Forward Declarations

Most programming language admit the definition of recursive data types and/or recursive functions.

- a recursive definition needs to mention a name that is currently being defined or that will be defined later on
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Consider the declaration of an alternating linked list in C:

```
struct list1;
struct list0 {
  int info;
  struct list1* next;
}
```

```
struct list1 {
  double info;
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```

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⇝ the first declaration `struct list1;` is a forward declaration.

Declarations of Function Names

An analogous mechanism is need for (recursive) functions:

- in case a *recursive function* merely calls itself, it is sufficient to add the name of a function to the symbol table before visiting its body; example:

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int fac(int i) {
  return i*fac(i-1);
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- for *mutually recursive functions* all function names at that level have to be entered (or declared as forward declaration). Example: ML and C:

```
fun odd 0 = false
  | odd 1 = true
  | odd x = even (x-1)
and even 0 = true
  | even 1 = false
  | even x = odd (x-1)
```

```
int even(int x);
int odd(int x) {
  return (x==0 ? 0 :
    (x==1 ? 1 : even(x-1)));
}
int even(int x) {
  return (x==0 ? 1 :
    (x==1 ? 0 : odd(x-1)));
}
```

Overloading of Names

The problem of using names before their declarations are visited is also common in object-oriented languages:

- for OO-languages with inheritance, a method's signature contributes to determining its binding
  - qualifies a function symbol with its parameters types
  - also requires resolution of parameter and return types
- the base class must be visited before the derived class in order to determine if declarations in the derived class are correct

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Once the types are resolved, other semantic analyses can be applied such as *type checking* or *type inference*.

Multiple Classes of Identifiers

int i;

typedef int i;

Some programming languages distinguish between several classes of identifiers:

- C: variable names and type names
- Java: classes, methods and fields
- Haskell: type names, constructors, variables, infix variables and -constructors

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In some cases a declaration may *change* the class of an identifier; for example, a **`typedef`** in C:

- the scanner generates a different token, based on the class into which an identifier falls
- the parser informs the scanner as soon as it sees a declaration that changes the class of an identifier

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the interaction between scanner and parser is *problematic*!

Type Synonyms and Variables in C

The C grammar distinguishes `typedef-name` and `identifier`. Consider the following declarations:

```
typedef struct { int x,y } point_t;
point_t origin;
```

Relevant C grammar:

declaration	→	(declaration-specifier)$^+$ declarator ;
declaration-specifier	→	`static` | `volatile` ... `typedef` | `void` | `char` | `char` ... `typename`
declarator	→	`identifier` | ...

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Problem:

- parser adds `point_t` to the table of types when the declaration is reduced
- parser state has at least one look-ahead token

Type Synonyms and Variables in C: Solutions

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Solution is difficult:

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id (id) id

Solution is difficult:

- try to fix the look-ahead inside the parser
- add a rule to the grammar: S/R- & R/R- Conflicts!!
  `typename` → `identifier`

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  `typename` → `identifier`
- register type name earlier

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declarator → `identifier` | ···

Solution is difficult:

- try to fix the look-ahead inside the parser
- add a rule to the grammar: S/R- & R/R- Conflicts!!
  `typename` → `identifier`
- register type name earlier
  - separate rule for `typedef` production
  - call alternative declarator production that registers `identifier` as type name

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Chapter 3:
Type Checking

Goal of Type Checking

In most mainstream (imperative / object oriented / functional) programming languages, variables and functions have a fixed type. for example: `int`, `void*`, `struct { int x; int y; }`.

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- manage memory
- to avoid certain run-time errors

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Types are useful to

- manage memory
- to avoid certain run-time errors

In imperative and object-oriented programming languages a declaration has to specify a type. The compiler then checks for a type correct use of the declared entity.

Type Expressions

typedefed id

Types are given using type-*expressions*.
The set of type expressions T contains:

1. base types: `int`, `char`, `float`, `void`, ...
2. type constructors that can be applied to other types

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example for type constructors in C:

- records: `struct { ` $t_1\ a_1; \ldots t_k\ a_k;$ ` }`
- pointer: $\boxed{t *}$
- arrays: $\boxed{t\ [\,]}$
  - the size of an array can be specified
  - the variable to be declared is written between t and $[n]$
- functions $\boxed{t}\boxed{(t_1, \ldots, t_k)}$
  - the variable to be declared is written between t and $(t_1, \ldots, t_k)$
  - in ML function types are written as: $t_1 * \ldots * t_k \rightarrow t$

Type Definitions in C

A type definition is a *synonym* for a type expression.
In C they are introduced using the **typedef** keyword.
Type definitions are useful

- as abbreviation:

```
typedef struct { int x; int y; } point_t;
```

- to construct *recursive* types:

Possible declaration in C:

```
struct list {
  int info;
  struct list* next;
}
struct list* head;
```

more readable:

```
typedef struct list*list_tp;
struct list {
  int info;
  list_tp next;
}
list_tp head;
```

Type Checking

Problem:

Given: a set of type declarations $\Gamma = \{t_1\ x_1; \ldots t_m\ x_m;\}$
Check: Can an expression $\boxed{e}$ be given the type $\boxed{t?}$

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Type Checking

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Check: Can an expression e be given the type t?

Example:

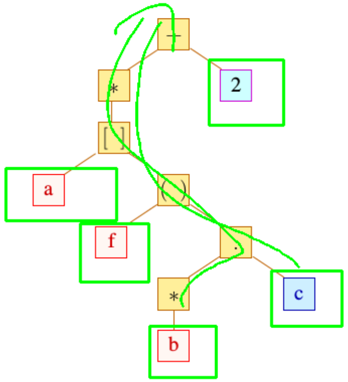
```
struct list { int info; struct list* next; };
int f(struct list* l) { return 1; };
struct { struct list* c;}* b;
int* a[11];
```

Consider the expression:

```
*a[f(b->c)]+2;
```

Type Checking using the Syntax Tree

Check the expression `*a[f(b->c)]+2`:



Idea:

- traverse the syntax tree bottom-up
- for each identifier, we lookup its type in Γ
- constants such as 2 or 0.5 have a fixed type
- the types of the inner nodes of the tree are deduced using *typing rules*

Type Systems

Formally: consider *judgements* of the form:

$$\Gamma \vdash e \; : \; t$$

// (in the type environment Γ the expression e has type t)

Axioms:

Const: $\Gamma \vdash c \; : \; t_c$ (t_c type of constant c)
Var: $\Gamma \vdash x \; : \; \Gamma(x)$ (x Variable)

Rules:

Ref: $\dfrac{\Gamma \vdash e \; : \; t}{\Gamma \vdash \& e \; : \; t*}$ Deref: $\dfrac{\boxed{\Gamma \vdash e \; : \; t*}}{\Gamma \vdash \boxed{*e} : \boxed{t}}$

Type Systems for C-like Languages

More rules for typing an expression:

Array: $\dfrac{\Gamma \vdash e_1 \; : \; t* \qquad \Gamma \vdash e_2 \; : \; \textbf{int}}{\Gamma \vdash e_1[e_2] \; : \; t}$

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Struct: $\dfrac{\Gamma \vdash e \; : \; \textbf{struct} \; \{t_1 \; a_1; \ldots t_m \; a_m;\}}{\Gamma \vdash e.a_i \; : \; t_i}$

App: $\dfrac{\Gamma \vdash e \; : \; t\,(t_1, \ldots, t_m) \qquad \Gamma \vdash e_1 \; : \; t_1 \; \ldots \; \Gamma \vdash e_m \; : \; t_m}{\Gamma \vdash e(e_1, \ldots, e_m) \; : \; t}$

Op: $\dfrac{\Gamma \vdash e_1 \; : \; \textbf{int} \qquad \Gamma \vdash e_2 \; : \; \textbf{int}}{\Gamma \vdash e_1 + e_2 \; : \; \textbf{int}}$

Cast: $\dfrac{\boxed{\Gamma \vdash e \; : \; t_1} \qquad t_1 \text{ can be converted to } \boxed{t_2}}{\Gamma \vdash \boxed{(t_2)\; e} : \boxed{t_2}}$

Example: Type Checking

Given expression `*a[f(b->c)]+2` and $\Gamma = \{$

```
struct list { int info; struct list* next; };
int f(struct list* l);
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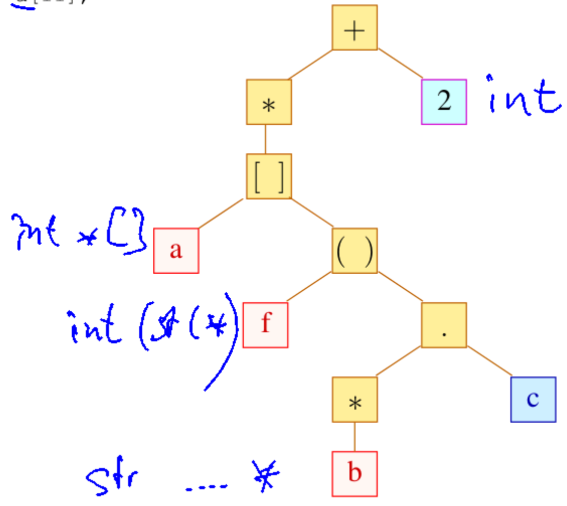

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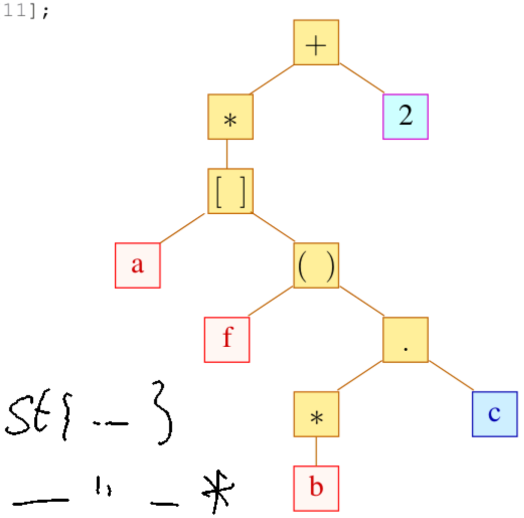

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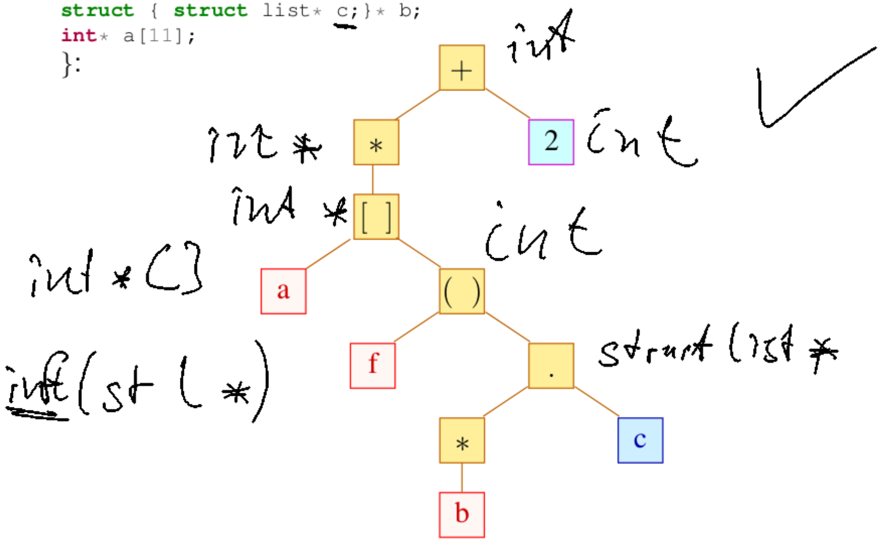


Equality of Types

Summary type checking:

- Choosing which rule to apply at an AST node is determined by the type of the child nodes
- ⇝ determining the rule requires a check for *equality* of types

type equality in C:

- `struct A {}` and `struct B {}` are considered to be different
  - ⇝ the compiler could re-order the fields of `A` and `B` independently (*not* allowed in C)
  - to extend an record `A` with more fields, it has to be embedded into another record:

```
typedef struct B {
          struct A a;
          int field_of_B;
        } extension_of_A;
```

- after issuing `typedef int C;` the types `C` and `int` are the same

Structural Type Equality

Alternative interpretation of type equality (*does not hold in C*):

semantically, two type t_1, t_2 can be considered as *equal* if they accept the same set of access paths.

Example:

```
struct list {
  int info;
  struct list* next;
}
```

```
struct list1 {
  int info;
  struct {
    int info;
    struct list1* next;
  }* next;
}
```

Consider declarations `struct list* l` and `struct list1* l`. Both allow

`l->info` `l->next->info`

but the two declarations of `l` have unequal types in C.

Algorithm for Testing Structural Equality

Idea:

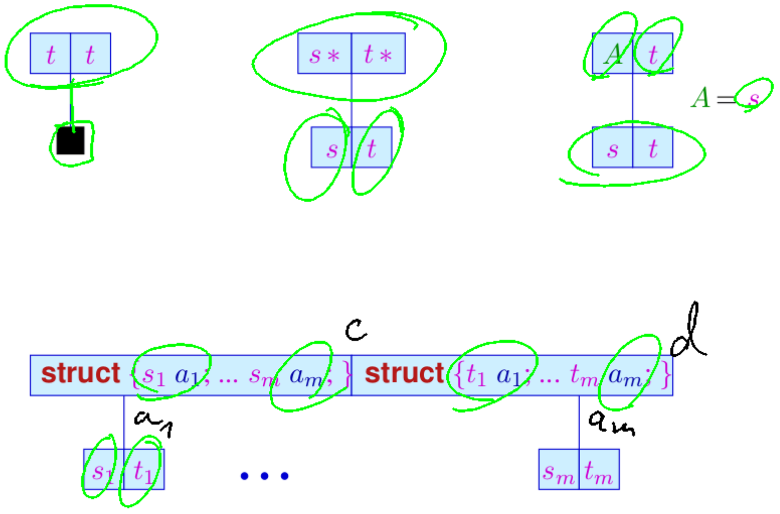
- track a set of equivalence queries of type expressions
- if two types are syntactically equal, we stop and report success
- otherwise, reduce the equivalence query to a several equivalence queries on (hopefully) simpler type expressions

Suppose that recursive types were introduced using type equalities of the form:

$$\boxed{A = t}$$

(we omit the Γ). Then define the following rules:

Rules for Well-Typedness



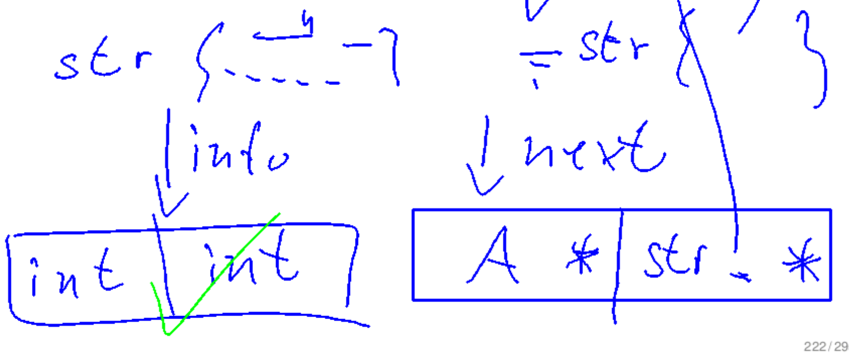
Example:

$$A = \text{struct}\ \{\text{int info};\ A * \text{next};\ \}$$
$$B = \text{struct}\ \{\text{int info};\ \text{struct}\ \{\text{int info};\ B * \text{next};\ \} * \text{next};\ \}$$

We ask, for instance, if the following equality holds:

$$\boxed{\text{struct}\ \{\text{int info};\ A * \text{next};\ \}} = \boxed{B}$$

We construct the following deduction tree:



Proof for the Example:

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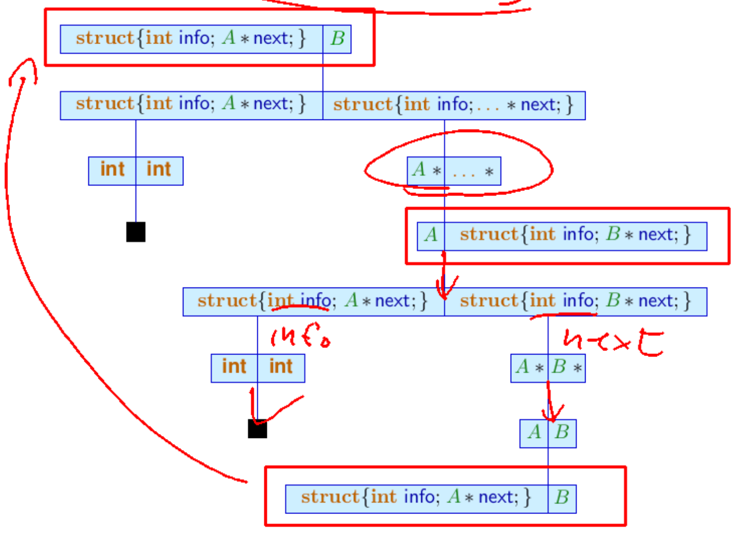

struct{int info; $A *$ next; } | B

struct{int info; $A *$ next; } | struct{int info; $\ldots *$ next; }

int | int

■

$A *$ | $\ldots *$

A | struct{int info; $B *$ next; }

struct{int info; $A *$ next; } | struct{int info; $B *$ next; }

int | int

■

$A *$ | $B *$

A | B

struct{int info; $A *$ next; } | B

Implementation

We implement a function that implements the equivalence query for two types by applying the deduction rules:

- if no deduction rule applies, then the two types are *not equal*
- if the deduction rule for expanding a type definition applies, the function is called recursively with a *potentially larger* type
- during the construction of the proof tree, an equivalence query might occur several times
- in case an equivalence query appears a second time, the types are by definition equal

Termination?

- the set D of all declared types is finite
- there are no more than $|D|^2$ different equivalence queries
- repeated queries for the same inputs are are automatically satisfied

$\leadsto$ termination is ensured

Overloading and Coercion

Some operators such as $+$ are *overloaded*:

- $+$ has *several possible* types
  for example: `int +(int,int)`, `float +(float, float)`
  but also `float* +(float*, int)`, `int* +(int, int*)`
- depending on the type, the operator $+$ has a different implementation
- determining which implementation should be used is based on the *arguments* only