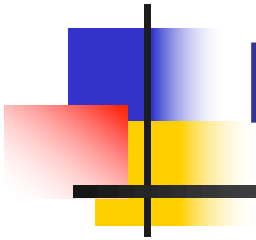


Data Abstraction and Types

Read: Scott, Chapters 7.1-7.2 and 8

Announcements

- Welcome back!
- Quiz 8
- Check your Rainbow grades
  - Exams 1-2, Quizzes 1-7, HWs 1-5
- HW 6 due Thursday
- HW 7 out

Quiz 8 Q1 to Q3

Combinator: A Lambda term with no free variables.

Combinators:

tru = $\lambda x.\lambda y.x$

pair = $\lambda f.\lambda s.\lambda b.\ b\ f\ s$

fst = $\lambda p.\ p$ tru

Rules:

1. When expanding an abbreviation (e.g. pair) always parenthesize!
2. Keep abbreviation for as long as possible! Until abbrev. is in some head position and we need to apply the function on arguments!

Q1. tru v w = ((tru v) w)

$(\lambda x.\lambda y.x)\ v\ w \to_\beta (\lambda y.v)\ w \to_\beta v$

Q2. pair v w = $(\lambda f.\lambda s.\lambda b.\ b\ f\ s)\ v\ w \to_\beta$

$(\lambda s.\lambda b.\ b\ v\ s)\ w \to_\beta \lambda b.\ b\ v\ w$

Q3. fst (pair v w) $\to_\beta^*$ fst ($\lambda b.\ b\ v\ w$)

$(\lambda p.\ p\ \text{tru})\ (\lambda b.\ b\ v\ w) \to_\beta (\lambda b.\ b\ v\ w)\ \text{tru} \to_\beta^*$ tru v w $\to$ v

(keep; Q1)

Lecture Outline

- *Types (last time)*
- *Type systems (last time)*
  - *Type checking*
  - *Type safety*
- *Type equivalence (last time)*
- *More on types in C*

- *Primitive types*
- *Composite types*

Type Equivalence

- Two ways of defining type equivalence
  - Structural equivalence: based on "shape"
    - Roughly, two types are the same if they consists of the same components, put together in the same way
  - Name equivalence: based on lexical occurrence of the type definition
    - Strict name equivalence: aliased types are distinct
    - Loose name equivalence: aliased types are same

```
T1 x; …
T2 y;
x = y;
```

Exercise: Structural Equivalence

```
type cell = ... // record type
type alink = pointer to cell
type blink = alink
p,q : pointer to cell
r : alink
s : blink
t : pointer to cell
u : alink
```

ANON 1

ANON 2

ANON 3

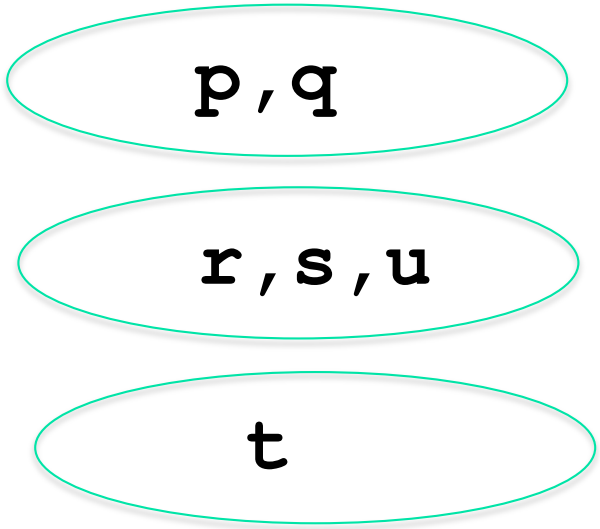
ANON 4

p,q,r,s,t,u

Exercise: Loose Name Equivalence

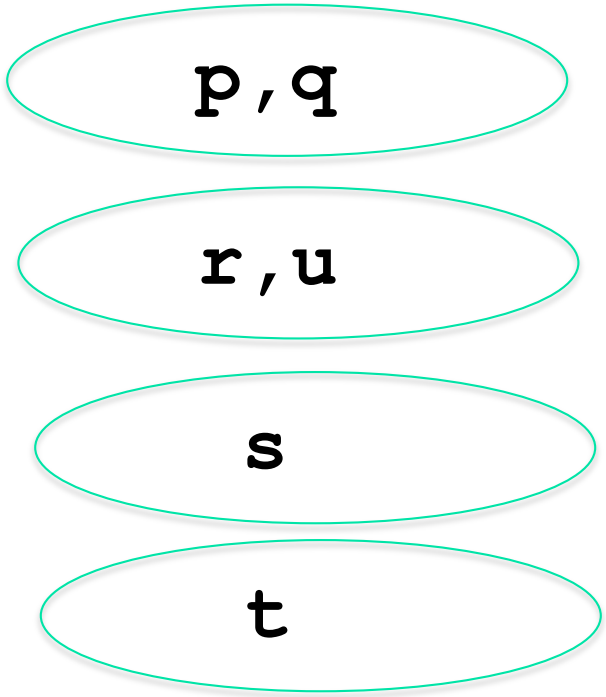
```
type cell = ... // record type
type alink = pointer to cell
type blink = alink
p,q : pointer to cell
r : alink
s : blink
t : pointer to cell
u : alink
```

ANON1 ANON2 ANON3 ANON4



Exercise: Strict Name Equivalence

```
type cell = ... // record type
type alink = pointer to cell
type blink = alink
p,q : pointer to cell
r : alink
s : blink
t : pointer to cell
u : alink
```



Not only ANON2, ANON3, ANON4 are distinct but alink and blink are new distinct types.

Example: Type Equivalence in C

- First, in the Algol family, field names are part of the record/struct constructed type. E.g., the record types below are NOT even structurally equivalent

```
type A = record
 x,y : real
end;
type B = record
 z,w : real
end;
```

Type Equivalence in C

- Compiler assigns internal (compiler-generated) names to anonymous types

This **struct** is of type ANON1.

```
struct RecA
{ char x;
  int y;
} a;

RecB b;
```

```
typedef struct
{ char x;
  int y;
} RecB;
```

```
struct
{ char x;
  int y;
} c;
```

ROUGHLY MEANS: struct {char x; int y;} = RecB

a b c

What variables are of **equivalent type** according to the rules in C?

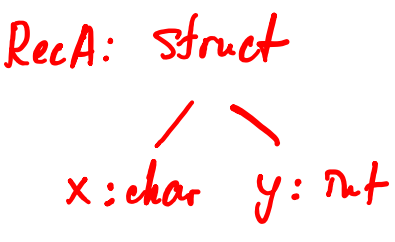
struct RecA, RecB and ANON1 are distinct types, even though they are structurally equivalent.

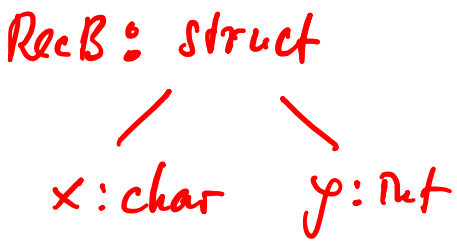
Type Equivalence in C

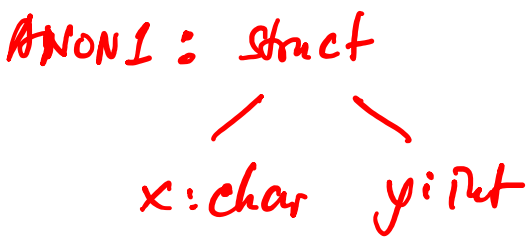
```
struct RecA
{ char x;
  int y;
} a;
RecB b;
```

```
typedef struct
{ char x;
  int y;
} RecB;
```

```
struct
{ char x;
  int y;
} c;
```







a = b; ✗

a = (struct RecA) b; ✓

struct RecB
{
char x;
int y;
}

RecA, RecB and ANON1 are distinct struct types.

Type Equivalence in C

- C uses structural equivalence for everything, except unions and structs, for which it uses loose name equivalence

```
struct A          struct B
{ char x;         { char x;
  int y;            int y;
}                 }
typedef struct A C;
typedef C *P;
typedef struct B *Q;
typedef struct A *R;
typedef int Age;
typedef int (*F)(int);
typedef Age (*G)(Age);
```

C is an alias of struct A.

P is a pointer to C, struct A.

Q is a pointer to struct B.

~ struct A = *R

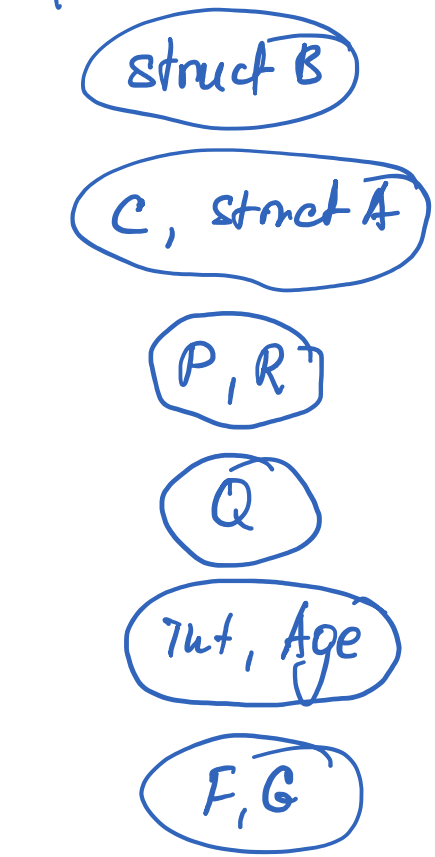
~ int = (*F)(int)

Type Equivalence in C

- C uses structural equivalence for everything, except unions and structs, for which it uses loose name equivalence

```
struct A                struct B
{ char x;               { char x;
  int y;                  int y;
}                       }
typedef struct A C;
typedef C *P;
typedef struct B *Q;
typedef struct A *R;
typedef int Age;
typedef int (*F)(int);
typedef Age (*G)(Age);
```

Equivalence classes:



Type Equivalence in C

```
struct B { char x; int y; };
typedef struct B A;
struct { A a; A *next; } aa;
struct { struct B a; struct B *next; } bb;
struct { struct B a; struct B *next; } cc;
```

ANON1

ANON2

```
A a;
struct B b;
```

a, b

aa

bb

cc

ANON1 and ANON2 are two distinct types.

```
a = b;    ✓
aa = bb;  ✗
bb = cc;  ✗
```

Which of the above assignments pass the type checker?

Question

- Structural equivalence for record types is considered a bad idea. Can you think of a reason why?

Lecture Outline

NO OFFICE HOURS 4÷5 TODAY

- *Types*
- *Type systems*
  - *Type checking*
  - *Type safety*
- *Type equivalence*
- *More on types in C*

VON Neumann
→ procedural, imperative
→ functions are third-class values
→ value model for variables

FORTRAN, ALGOL, C

- *Primitive types*
- *Composite types*

Pointers and Arrays in C

- Pointers and arrays are interoperable:

```
int n;
int *a;
int b[10];
```

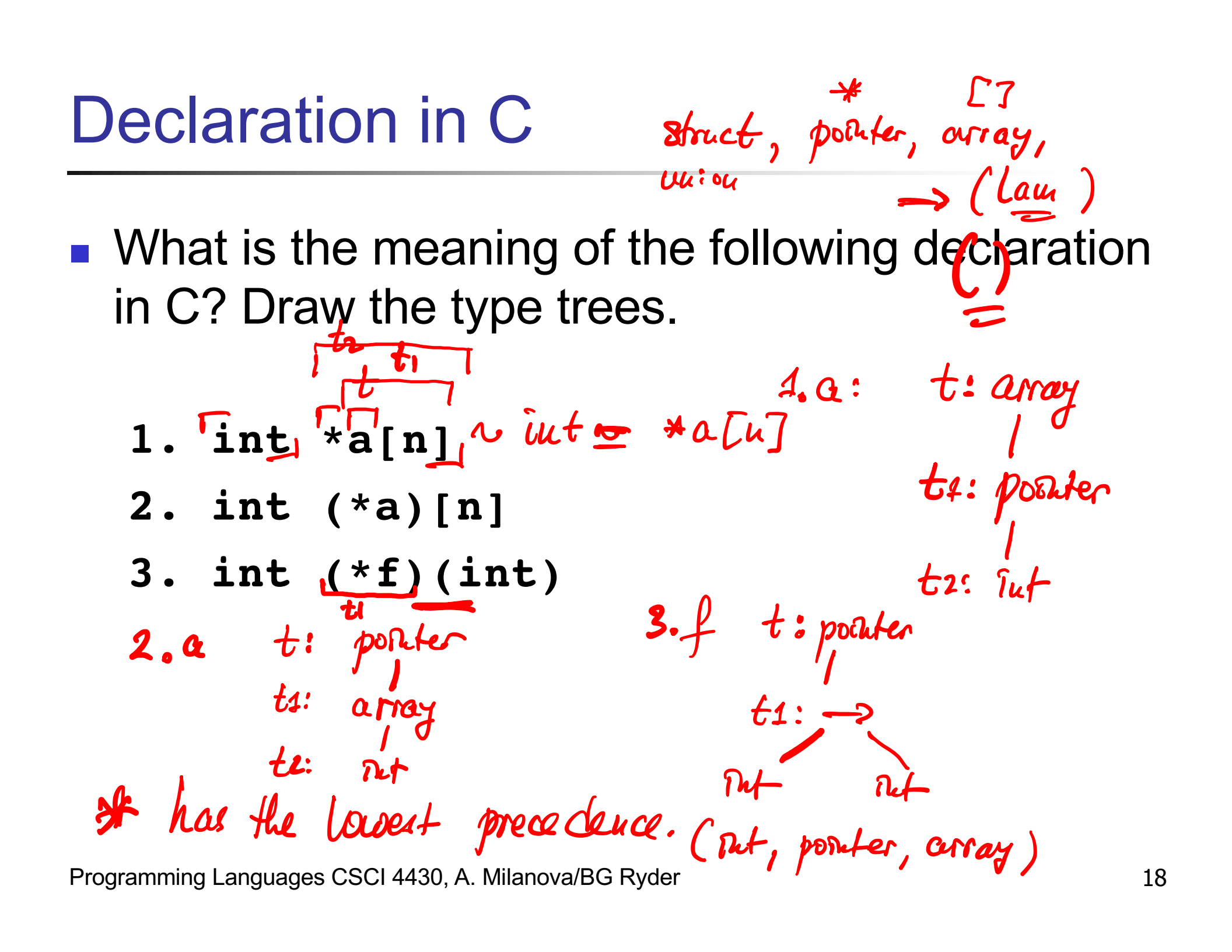
Interoperable means, we can use a pointer type where an array type is expected, and vice versa, we can use an array type where a pointer type is expected. We can assign an array variable to a pointer variable.

```
1.  a = b;
2.  n = a[3];
3.  n = *(a+3);
4.  n = b[3];
5.  n = *(b+3);
```

Declaration in C

- What is the meaning of the following declaration in C? Draw the type trees.

```
1. int *a[n]
2. int (*a)[n]
3. int (*f)(int)
```



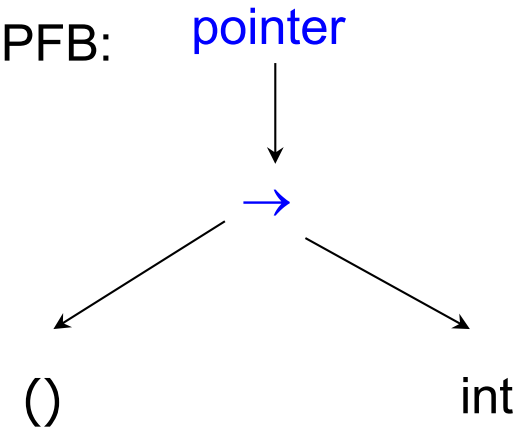
Declaration in C

```
typedef int (*PFB)();                  // Type variable PFB: what type?
struct parse_table {                   // Type struct parse_table: what type?
    char *name;
    PFB func; };
int func1() { ... }                    // Function func1: what type?
int func2() { ... }

struct parse_table table[] = {         // Variable table: what type?
    {"name1", &func1},
    {"name2", &func2}
};
PFB find_p_func(char *s) {             // Function find_p_func: what type?
    for (i=0; i<num_func; i++)
            if (strcmp(table[i].name,s)==0) return table[i].func;
    return NULL; }
int main(int argc,char *argv[]) {
    ... }
```

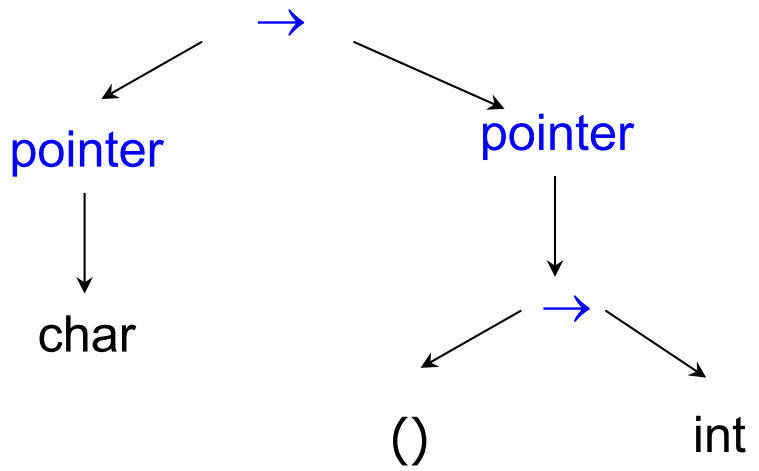
Declarations in C

Type tree for PFB:



Type tree for type of find_p_func:

English: a function that takes
a pointer to char as argument,
and returns a pointer to a function
that takes void as argument and
returns int.



Exercise

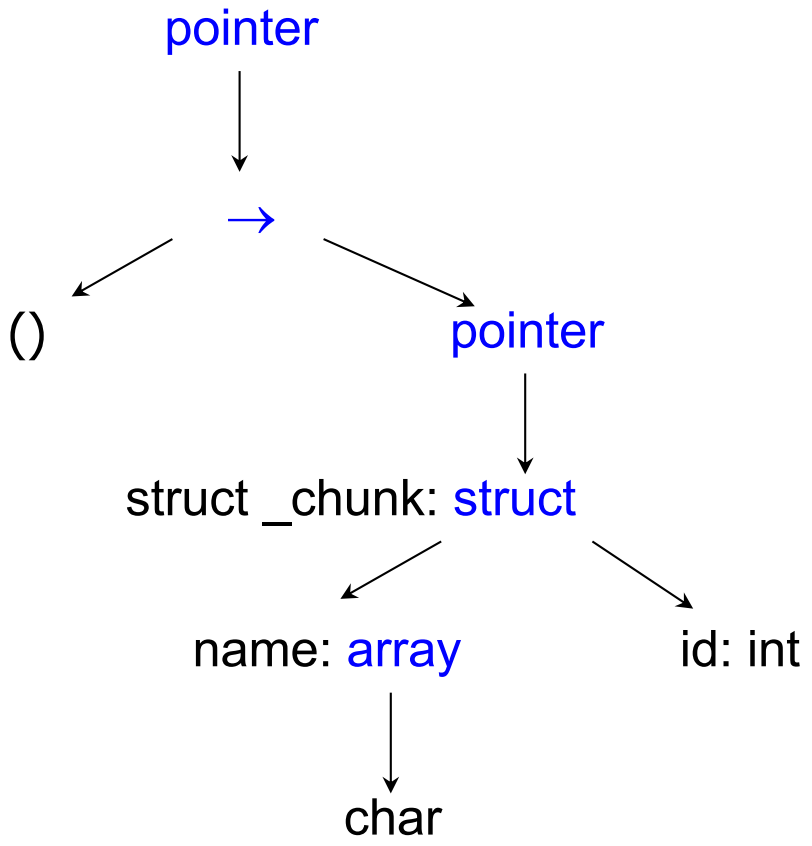
```
struct _chunk {                                   // Type struct_chunk: what type?
    char name[10];
    int   id; };
struct obstack {                                  // Type struct obstack: what type?
    struct _chunk *chunk;
    struct _chunk *(*chunkfun)();
    void (*freefun) (); };

void chunk_fun(struct obstack *h, void *f) {      // Function chunk_fun: what type?
    h->chunkfun = (struct _chunk *(*)()) f; }
void free_fun(struct obstack *h, void *f) {       // Function free_fun: what type?
    h->freefun = (void (*)()) f; }

int main() {
    struct obstack h;
    chunk_fun(&h,&xmalloc);
    free_fun(&h,&xfree); ... }
```

Declarations in C

Type tree for type of field chunkfun:



Lecture Outline

- *Types*
- *Type systems*
  - *Type checking*
  - *Type safety*
- *Type equivalence*
- *More on types in C*

- *Primitive types*
- *Composite types*

struct, array, pointer, union, $\rightarrow$, $=$

Primitive Types

- A small collection of built-in types
  - integer, float/real, etc.
- Design issues: e.g., boolean
  - Use integer non-0/0 vs. true/false?
- Implementation issues: representation in the machine
  - Integer
    - Length fixed by standards or implementation (portability issues)
    - Multiple lengths (C: short, int, long)
    - Signs
  - Float/real
    - All issues of integers and more

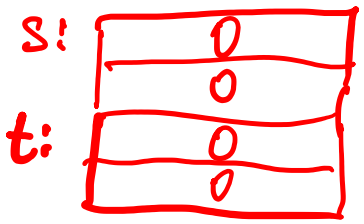
Int

Integer

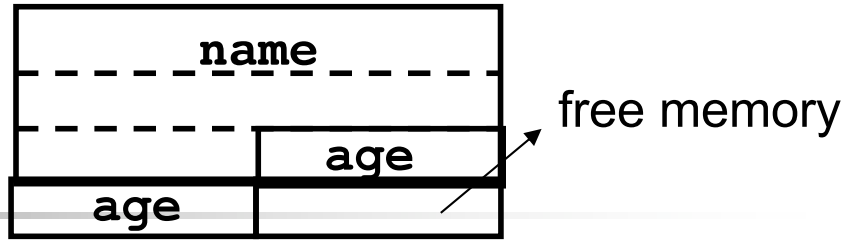
Composite Types: Record (Struct)

- Collection of heterogeneous fields
- Operations
  - Selection through field names **(e.g.,s.num)**
  - Assignment
  - Example: structures in C

```
typedef struct cell listcell;
struct cell {
        int num;
        listcell *next;
} s,t;
s.num = 0;
s.next = 0;
t = s;
```



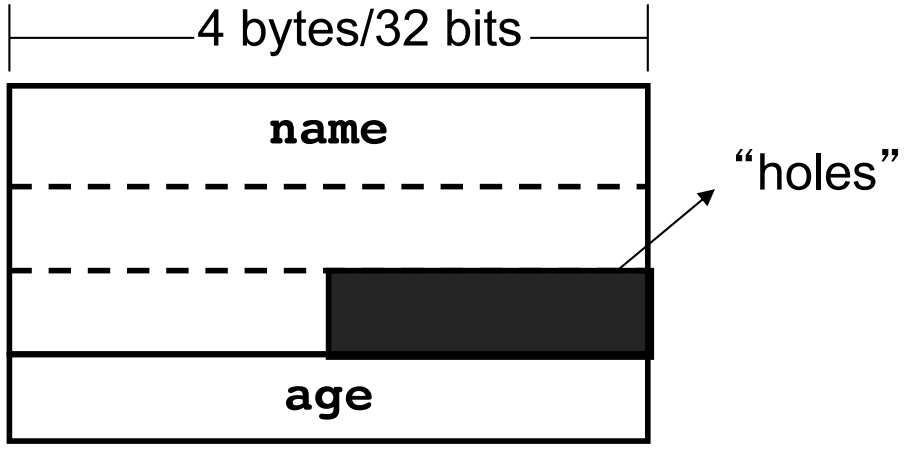
Record (Struct)



- Definition of type. What is part of the type?
  - order and type of fields (but not the name)
  - name and type of fields
  - order, name and type of fields
- Implementation issues: memory layout
  - Successive memory locations at offset from first byte. Usually, word-aligned, but sometimes packed

```
typedef struct {
    char name[10];
    int age;
} Person;

Person p;
```



Composite Types: Variant (Union)

- Collection of alternative fields; only one alternative is valid during execution
  - Fortran: equivalence
  - Algol68 and C: unions
  - Pascal: variant records
- Problem: how can we assure type safety?
  - Pascal and C are not type-safe
  - Algol68 is type-safe due to run-time checks
- Usually, alternatives use same storage; value access is mutually exclusive

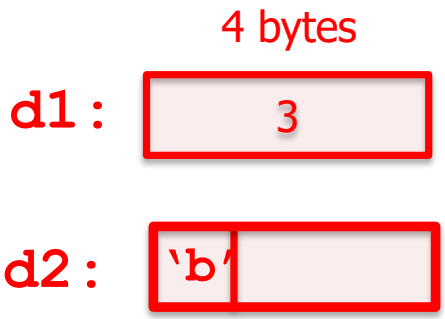
Variant (Union)

- Example: unions in C

```
union data {
   int k;
   char c;
} d1,d2;
```

4 bytes

1 byte



  - Operations
    - Selection through field names, Assignment:

```
d1.k = 3; d2 = d1; d2.c = 'b';
```

  - What about type safety?

```
if (n>0) d1.k=5 else d1.c='a';
… d1.k << 2 … // What is the problem?
```

Pascal's Variant Record

```
program main(input,output);
type paytype = (salaried,hourly);
var employee : record
        id : integer;
        dept: integer;
        age : integer;
        case payclass: paytype of
          salaried:
              (monthlyrate : real;
               startdate : integer);
          hourly:
              (rateperhour : real;
               reghours : integer;
               overtime : integer);
        end;
```

Type tag

```
begin
employee.id:=001234;
employee.dept:=12;
employee.age:=38;
employee.payclass:=hourly;
employee.rateperhour:=2.75;
employee.reghours:=40;
employee.overtime:=3;
writeln(employee.rateperhour,
        employee.reghours,
        employee.overtime);
{this should bomb as there is no
    monthlyrate because
    payclass=hourly}
writeln(employee.monthlyrate);
```

Output:

2.750000E+00 40 3

2.750000E+00

Pascal's Variant Record

```
type paytype = (salaried,hourly);
var employee : record
        id : integer;
        dept: integer;
        age : integer;
        case payclass: paytype of
          salaried:(
             monthlyrate : real;
             startdate : integer);
          hourly: (
             rateperhour : real;
             reghours : integer;
             overtime : integer);
        end;
```

```
employee.payclass:=salaried;
employee.monthlyrate:=575.0;
employee.startdate:=13085;
{this should bomb as there are no
    rateperhour, etc. because
    payclass=salaried}
writeln(employee.rateperhour,
employee.reghours
employee.overtime);
writeln(employee.monthlyrate);
end.
```

Output:

5.750000E+02 13085 3
5.750000E+02

Composite Types: Array

- Homogeneous, indexed collection of values
- Access to individual elements through subscript

- There are many design choices
  - Subscript syntax
  - Subscript type, element type
  - When to set bounds, compile time or run time?
  - How to initialize?
  - What built-in operations are allowed?

Array

- Definition of type. What is part of the type?
  - bounds/dimension/element type
    - Pascal
  - dimension/element type
    - C, FORTRAN, Algol68
- What is the lifetime of the array?
  - Global lifetime, static shape (in static memory)
  - Local lifetime (in stack memory)
    - Static shape (stored in stack frame)
    - Shape bound when control enters a scope
  - "Global" lifetime, dynamic shape (in heap memory)

Example: Algol68 Arrays

- Array type includes dimension and element type; it does not include bounds

```
[1:12] int month; [1:7] int day;
[0:10,0:10] real matrix;
[-4:10,6:9] real table;
```

row int

(row,row) real

Ex.,: **`[1:10] [1:5,1:5] int kinglear;`**

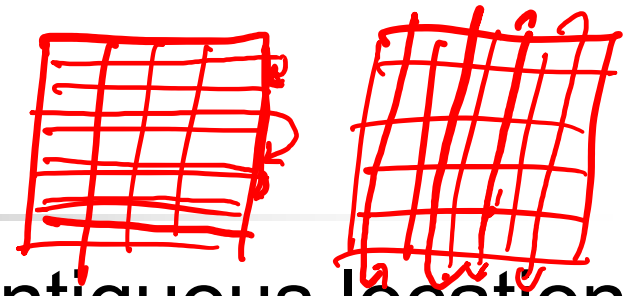
- What is the type of **`kinglear`**? row ((row,row) int)
- What is the type of **`kinglear[j]`**? (row,row) int
- What is the type of **`kinglear[j][1,2]`**? int
- **`kinglear[1,2,3]`** ? ERROR

Array Addressing

- One dimensional array
  - **`X[low:high]`** each element is **`E`** bytes
  - Assuming elements are stored into consecutive memory locations, starting at address **`addr(X[low])`**, what is the address of **`X[j]`**?

  addr(**`X[low]`**) + (**`j-low`**)*E
  - E.g, let **`X[0:10]`** be an array of reals (4 bytes)
    - **`X[3]`**? is addr(**`X[0]`**) + (3-0)***`4`** = addr(**`X`**) + **`12`**
    - **`X[1]`** is at address addr(**`X[0]`**) + **`4`**
    - **`X[2]`** is at address addr(**`X[0]`**) + **`8`**, etc

Array Addressing



- Memory is a sequence of contiguous locations
- Two memory layouts for two-dimensional arrays:
  - Row-major order and column-major order
- Row-major order:
  - **`y[0,0],y[0,1],y[0,2], …,y[0,n],y[1,*], y[2,*],…`**
- **`y[low1:hi1,low2:hi2]`** in Algol68, location **`y[j,k]`** is

addr(**`y[low1,low2]`**) + (**`hi2-low2+1`**)*E*(**`j-low1`**) + (**`k-low2`**)*E

#locs per row #rows in front of row **`j`** # elements in row **`j`** in front of element **`[j,k]`**

Array Addressing

Array `y` is a `[0:2,0:5] int` matrix

Assume row-major order and find the address of `y[1,3]`

address of `y[1,3]` = addr(`y[0,0]`)+`(5-0+1)*4*(1-0)+(3-0)*4`

6 elements per row

1 row before row 1

3 elements in row 1 before 3

= addr(`y[0,0]`)+`24+12`

= addr(`y[0,0]`)+`36`

- Analogous formula holds for column-major order
- Row-major and column-major layouts generalize to n-dimensional arrays

Array Addressing

- Row-major and column-major layouts generalize to n-dimensional arrays

X[0:L, 0:M, 0:N]

X[0,0,0], X[0,0,1], X[0,0,2],
X[0,1,0], X[0,1,1] ...

X[0,0,0], X[1,0,0], X[2,0]
X[0,1,0], X[1,1,0] ...

Composite Types: Pointers

- A variable or field whose value is a reference to some memory location
  - In C: `int *p;`
- Operations
  - Allocation and deallocation of objects on heap

    `p = malloc(sizeof(int)); free(p);`
  - Assignment of one pointer into another, e.g.,

    `int *q = p; int *p = &a;`
  - Dereferencing of pointer: e.g., `*q = 1;`
  - Pointer arithmetic, e.g., `p + 2`

Pointers: Recursive Types

- A recursive type is a type whose objects may contain objects of the same type
  - Necessary to build linked structures such as linked lists
- Pointers are necessary to define recursive types in languages that use the value model for variables:

```
struct cell {
    int num;
    struct cell *next;
}
```

Pointers: Recursive Types

- Recursive types are defined naturally in languages that use the reference model for variables:

```
class Cell {
    int num;
    Cell next;

    Cell() { … }
    …
}
```

The End