G53CMP: Lecture 15

Run-Time Organization II

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This Lecture

Data Representation: how to store various kinds of data.

- General issues
- Primitive types
- Record types
- Arrays
- Disjoint unions
- Recursive types

Data Representation?

- ***Objective***: to store various kinds of data. Integers, characters, strings, arrays, trees, . . .
- At our disposal: the ***memory***:

address	contents
. . .	. . .
`10200008`	`3E124C21`
`1020000C`	`FE7B3811`
`10200010`	`7A7CBBA3`
. . .	. . .

- We need to ***encode*** the data to be stored.

Data Representation: Issues (1)

- ***Nonconfusion***: Different values of a given type ***must*** have different representations.
- ***Uniqueness***: Each value should have exactly one representation.

[Note: The discussion concerns ***run-time*** representation. Any value that is known ***statically*** potentially need no run-time representation at all.]

Nonconfusion (1)

Self-evident: if two ***different*** values are represented the ***same*** way, they cannot be told apart.

- ***Dynamically checked language***: ***Every*** possible value must have a distinct representation.
- ***(Statically) typed language***: Values of the ***same*** type must have distinct representations; the same representation may be reused for values of ***different*** types.

Nonconfusion (2)

Example: suppose both characters and small integers represented by 8-bit bytes:

- $\mathrm{repr}(\texttt{'A'}) = 01000001$
- $\mathrm{repr}(\texttt{65}) = 01000001$

Suppose a variable `x` contains this value 01000001: Should `print(x)` print `'A'` or 65?

- No way to tell the representation of `'A'` and `65` apart in a dynamically checked setting.
- In a statically typed setting, the type is used to disambiguate.

Nonconfusion (3)

Example: Consider two enumeration types:

```
data Colour = Red | Green
data Size   = Small | Large
```

It must *always* be the case that

$$\begin{aligned}\mathrm{repr}(\texttt{Red}) &\neq \mathrm{repr}(\texttt{Green})\\ \mathrm{repr}(\texttt{Small}) &\neq \mathrm{repr}(\texttt{Large})\end{aligned}$$

Further, in a dynamically checked setting:

$$\{\mathrm{repr}(\texttt{Red}), \mathrm{repr}(\texttt{Green})\} \cap \{\mathrm{repr}(\texttt{Small}), \mathrm{repr}(\texttt{Large})\} = \emptyset$$

Uniqueness

Comparison of values is facilitated if each value has exactly one representation.

However, not essential. One exception:

- Floating-point representations typically have a separate sign bit. Thus, the representation of $+0$ is distinct from the representation of -0.

Data Representation: Issues (2)

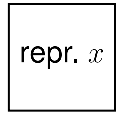
- ***Constant-size representation***: The representations of all values of a given type occupy the same amount of space.
- ***Direct*** or ***indirect*** (via pointer) representation.

Constant-size representation enables compiler to statically plan storage allocation (since type and hence size is known statically).

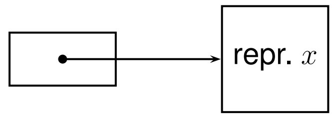
If not possible/too wasteful: use some form of indirect representation.

Direct or Indirect Representation (1)

- ***Direct representation***: the representation of a value x is the binary representation of x:



- ***Indirect representation***: x represented by a ***handle*** that points to a binary representation of x (on the stack or in the heap):



Direct or Indirect Representation (2)

- Pros direct representation:
  - efficient access
  - no heap allocation/deallocation overhead
- Pros indirect representation:
  - supports varying size data (like dynamic arrays)
  - supports ***recursive*** types (like linked lists, trees)
  - facilitates implementation of ***parametric polymorphism*** (as handles can be uniform)

Representing Primitive Types (1)

Primitive types are often supported directly by the underlying hardware. For example, a 32-bit machine might support:

- addressing of 8-bit bytes and 32-bit words
- 32-bit twos-complement integer arithmetic
- 64-bit floating point operations

There are also standard encoding conventions, such as the 7-bit ASCII or 8-bit ISO character codes, or the Unicode standard. Adopting such conventions facilitates interoperability and communication.

Representing Primitive Types (2)

On such a 32-bit machine, the following is a possible representation choice:

Type	Representation	Size
`Boolean`	0 for false; 1 for true	8-bit byte
`Char`	ISO Latin 1 encoding	8-bit byte
`Integer`	twos-complement repr.	32-bit word
`Real`	floating point repr.	64-bit word

Representing Records (1)

A record consists of several fields, each of which has an identifier. For example:

```
type Date = record
                y: Integer,
                m: Integer,
                d: Integer
            end;
type Details = record
                  female: Boolean,
                  dob:    Date,
                  status: Char
               end;
```


Representing Records (2)

Representation of records:

- Sequence of representations of individual fields.
- Caveat: ***alignment restrictions***. The underlying architecture might require that e.g. word-sized quantities start at a word boundary.
- Relaxing this is possible, but may require extra work; e.g., accessing a word byte by byte (four instructions instead of one).

Alignment

- An address a is ***n-byte aligned*** iff $a \equiv 0 \pmod{n}$.
- A variable/field etc. is n-byte aligned iff it is stored ***starting*** at an n-byte aligned address.
- To satisfy alignment requirements of its components, a variable of ***aggregate type*** like a record is commonly aligned according to the ***maximum*** alignment of its components.
- ***Padding*** may be needed between variables/ components to ensure the alignment requirements of each is met.

Exercise: Representing Records (1)

Assume:

- 1 word = 4 byte = 32 bit Integers
- 1 byte = 8 bit Boolean and Char
- Integer must be word aligned

What is the alignment and size of the type Date?

```
type Date = record
                y: Integer,
                m: Integer,
                d: Integer
            end;
```


Exercise: Representing Records (2)

What is the alignment and size of the type Details?

```
type Details = record
                   female: Boolean,
                   dob:    Date,
                   status: Char
               end;
```

Given a variable `x : Details`, what are the addresses of `x.female`, `x.dob.y`, `x.dob.m`, `x.dob.d`, `x.status` relative to $\mathrm{addr}(x)$?

Exercise: Representing Records (3)

Size of `Date` is 3 32-bit words, size of `Details` is 1 + 3 + 1 = 5 32-bit words:

variable	address	contents
`x.female`	addr(x)	1 (true)
`x.dob.y`	addr(x) + 4	1984
`x.dob.m`	addr(x) + 8	7
`x.dob.d`	addr(x) + 12	25
`x.status`	addr(x) + 16	117 ('u')

Example: Records in MiniTriangle

Consider the following MiniTriangle program and the resulting (unoptimized) TAM code:

```
let var r :                  LOADLB     0 3
        {a : Integer,        LOADL      1
         b : Boolean,        LOADA      [SB + 0]
         c : Integer}        LOADL      1
in                           ADD
    r.b := true              STOREIB    1
                             POP        0 3
                             HALT
```

Record Field Order

The order of the fields in the representation of a record need not be the same as at the source level:

- Fields could be reordered to attempt to reduce waste of space due to alignment restrictions.
- The language design might stipulate that a record is a ***set*** of named fields; i.e., their order is irrelevant.

MiniTriangle adopts the set view (and HMTC orders fields alphabetically in a record representation).

Representing Arrays (1)

- Array represented by sequence of representations of individual array elements.
- Two cases:
  - ***Static Array:*** Number of elements known at compile time.
  - ***Dynamic Array:*** Number of elements determined at run time.
- When accessing array elements, must ensure indices are within bounds.
- Address of element computed from base address of array, index, and size of elements.

Representing Arrays (2)

Static array: required storage space and array bounds known at compile time. Consider:

`var x :` T`[`n`]`

- Required storage: $n \times \text{sizeof}(T)$
- Access of `x[`i`]`:
  - Verify that $0 \leq i \leq (n - 1)$
  - Compute address a of desired element:

$$a = \text{addr}(\texttt{x[0]}) + \texttt{i} \times \text{sizeof}(T)$$

  - Fetch/store value at address a.

Representing Arrays (3)

Example: TAM code for `a[3] := 7` given `var a: Integer[10]` (at `[SB + 0]`)

```
    LOADL     7                  LSS
    LOADA     [SB + 0]           JUMPIFNZ  #1
    LOADL     3             #0:  CALL      ixerror
    LOAD      [ST - 1]      #1:  LOADL     1
    LOADL     0                  MUL
    LSS                          ADD
    JUMPIFNZ  #0                 STOREI    0
    LOAD      [ST - 1]
    LOADL     10
```

Representing Arrays (4)

- ***Dynamic array***: size of array not known at compile time.
  - ***indirect representation***: array accessed via a ***handle***
  - handle itself has ***fixed size***
  - handle contains ***pointer*** to array proper and the ***array bounds***
  - ***storage*** for array proper allocated ***at runtime***
  - index checked by comparing with array bounds stored in the handle.

Representing Disjoint Unions (1)

- A ***disjoint union*** consists of a ***tag*** and a ***variant*** part.
- The value of the tag determines the type of the variant part.
- Mathematically: $T = T_1 + \ldots + T_n$; given tag i, the variant part is a value chosen from type T_i.
- Disjoint unions occur as
  - ***variant records*** in Pascal and Ada
  - ***algebraic data types*** in Haskell and ML
  - ***object types*** in OO languages like Java, C#

Representing Disjoint Unions (2)

- A disjoint union can be represented like a record.
- The value of the tag field determines the layout of the rest of the record.
- If constant size is necessary, size is the maximal size over the various possible layouts.

Representing Disjoint Unions (3)

Some Haskell Examples:

- `data OptInt = NoInt | JustInt Int`
  - The first tag is `NoInt`; no variant part. (Which is the same as saying that we have a trivial variant part of the unit type `()`.)
  - The second tag is `JustInt`; the variant part is a single integer field.

Representing Disjoint Unions (4)

- `data Shape`
  ```
        = Triangle Point Point Point
        | Rectangle Point Point
        | Circle Point Radius
  ```
  - three tags; the variant parts are:
    - `Point` triple
    - `Point` pair
    - `Point` and `Radius` pair.
- `data Colors = Red | Green | Blue`
  - three tags; no variant parts.
  - this is thus just an ***enumeration type***.

Representing Recursive Types

- A ***recursive*** type is one defined in terms of itself.
- Examples are linked lists and trees.
- Recursive types are usually represented ***indirectly*** since this allows values of arbitrary size to be referenced through a ***fixed size*** handle.

Uniform Representation (1)

Languages like Haskell and ML adopts a ***uniform*** data representation: ***all*** values (even "primitive" ones) have an indirect representation (pointer):

- Uniform representation facilitates ***parametric polymorphism***. E.g., the identity function

  ```
  id x = x
  ```

  can be compiled to a single piece of code working for values of ***any*** type because all values are represented same way.
- Recursive types supported automatically: "everything is already a pointer".

Uniform Representation (2)

- Many OO languages, like Java and C#, adopt a mostly uniform representation:
  - All ***objects*** are represented by pointers.
  - Recursive types thus supported.
  - OO-style polymorphism: an object of a class is also an object of any of the superclasses.
  - Uniform layout of "common part" of object to allow superclass methods to work on subclass objects.

Example: Haskell Tree Type (1)

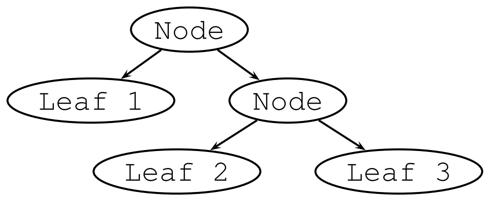
This example illustrates

- disjoint union representation
- recursive type representation
- uniform representation (through pointers) of values of *all* types.

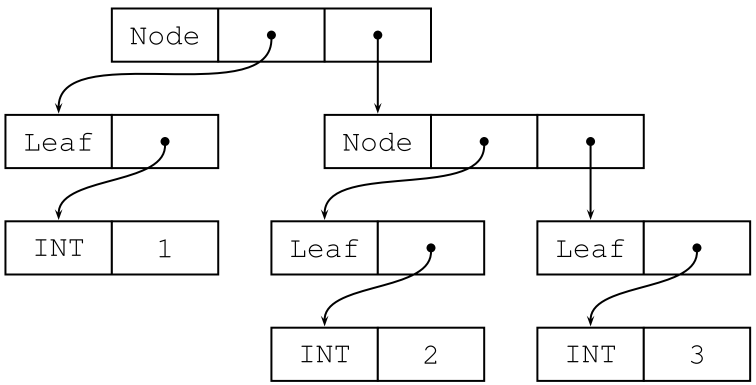
Example: Haskell Tree Type (2)

```
data Tree = Leaf Int
          | Node Tree Tree

aTree = Node (Leaf 1)
             (Node (Leaf 2) (Leaf 3))
```



Example: Haskell Tree Type (3)



Example: Haskell Tree Type (4)

address	contents
...	...
10200008	INT
1020000C	1
10200010	INT
10200014	2
...	...
2E4D0100	Leaf
2E4D0104	10200010
2E4D0108	Leaf
2E4D010C	10200018
...	...

address	contents
...	...
2E4D0200	Node
2E4D0204	2E4D0100
2E4D0208	2E4D0108
2E4D020C	Leaf
2E4D0210	10200008
2E4D0214	Node
2E4D0218	2E4D020C
2E4D021C	2E4D0200
...	...

Example: Haskell Tree Type (5)

Of course, the tags (`Leaf`, `Node`, and `INT`) must also be represented. Two possibilities:

- A small integer, subject to nonconfusion. E.g.

  $$\texttt{Leaf} = 0,\ \texttt{Node} = 1,\ \texttt{INT} = 0$$

  (Representing both `Leaf` and `INT` with the small integer 0 does not lead to confusion in a statically typed language like Haskell.)
- A pointer to an information table.