Disjoint Union Types in P0

Project 9 / Group 8

Jason Balaci

McMaster University

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What are Disjoint Union Types?

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- An instance of a DUT may take on the form of **only one** of it's variants.
- They are often found in functional programming languages, where they are usually known as **Algebraic Data Types** (ADTs).

What do they look like?

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a = Cons 1 (Cons 2 (Cons 3 Nil))
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- Instantiation in our implementation,
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a := Cons(1, Cons(2, Cons(3, Nil())))
b := Red()
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How do we use DUTs?

The anatomy of the case statement.

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   ...  or ...
   [default nothing]
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case <variable> of {
    [nil:  <stmtSuite>]
    Kind A: <stmtSuite>
    Kind B: <stmtSuite>
    ...
    [default:  <stmtSuite>]
    ...  or ...
    [default nothing]
}
```

Cover your cases!

If you create a non-exhaustive case statement, the compiler will warn you.

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Example: Maybe

```
type Maybe = Just(value: integer)
           | Nothing

procedure valOr(v: Maybe, n: integer) → (r: integer)
    case v of {
        Just:
            r := v.value
        default:
            r := n
    }

program Main
    var maybe: Maybe

    maybe <— Nothing()
    writeln(valOr(maybe, —1))

    maybe <— Just(1111)
    writeln(valOr(maybe, 0))
```

Example: Maybe

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procedure valOr(v: Maybe, n: integer) → (r: integer)
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program Main
    var maybe: Maybe

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```

Output

-1

1111

Example: Integer Lists

```
type List = Cons(head: integer, tail: List)
          | Nil

procedure upToList(n: integer) → (l: List)
    if n < 1 then l := Nil() else l := Cons(n, upToList(n−1))

procedure printList(l: List)
    case l of {
        Cons: writeln(l.head); printList(l.tail)
        default nothing
    }

procedure sumList(l: List) → (n: integer)
    case l of {
        Cons: n := sumList(l.tail) + l.head
        default: n := 0
    }

program Main
    var myList: List
    myList := upToList(5)
    printList(myList)
    writeln(sumList(myList))
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program Main
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    myList := upToList(5)
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```

Output

5
4
3
2
1
15

Example: Strings

… lists in disguise?

```
type String = SCons(ch: integer, tail: String)
            | SNil

procedure printStr(s: String, ln: boolean)
    case s of {
        SCons: writeChar(s.ch); printStr(s.tail, ln)
        default: if ln then writeNewLine()
    }

// inclusively generating alphabets in a range
procedure genBetwn(start: integer, end: integer) -> (s: String)
    var ch: integer
    ch := end
    s := SNil()

    while start <= end do
        s, start, ch := SCons(ch, s), start + 1, ch - 1

program Main
    // print capital letters
    printStr(genBetwn('A', 'Z'), true)

    // print lowercase letters
    printStr(genBetwn('a', 'z'), true)

    // print numbers 0-9
    printStr(genBetwn('0', '9'), true)

    // print Greek letters
    printStr(genBetwn('α', 'ω'), true)
```

Note

We convert single-quoted characters into their UTF-8 integer representation when reading in P0 programs.

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    // print Greek letters
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```

Output

ABCDEFGHIJKLMNOPQRSTUVWXYZ
abcdefghijklmnopqrstuvwxyz
0123456789
$\alpha\beta\gamma\delta\epsilon\zeta\eta\theta\iota\kappa\lambda\mu\nu\xi o\pi\rho\sigma\tau\upsilon\phi\chi\psi\omega$

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Other Examples

```
type RainbowColour = Red | Orange | Yellow | Green | Blue | Indigo | Violet

type Either = Left(value: integer)
            | Right(value: boolean)

type Tree = Branch(left: Tree, right: Tree)
          | Leaf(value: integer)

type Expr = Add(left: Expr, right: Expr)
          | Sub(left: Expr, right: Expr)
          | Mul(left: Expr, right: Expr)
          | Div(num: Expr, den: Expr)
          | Pow(base: Expr, exponent: Expr)
          | Int(value: integer)

type StringIntMap = SIMCons(key: String, value: integer, tail: StringIntMap)
                  | SIMEmpty
```

Remark

Modelling is nice with disjoint union types!

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Focal Grammar Changes

- Disjoint union type declarations

```
type ::=
    ident ["(" typedIds ")"] {"|" ident ["(" typedIds ")"]}
    | ...
```

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```
type ::=
    ident ["(" typedIds ")"] {"|" ident ["(" typedIds ")"]}
    | ...
```

- case statements

```
statement ::= ... | "case" ident "of" "{" INDENT
                    ["nil" ":" statementSuite]
                    {ident ":" statementSuite}
                    ["default" (":" statementSuite | "nothing")]
                   DEDENT "}"
```

Supplementary Grammar and Procedure Changes

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- "$>=$" and "$<=$" as alternatives for "$\geq$" and "$\leq$", respectively
- "$*$" as an alternative for "$\times$"
- Standard procedures
  - `write` - no longer prints a newline character
  - `writeln` - writes single integer to std. out. with a newline afterwards
  - `writeChar` - writes single integer converted into a utf-8 character to std. out.
  - `writeCharLn` - writes single integer converted into a utf-8 character to std. out. with a newline afterwards
  - `writeNewLine` - writes a newline character to std. out.

Example: case WebAssembly Generation

The WebAssembly code on the right-hand side is generated for the below case statement.

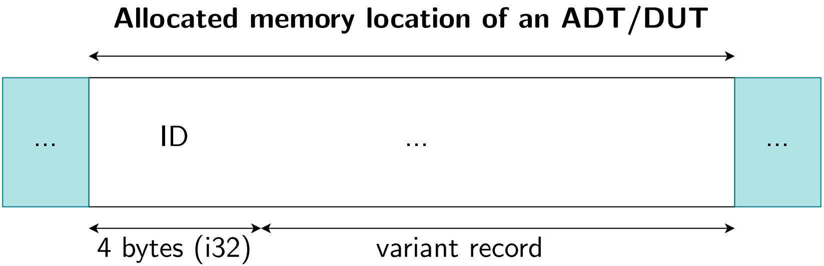
```
type Colour = R | G | Unknown

procedure printCol(col: Colour)
    case col of {
        nil: writeCharLn('?')
        R: writeCharLn('R')
        G: writeCharLn('G')
        default: writeCharLn('?')
    }
```

```
...
local.get $col
i32.load
i32.const 0                  ;; check if nil/0
i32.eq
if                           ;; if it is nil
  i32.const 63
  call $writeCharLn          ;; print '?'
else                         ;; otherwise
  local.get $col
  i32.load
  i32.const 1                ;; check if ‘R‘
  i32.eq
  if                         ;; if it is ‘R‘
    i32.const 82
    call $writeCharLn        ;; print 'R'
  else                       ;; otherwise
    local.get $col
    i32.load
    i32.const 2              ;; check if ‘G‘
    i32.eq
    if                       ;; if it is ‘G‘ kind
      i32.const 71
      call $writeCharLn      ;; print 'G'
    else
      i32.const 63           ;; otherwise, default
      call $writeCharLn      ;; print '?'
    end
  end
end
```

Memory Impact & Management

- Each instance of a DUT is located on the heap, and instances of local/global DUTs are pointers to locations on the heap.



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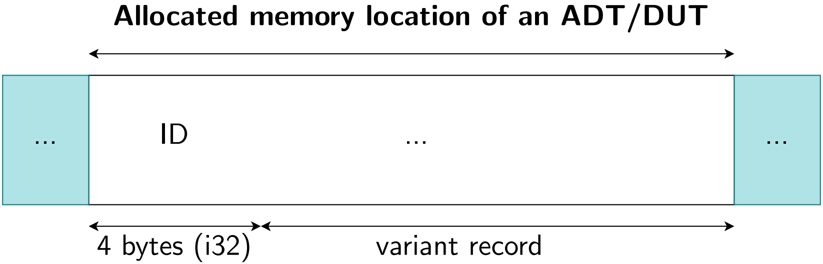

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Allocated memory location of an ADT/DUT

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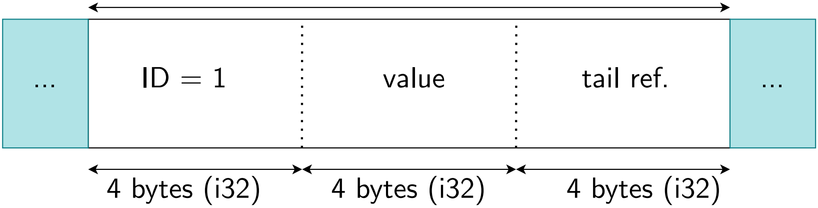
- Size of an allocation depends on the size of the variant being instantiated
- Offsets to accessing variables work similar to records, with a 4 byte offset for the variant id.
- Memory usage can be fairly inefficient for certain constructions (e.g., `Strings`, `Lists`, etc).

Allocated memory location of an ADT/DUT

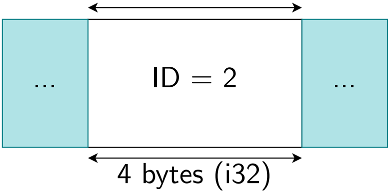
Example: Integer Lists in Memory

Strings are very similar

Allocated memory location of a ‘Cons‘ (12 bytes)



Allocated memory location of a ‘Nil‘ (4 bytes)



Notable Design Decisions

- The first 4 bytes of a program are always left as 0 so that we can always have uninitialized DUT pointers pointing to it naturally, then when this uninitialized DUT is read in, we will always see that the "instance" has $id = 0$, meaning it hasn't been instantiated.

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- The data within the records are mutable, but you can only access them through caseing.
- When parsing DUTs, we create "instantiation helper functions" for each DUT variant.
  - "DUT variant instantiation" is secretly rewritten into procedure calls.
  - This simplifies parsing, and trims down generated code size.

Example of DUT instantiation helper

This function is used when wanting to instantiate a "Cons" variant (of a List).

```
(func $__mk_Cons (param $head i32) (param $tail i32) (result i32)
global.get $_memsize           ;; get known unused memory location
i32.const 1                    ;; get Cons's kind index
i32.store                      ;; store it
global.get $_memsize           ;; get known unused memory location
i32.const 4                    ;; get offset of the next type
i32.add                        ;; impose offset onto total memory size
local.get $head                ;; get param head
i32.store                      ;; store it in it's area
global.get $_memsize           ;; get known unused memory location
i32.const 8                    ;; get offset of the next type
i32.add                        ;; impose offset onto total memory size
local.get $tail                ;; get param tail
i32.store                      ;; store it in it's area
global.get $_memsize           ;; get global memory size
global.get $_memsize           ;; get global memory size (again)
i32.const 12                   ;; get size of kind (Cons)
i32.add                        ;; add to memory size
global.set $_memsize           ;; set memory size, leftover i32 on stack which is the
     returned pointer to the generated Cons
)
```

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- This causes issues for **pywasm**
  - Due to being interpreted in Python, a recursive call stack size limitation is imposed onto our programs.
- Thankfully, **wasmer** has no issues!
- In-browser WebAssembly execution also has no issues, but we don't ship a web browser with the compiler.

Challenges

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- Recursive disjoint union types (self-references)
  - Assume type existence while parsing
  - Instances are references to other memory locations
- Making the grammar reasonably "natural" feeling in P0

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- Type variables!
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Future Work

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- More built-in types and syntactic sugars
  - Strings, Lists, Maps as a basic set of built-in DUTs
  - Syntactic sugar for String generation (e.g., “abcd...” for quickly instantiating large strings)
- Improved Memory Management
  - Memory freeing!
  - Memory reuse!
  - Allocation specialization for built-in DUTs!

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- DUTs are easy to implement!
- DUTs are nice to work with!

References