

Disjoint Union Types in P0

Project 9 / Group 8

Jason Balaci

McMaster University

April 2021

Table of Contents

- 1 Objective & Implementation
- 2 Examples
- 3 Implementation Evaluation and Notes
- 4 Future Work

Table of Contents

- 1 Objective & Implementation
- 2 Examples
- 3 Implementation Evaluation and Notes
- 4 Future Work

What are Disjoint Union Types?

- **Disjoint union types** (DUTs) are types which can take the form of one of many different types, differentiated by a **unique identifier tag**.

What are Disjoint Union Types?

- **Disjoint union types** (DUTs) are types which can take the form of one of many different types, differentiated by a **unique identifier tag**.
- Each DUT has a set of possible types it can take on, called “variants”, or “kinds”.

What are Disjoint Union Types?

- **Disjoint union types** (DUTs) are types which can take the form of one of many different types, differentiated by a **unique identifier tag**.
- Each DUT has a set of possible types it can take on, called “variants”, or “kinds”.
- These “variants” it may take on may be records or the unit type.

What are Disjoint Union Types?

- **Disjoint union types** (DUTs) are types which can take the form of one of many different types, differentiated by a **unique identifier tag**.
- Each DUT has a set of possible types it can take on, called “variants”, or “kinds”.
- These “variants” it may take on may be records or the unit type.
- An instance of a DUT may take on the form of **only one** of it's variants.

What are Disjoint Union Types?

- **Disjoint union types** (DUTs) are types which can take the form of one of many different types, differentiated by a **unique identifier tag**.
- Each DUT has a set of possible types it can take on, called “variants”, or “kinds”.
- These “variants” it may take on may be records or the unit type.
- 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?

- In Haskell,
data List a = Nil | Cons a (List a)
data RGB = Red | Green | Blue

What do they look like?

- In Haskell,
data **List** a = Nil | Cons a (**List** a)
data RGB = Red | Green | Blue
- In our implementation,
type List = Nil | Cons(value: **integer**, tail: List)
type RGB = Red | Green | Blue

What do they look like?

- In Haskell,
data **List** a = Nil | Cons a (**List** a)
data RGB = Red | Green | Blue
- In our implementation,
type List = Nil | Cons(value: **integer**, tail: List)
type RGB = Red | Green | Blue
- Instantiation in Haskell,
a = Cons 1 (Cons 2 (Cons 3 Nil))
b = Red

What do they look like?

- In Haskell,
data List = Nil | Cons a (List a)
data RGB = Red | Green | Blue
- In our implementation,
type List = Nil | Cons(value: **integer**, tail: List)
type RGB = Red | Green | Blue
- Instantiation in Haskell,
a = Cons 1 (Cons 2 (Cons 3 Nil))
b = Red
- Instantiation in our implementation,
a := Cons(1, Cons(2, Cons(3, Nil())))
b := Red()

How do we use DUTs?

The anatomy of a case statement.

- cases are the only way to access data inside of DUTs.

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

How do we use DUTs?

The anatomy of a case statement.

- cases are the only way to access data inside of DUTs.
- Check if DUTs were *initialized* using a `nil` case at the start.

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

How do we use DUTs?

The anatomy of a case statement.

- cases are the only way to access data inside of DUTs.
- Check if DUTs were *initialized* using a `nil` case at the start.
- case on any of the variants you'd like to.

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

How do we use DUTs?

The anatomy of a case statement.

- cases are the only way to access data inside of DUTs.
- Check if DUTs were *initialized* using a `nil` case at the start.
- case on any of the variants you'd like to.
- default case allows you to perform either a statement suite or a no-op on all non-covered cases.

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


How do we use DUTs?

The anatomy of a case statement.

- cases are the only way to access data inside of DUTs.
- Check if DUTs were *initialized* using a `nil` case at the start.
- case on any of the variants you'd like to.
- default case allows you to perform either a statement suite or a no-op on all non-covered cases.
- Within the statement suite of each variant case, the variable in question is assumed to be an instance of the variant's record.

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

How do we use DUTs?

The anatomy of a case statement.

- cases are the only way to access data inside of DUTs.
- Check if DUTs were *initialized* using a `nil` case at the start.
- case on any of the variants you'd like to.
- default case allows you to perform either a statement suite or a no-op on all non-covered cases.
- Within the statement suite of each variant case, the variable in question is assumed to be an instance of the variant's record.

```
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.

Table of Contents

- 1 Objective & Implementation
- 2 Examples
- 3 Implementation Evaluation and Notes
- 4 Future Work

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

```
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))
```

Output

```
-1
1111
```

Example: 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 consumeList(l: List)
  case l of {
    Cons: writeln(l.head); consumeList(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)
  consumeList(myList)
  writeln(sumList(myList))
```

Example: 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 consumeList(l: List)
  case l of {
    Cons: writeln(l.head); consumeList(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)
  consumeList(myList)
  writeln(sumList(myList))
```

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.

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)
```

Output

```
ABCDEFGHIJKLMNOPQRSTUVWXYZ
abcdefghijklmnopqrstuvwxyz
0123456789
αβγδεζηθικλμνξοπρστυφχψω
```

Note

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

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!

Table of Contents

- 1 Objective & Implementation
- 2 Examples
- 3 Implementation Evaluation and Notes**
- 4 Future Work

Focal Grammar Changes

- Disjoint union type declarations

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

Focal Grammar Changes

- Disjoint union type declarations

```
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

- Single-value returning procedures may be used “in-place” in expressions

Supplementary Grammar and Procedure Changes

- Single-value returning procedures may be used “in-place” in expressions
- Single characters wrapped in single-quotes (‘a’) is a syntactic sugar for converting single utf-8 characters into P0 integers

Supplementary Grammar and Procedure Changes

- Single-value returning procedures may be used “in-place” in expressions
- Single characters wrapped in single-quotes (‘a’) is a syntactic sugar for converting single utf-8 characters into P0 integers
- “< -” and “- >” as alternatives for “←” and “→”, respectively

Supplementary Grammar and Procedure Changes

- Single-value returning procedures may be used “in-place” in expressions
- Single characters wrapped in single-quotes (‘a’) is a syntactic sugar for converting single utf-8 characters into P0 integers
- “< -” and “- >” as alternatives for “←” and “→”, respectively
- “>=” and “<=” as alternatives for “≥” and “≤”, respectively

Supplementary Grammar and Procedure Changes

- Single-value returning procedures may be used “in-place” in expressions
- Single characters wrapped in single-quotes (‘a’) is a syntactic sugar for converting single utf-8 characters into P0 integers
- “< -” and “- >” as alternatives for “←” and “→”, respectively
- “>=” and “<=” as alternatives for “≥” and “≤”, respectively
- “*” as an alternative for “×”

Supplementary Grammar and Procedure Changes

- Single-value returning procedures may be used “in-place” in expressions
- Single characters wrapped in single-quotes (‘a’) is a syntactic sugar for converting single utf-8 characters into P0 integers
- “< -” and “- >” as alternatives for “←” and “→”, respectively
- “>=” and “<=” as alternatives for “≥” and “≤”, respectively
- “*” as an alternative for “×”
- 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

For example, the WebAssembly code on the right-hand side 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('?')
  }
```

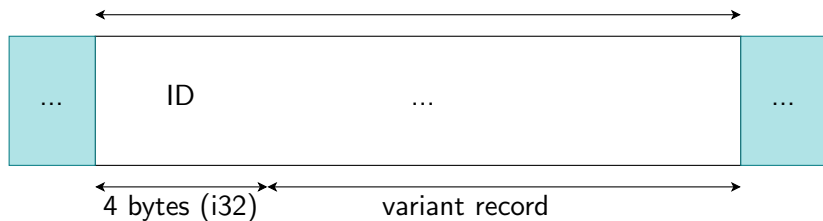
```
...
local.get $col
i32.load
i32.const 0           ;; check if nil
i32.eq                ;; if it is nil
if                    ;; if it is nil
i32.const 63
call $writeCharLn    ;; print '?'
else                  ;; otherwise
local.get $col
i32.load
i32.const 1           ;; check if 'R'
i32.eq                ;; if it is 'R'
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 it is 'G'
if                    ;; if it is 'G'
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 the locations of their corresponding DUT on the heap.

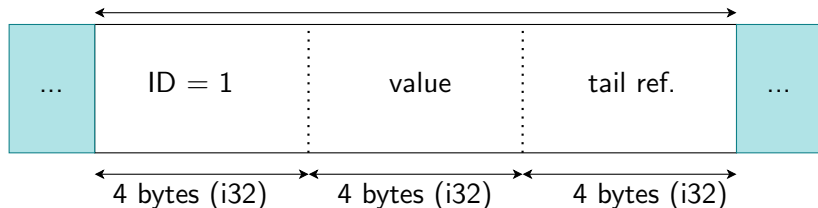
- Size of an allocation depends on the size of the variant being instantiated
- Offsets to accessing variables work similar to records, with a 4 byte offset for the variant id.

Allocated memory location of an ADT/DUT

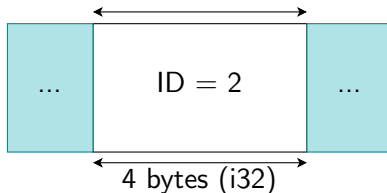


Example: Lists in Memory

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 to be always initialized to 0 so that we can always have uninitialized DUT pointers pointing to it, then when this uninitialized DUT is read in, we will always see that the “instance” has *kindId* = 0, meaning it hasn’t been instantiated.

Notable Design Decisions

- The first 4 bytes of a program are to be always initialized to 0 so that we can always have uninitialized DUT pointers pointing to it, then when this uninitialized DUT is read in, we will always see that the “instance” has *kindId* = 0, meaning it hasn’t been instantiated.
- When DUTs are read in, we create “helper functions” for each DUT variant. These “helper functions” are then used whenever we want to instantiate any particular DUT variant. DUT variant instantiation is hence secretly just a function call (to some function that creates a DUT on the heap and returns it’s memory location).

Notable Design Decisions

- The first 4 bytes of a program are to be always initialized to 0 so that we can always have uninitialized DUT pointers pointing to it, then when this uninitialized DUT is read in, we will always see that the “instance” has *kindId* = 0, meaning it hasn’t been instantiated.
- When DUTs are read in, we create “helper functions” for each DUT variant. These “helper functions” are then used whenever we want to instantiate any particular DUT variant. DUT variant instantiation is hence secretly just a function call (to some function that creates a DUT on the heap and returns it’s memory location).
- Disjoint union type variants are mutable records. You may modify the values of a DUT variant only when caseing on it from within it’s case.

Notable Design Decisions

- The first 4 bytes of a program are to be always initialized to 0 so that we can always have uninitialized DUT pointers pointing to it, then when this uninitialized DUT is read in, we will always see that the “instance” has *kindId* = 0, meaning it hasn’t been instantiated.
- When DUTs are read in, we create “helper functions” for each DUT variant. These “helper functions” are then used whenever we want to instantiate any particular DUT variant. DUT variant instantiation is hence secretly just a function call (to some function that creates a DUT on the heap and returns it’s memory location).
- Disjoint union type variants are mutable records. You may modify the values of a DUT variant only when caseing on it from within it’s case.
- DUT variant kind identifiers are immutable!

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
)
```

- When working with DUTs/ADTs, we often tend to create recursive algorithms...

- When working with DUTs/ADTs, we often tend to create recursive algorithms...
- This causes issues for **pywasm**
 - Due to being interpreted in Python, a recursive call stack size limitation is imposed onto our programs.

- When working with DUTs/ADTs, we often tend to create recursive algorithms...
- 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!

- When working with DUTs/ADTs, we often tend to create recursive algorithms...
- 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.

Table of Contents

- 1 Objective & Implementation
- 2 Examples
- 3 Implementation Evaluation and Notes
- 4 Future Work

- Type variables!
 - Polymorphic disjoint union types! No more StringLists, IntLists, BooleanLists, etc!
 - More code reuse!

- Type variables!
 - Polymorphic disjoint union types! No more StringLists, IntLists, BooleanLists, etc!
 - More code reuse!
- More built-in types and syntactic sugars
 - Strings, Lists, Maps as a basic set of built-in DUTs
 - Stronger syntactic sugar for String generation (e.g., “abcd...” for quickly instantiating large strings)

- Type variables!
 - Polymorphic disjoint union types! No more StringLists, IntLists, BooleanLists, etc!
 - More code reuse!
- More built-in types and syntactic sugars
 - Strings, Lists, Maps as a basic set of built-in DUTs
 - Stronger 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!

References