Miniboxing

Load-time Specialization on the JVM

OOPSLA, 29th of October 2013

Vlad Ureche
Cristian Talau
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We all like generics

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a trivial example

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```
def identity[T](t: T): T = t
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- will take any type and
- will return **that same type**

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def identity[T](t: T): T = t
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but under **erasure:**

```
def identity(t: Any): Any = t
```

We all like generics

a trivial example

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def identity[T](t: T): T = t
```

but under **erasure:**

Any is the top of the Scala type system

```
def identity(t: Any): Any = t
```

We all like generics

a trivial example

```
x = identity(3)
```

We all like generics

a trivial example

```
x = identity(3)
```

under **erasure:**

```
x = unbox(identity(box(3)))
```

We all like generics

but under **erasure**

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generics execute similarly to **dynamic languages**

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- generic values **lose** their **type information**

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Dynamic language VMs use **specialization** to improve performance*

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generics execute similarly to **dynamic languages**

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- primitives need **boxing**
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Dynamic language VMs use **specialization** to improve performance*

*but the HotSpot JVM **doesn't**

Generics

WE ARE HERE

Specialization

Miniboxing

Performance

Evaluation

Scala has a solution

Scala has a solution

it's called specialization*

[*] Iulian Dragos – PhD thesis, EPFL, 2010

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Compile-time (static) transformation

- **duplicates** the original code
- **adapts it** for each primitive type
- **rewrites** programs to use the adapted code

Scala has a solution

it's called specialization[*]

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Compile-time (static) transformation

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Adapted code doesn't need to box

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Adapted code doesn't need to box

Performance is regained.

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Specialization

let's revisit `def identity`

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def identity[T](t: T): T = t
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let's revisit `def identity`

```
def identity[T](t: T): T = t
```

```
def identity_V(t: Unit): Unit = t
def identity_Z(t: Boolean): Boolean = t
def identity_B(t: Byte): Byte = t
def identity_C(t: Char): Char = t
def identity_S(t: Short): Short = t
def identity_I(t: Int): Int = t
def identity_J(t: Long): Long = t
def identity_F(t: Float): Float = t
def identity_D(t: Double): Double = t
```

Specialization

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def identity_F(t: Float): Float = t
def identity_D(t: Double): Double = t
```

Generates 10 times the original code

Specialization

… it gets even worse

Specialization

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```
def pack[T1, T2](t1: T1, t2: T2) = ...
```

Specialization

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```
def pack[T1, T2](t1: T1, t2: T2) = ...
```

```
def pack_VV(t1: Unit, t2: Unit)
def pack_VZ(t1: Unit, t2: Boolean)
def pack_VB(t1: Unit, t2: Byte)
def pack_VC(t1: Unit, t2: Char)
def pack_VS(t1: Unit, t2: Short)
def pack_VI(t1: Unit, t2: Int)
def pack_VJ(t1: Unit, t2: Long)
def pack_VF(t1: Unit, t2: Float)
def pack_VD(t1: Unit, t2: Double)
```

Specialization

… it gets even worse

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def pack[T1, T2](t1: T1, t2: T2) = ...
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def pack_VV(t1: Unit, t2: Unit)
def pack_VZ(t1: Unit, t2: Boolean)
de
de
def pack_VS(t1: Unit, t2: Short)
def pack_VI(t1: Unit, t2: Int)
def pack_VJ(t1: Unit, t2: Long)
def pack_VF(t1: Unit, t2: Float)
def pack_VD(t1: Unit, t2: Double)
```

10^n, where n is the number of type params

Specialization

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def pack[T1, T2](t1: T1, t2: T2) = ...
```

```
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de
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```

10^n, where n is the number of type params

And this is common: Maps, Tuples, Functions

Specialization

... it gets even worse

```
def pack[T1, T2](t1: T1, t2: T2) = ...
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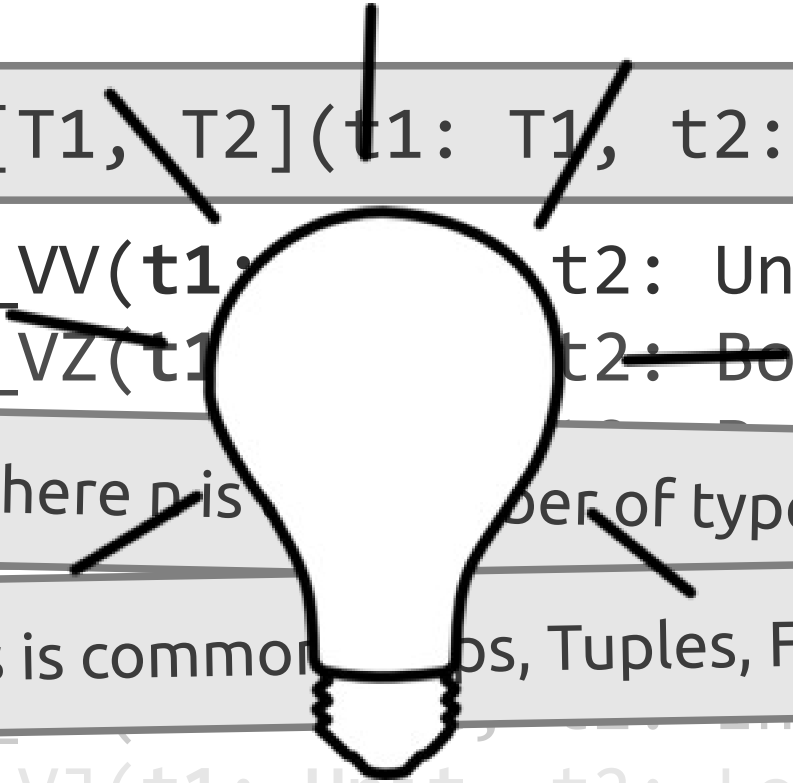

```
def pack_VV(t1:          t2: Unit)
def pack_VZ(t1           t2: Boolean)
de
de
de
de                             Int)
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10^n, where n is   ber of type params

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Generics

Specialization

Miniboxing

WE ARE HERE

Performance

Evaluation

Miniboxing

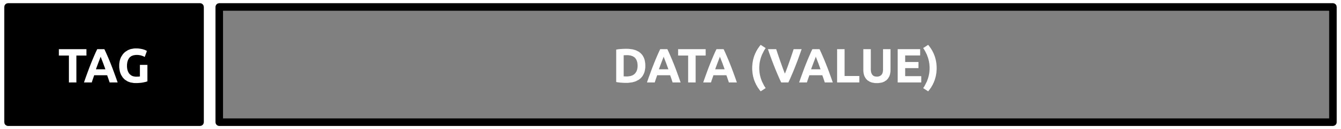
Miniboxing

reduces the variants

Miniboxing

reduces the variants

by using something like a **tagged union**



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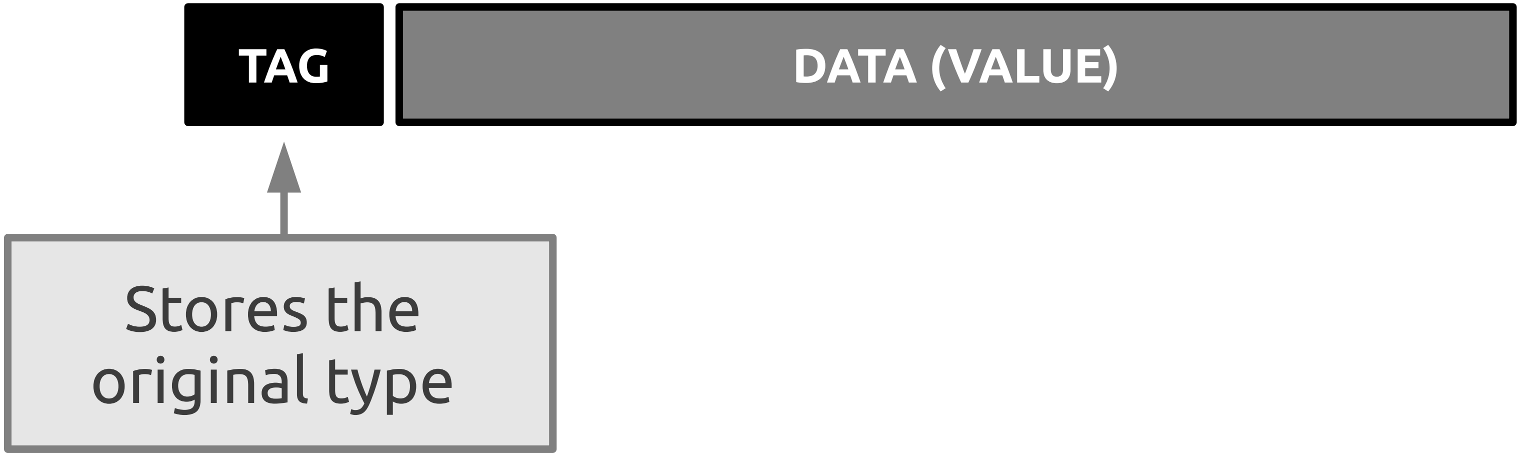

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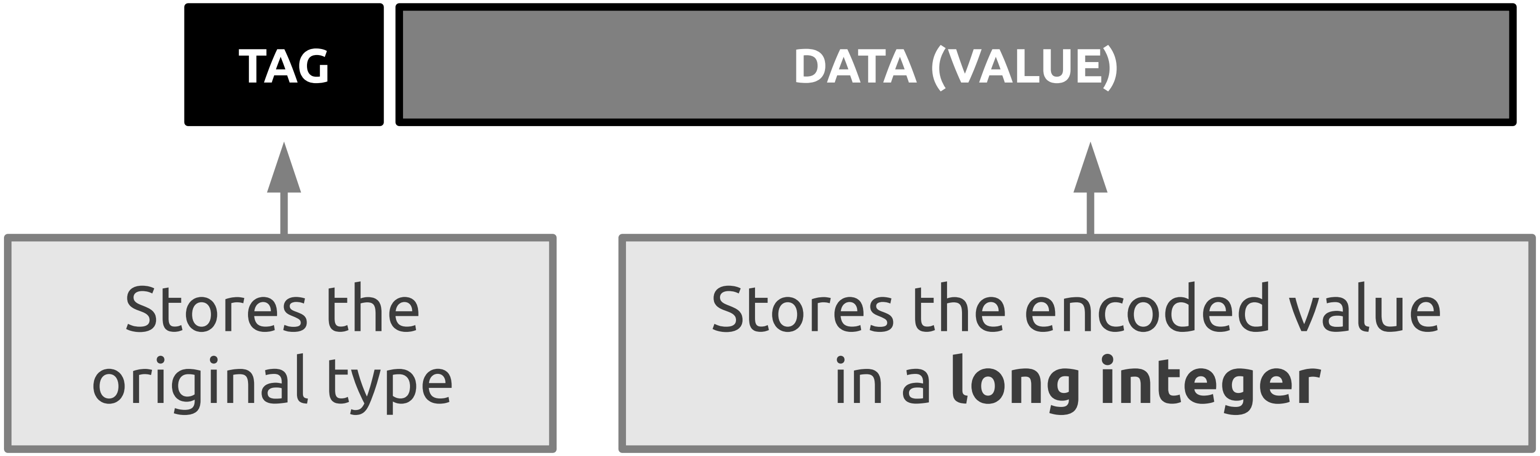


TAG

DATA (VALUE)

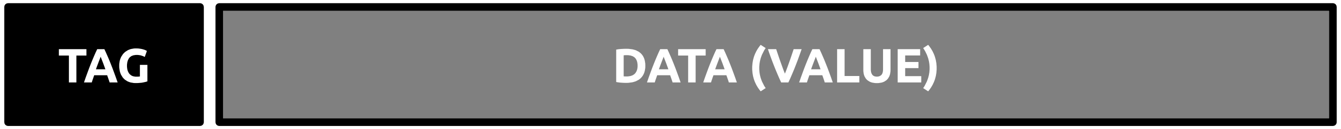
Stores the original type

Stores the encoded value in a **long integer**

Miniboxing

reduces the variants

by using something like a **tagged union**



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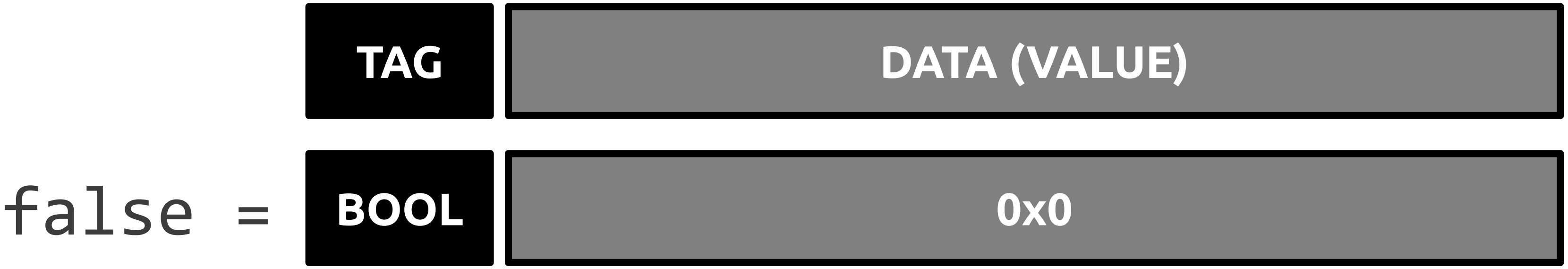

	TAG	DATA (VALUE)
`false =`	BOOL	0x0

Miniboxing

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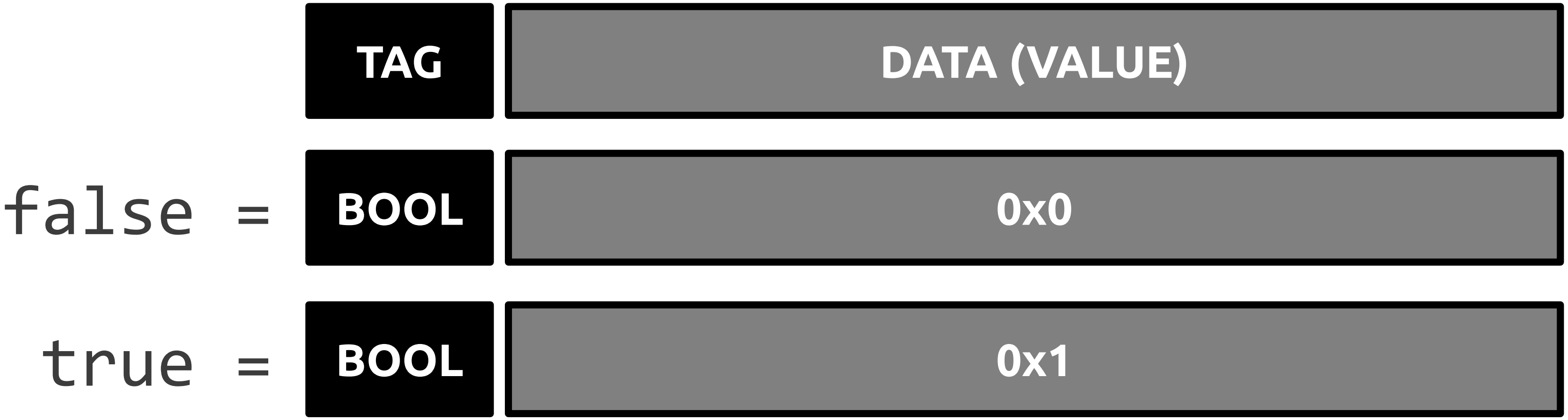


	TAG	DATA (VALUE)
`false =`	BOOL	0x0
`true =`	BOOL	0x1

Miniboxing

reduces the variants

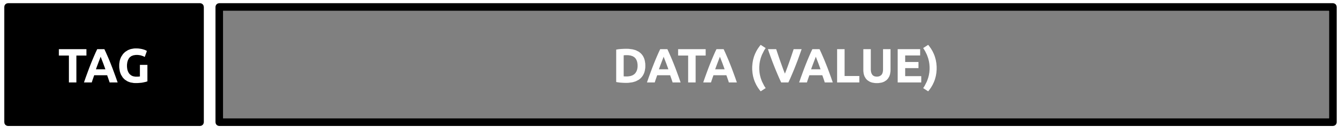
by using something like a **tagged union**

	TAG	DATA (VALUE)
`false =`	BOOL	0x0
`true =`	BOOL	0x1
`42 =`	INT	0x2A

Miniboxing

reduces the variants

by using something like a **tagged union**



TAG

DATA (VALUE)

Miniboxing
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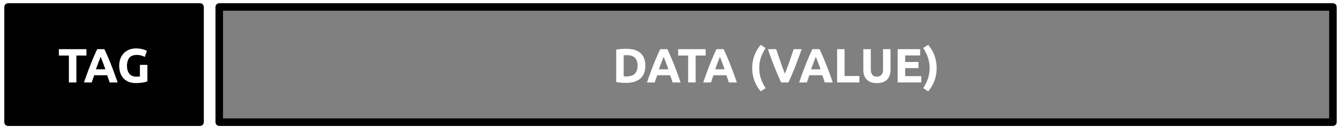

TAG

DATA (VALUE)

and using the **static type information**

- tags are attached to **code**, not to values

Miniboxing

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def identity[T](t: T): T = t
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Miniboxing

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def identity[T](t: T): T = t
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def identity_M(T_tag: Byte, t: Long): Long
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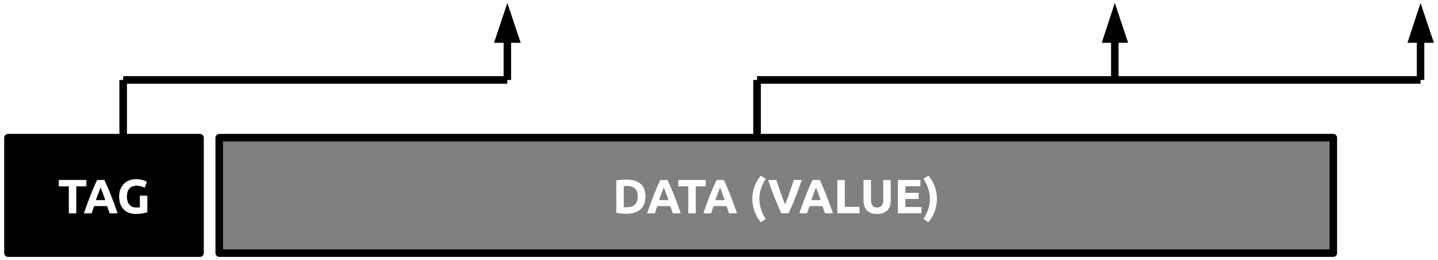

TAG

DATA (VALUE)

Miniboxing

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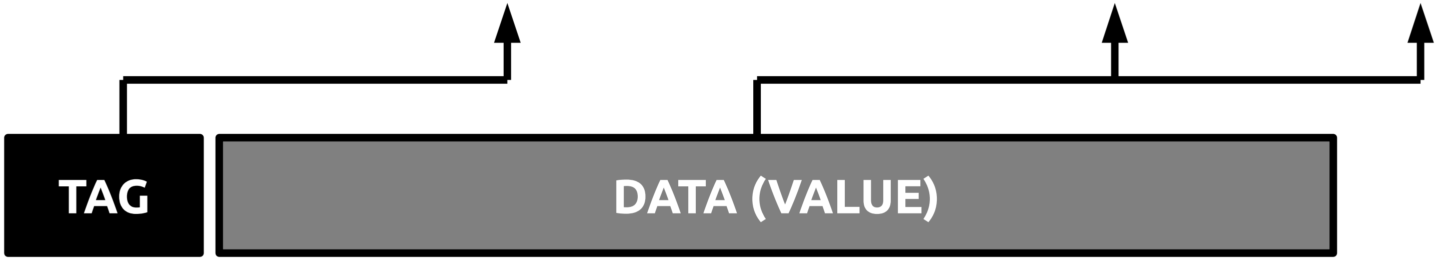

T_tag corresponds to the **type parameter**, instead of the values being passed around.

Miniboxing

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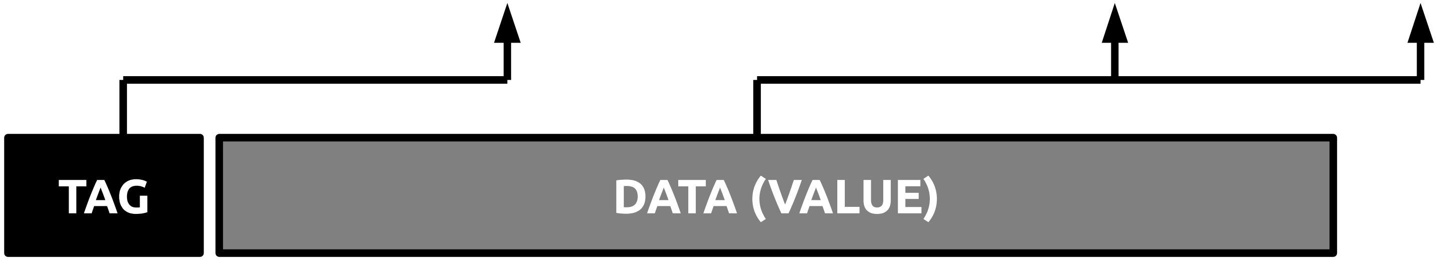

T_tag corresponds to the **type parameter**, instead of the value [illegible] und.

Tag hoisting

Miniboxing

let's revisit `def identity`

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def identity[T](t: T): T = t
```

```
def identity_M(T_tag: Byte, t: Long): Long
```

Two variants per type parameter (reference + minibox)

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Two variants per type parameter (reference + minibox)

`def pack` will have 4 variants

Miniboxing

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Two variants per type parameter (reference + minibox)

`def pack` will have 4 variants

Tag hoisting is instrumental in obtaining good performance

Generics

Specialization

Miniboxing

Performance

WE ARE HERE

Evaluation

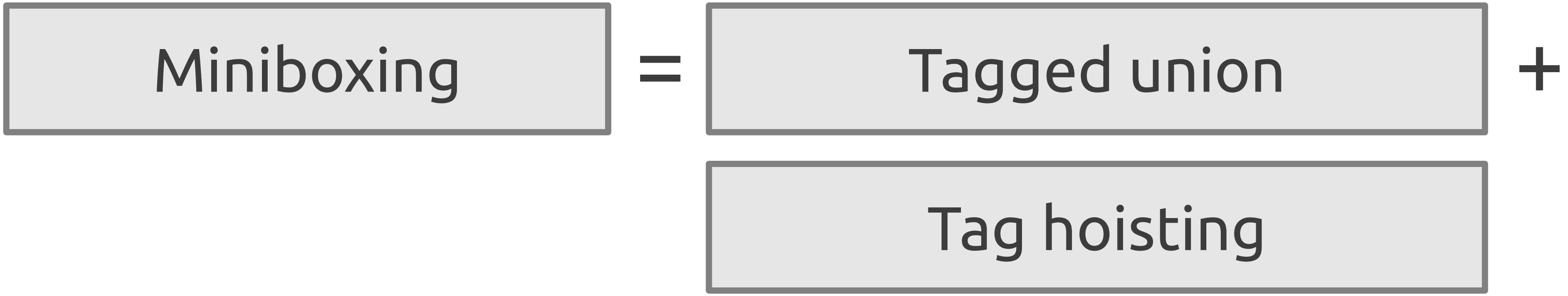
Performance

needs one more ingredient

Miniboxing = Tagged union

Performance

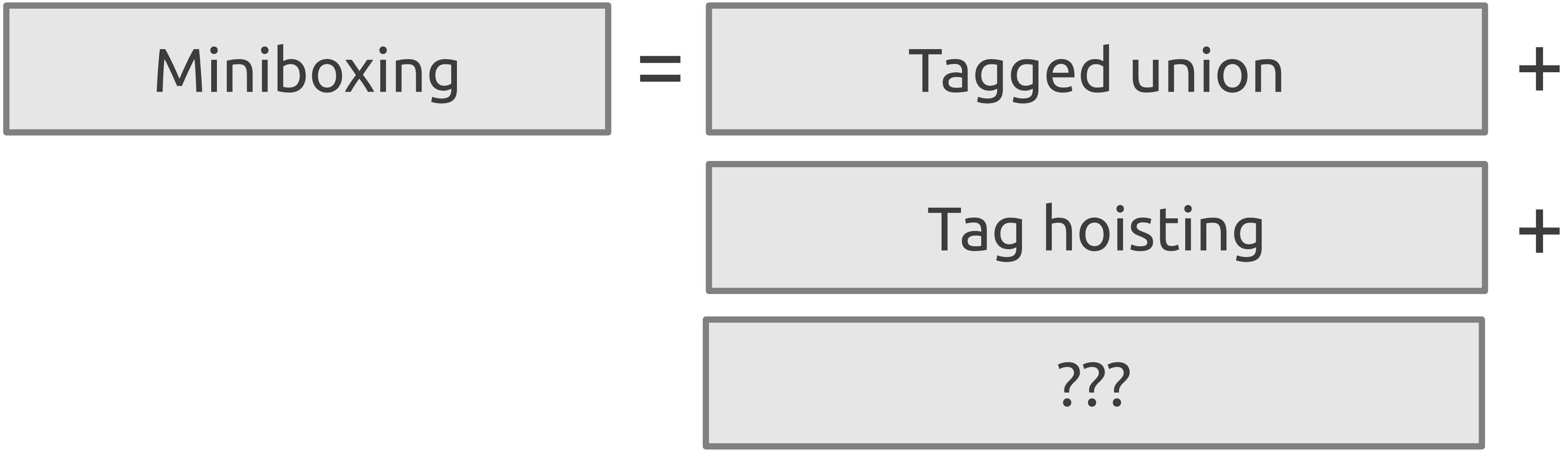
needs one more ingredient



Miniboxing = Tagged union + Tag hoisting

Performance

needs one more ingredient



Miniboxing = Tagged union + Tag hoisting + ???

Performance

needs one more ingredient

Miniboxing = Tagged union + Tag hoisting + ???

Why do we need a **secret ingredient?**

Switching on tags

kills performance

Switching on tags

kills performance

```
def toString(T_tag: Byte,
             value: Long): String =
  T_tag match {
    case UNIT => ...
    case BOOL => ...
    ...
  }
```

Switching on tags

kills performance

```
def toString(T_tag: Byte,
             value: Long): String =
  T_tag match {
    case UNIT => ...
    case BOOL => ...
    ...
  }
```

Even more so for consecutive switches

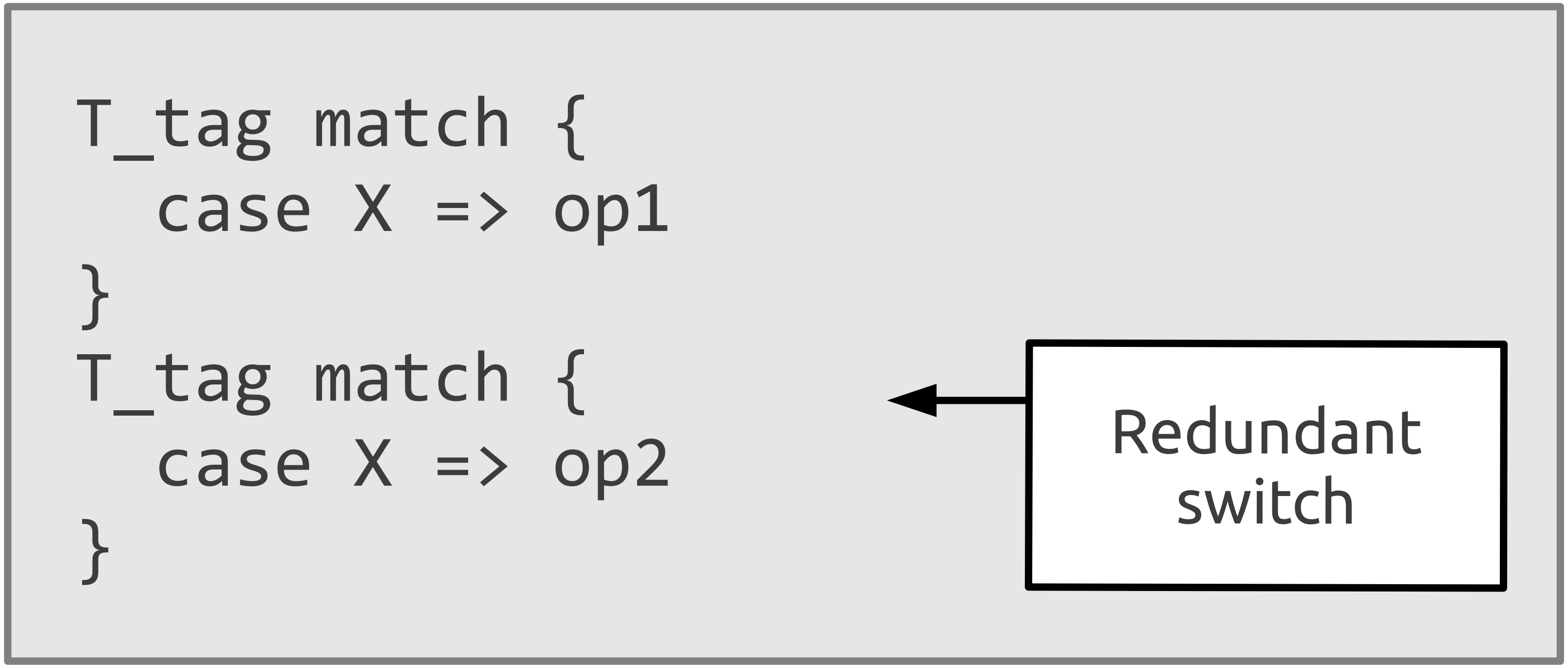
Switching on tags

kills performance

```
T_tag match {
  case X => op1
}
T_tag match {
  case X => op2
}
```

Switching on tags

kills performance



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}
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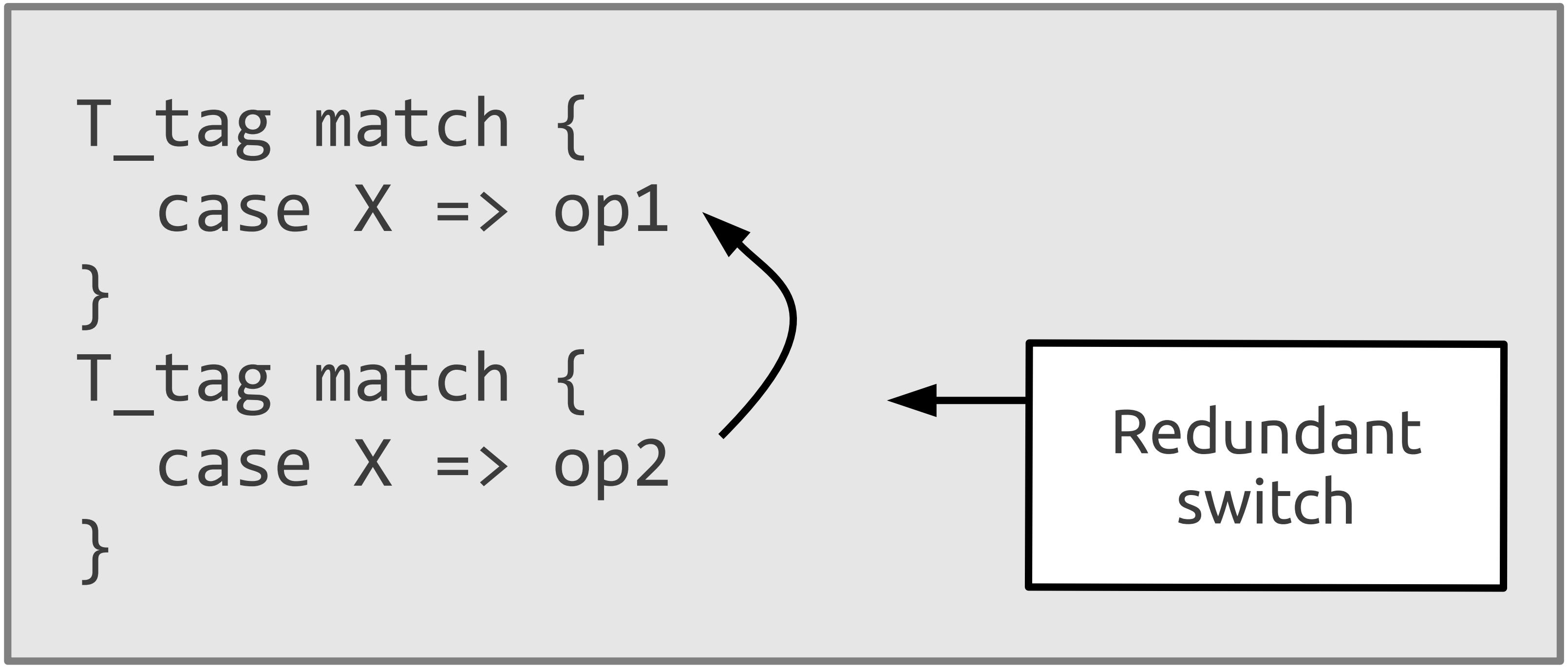
Redundant switch

Switching on tags

kills performance



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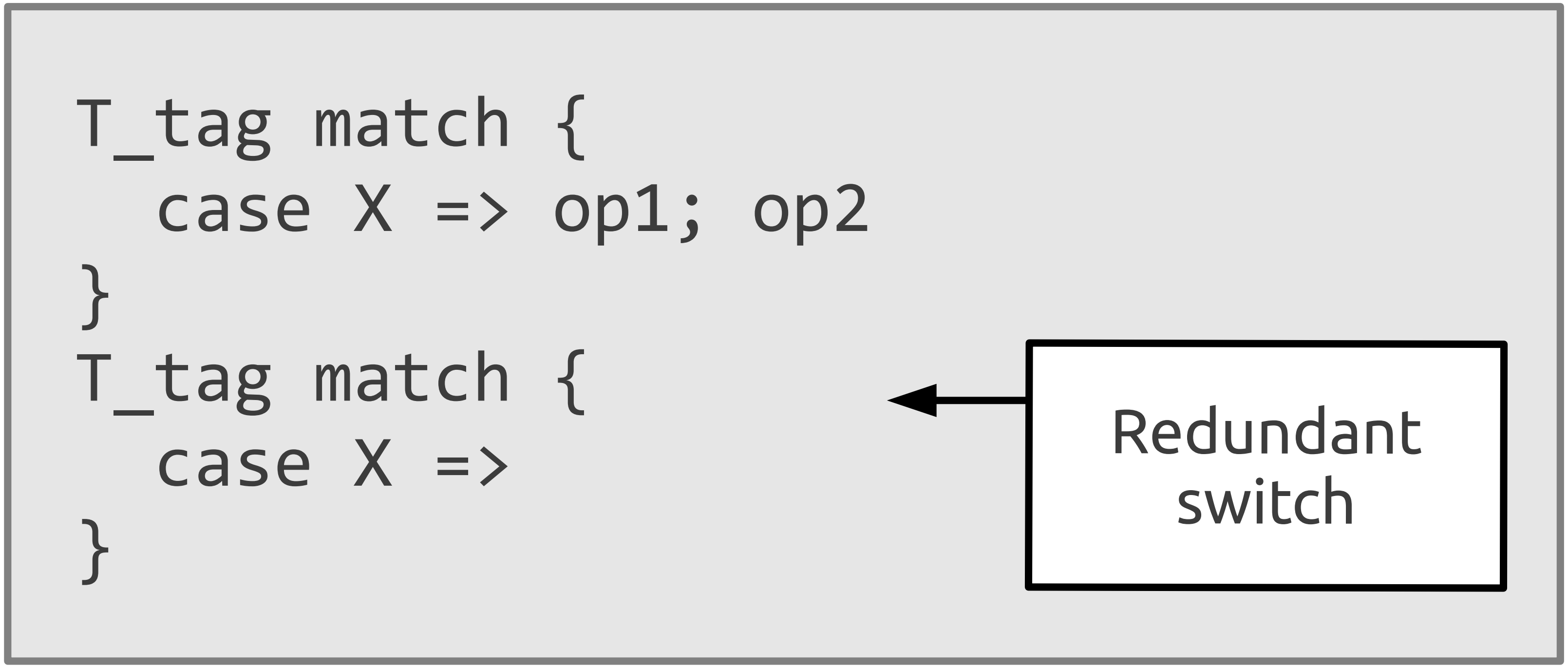
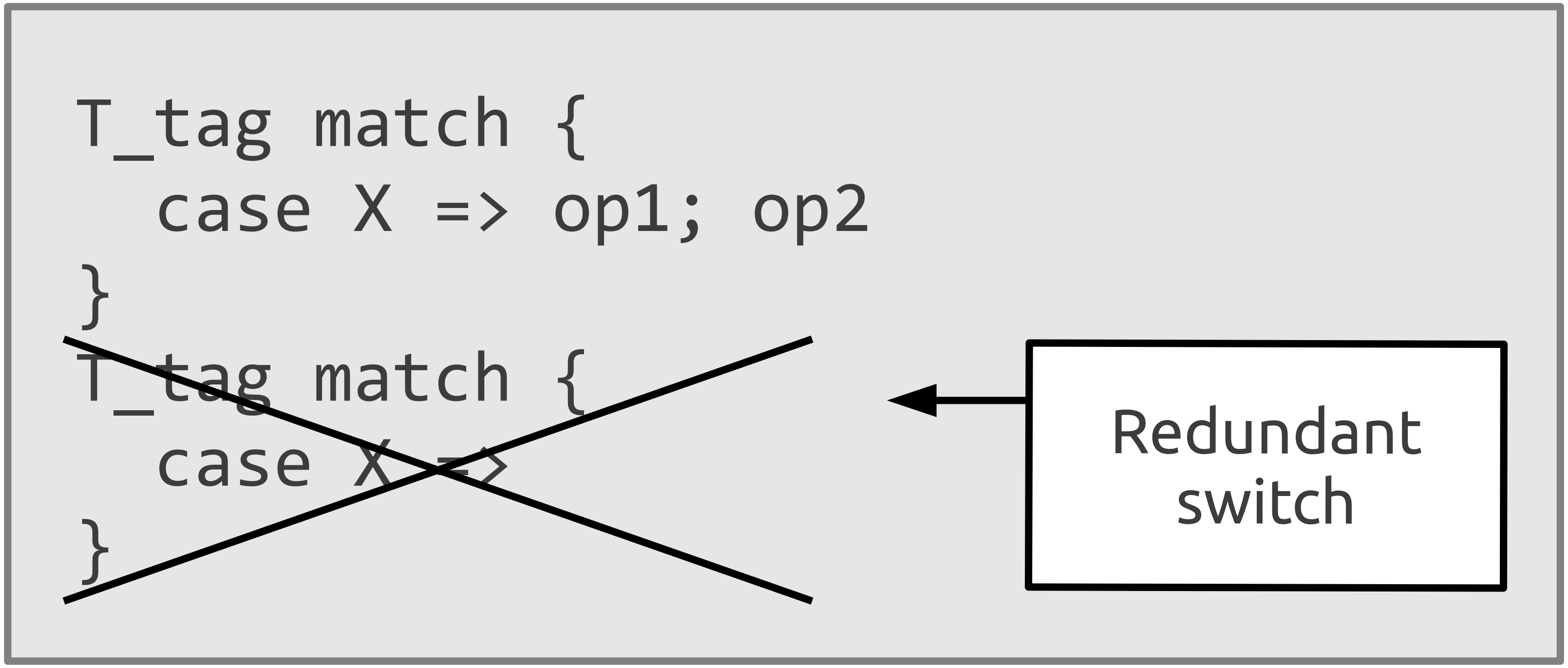


```
T_tag match {
  case X => op1; op2
}
T_tag match {
  case X =>
}
```

Redundant switch

Switching on tags

kills performance



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T_tag match {
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~~T_tag match {~~
~~case X =>~~
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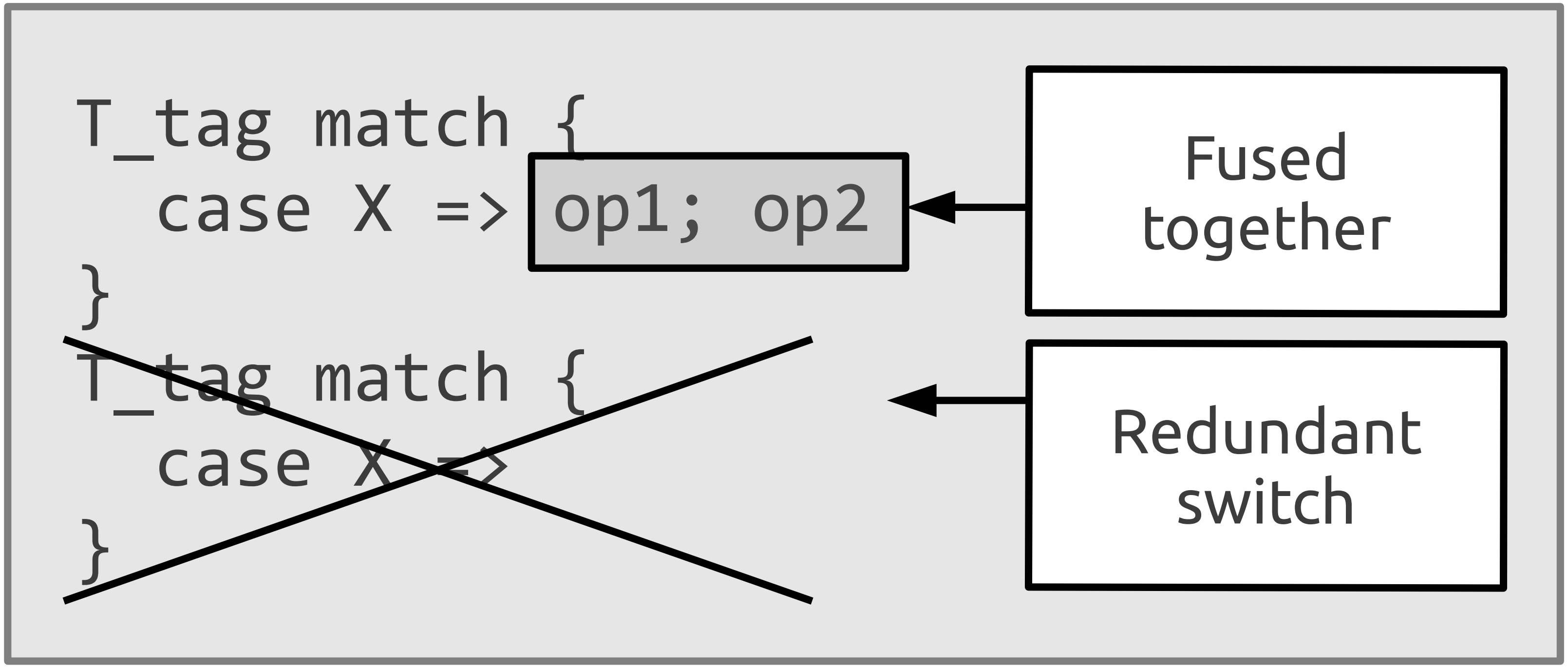
Redundant switch

Switching on tags

kills performance



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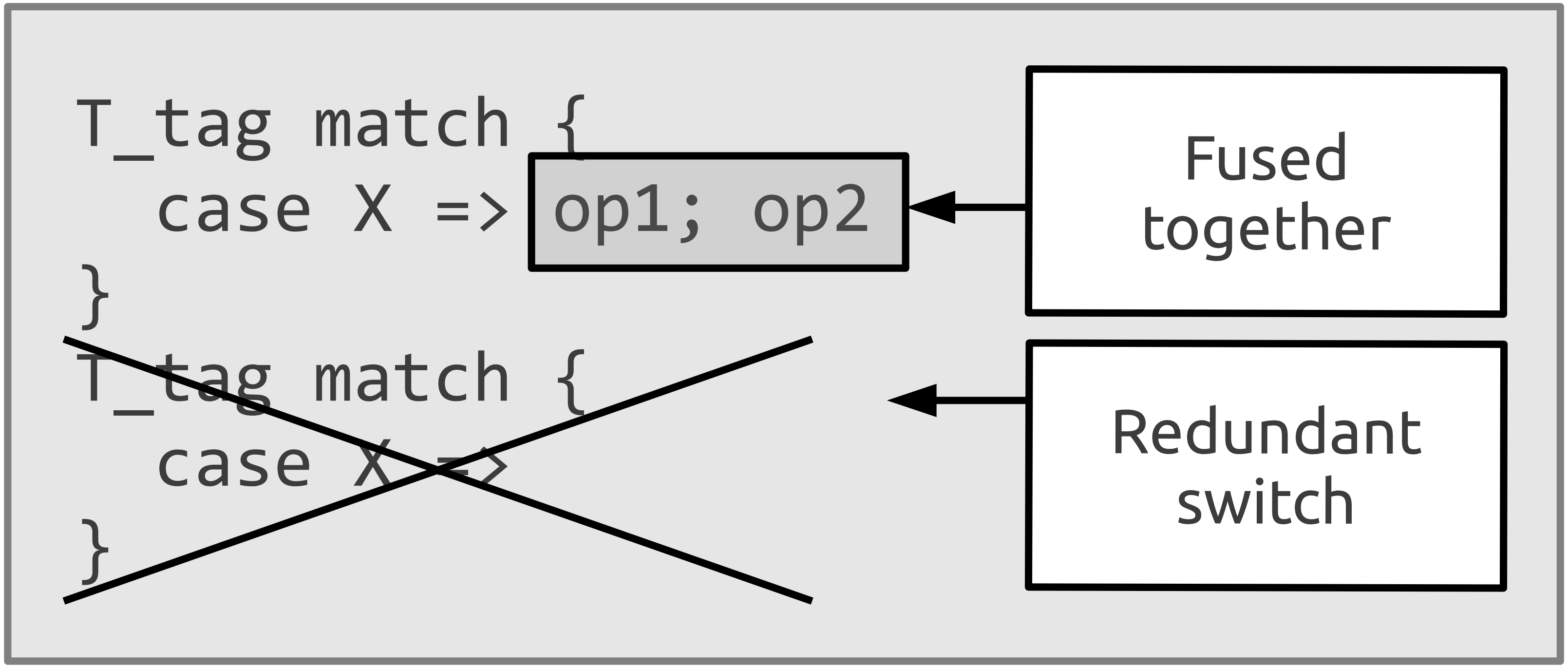
Switching on tags
kills performance



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T_tag match {
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```

~~T_tag match {~~
~~case X =>~~
~~}~~

This is critical for **array operations**

Switching

ArrayBuffer.reverse()

```
def reverse(): Unit {
  var index = 0
  while (index * 2 < length) {
    val opposite = length-index-1
    val tmp1: T = array(index)
    val tmp2: T = array(opposite)
    array(index) = tmp2
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    index += 1
  }
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```

Switching

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```
T_tag match {
  case INT => ...
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Switching

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Switching

```
ArrayBuffer.reverse()
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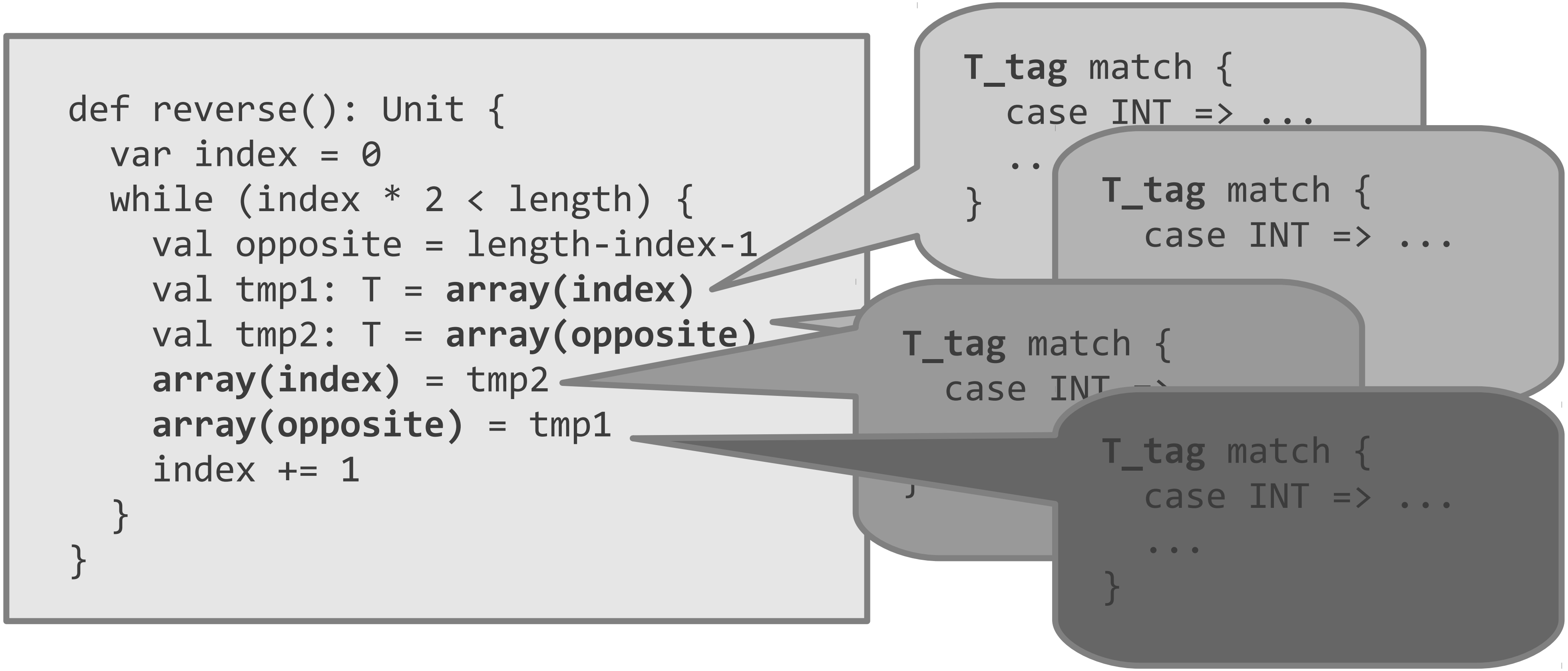

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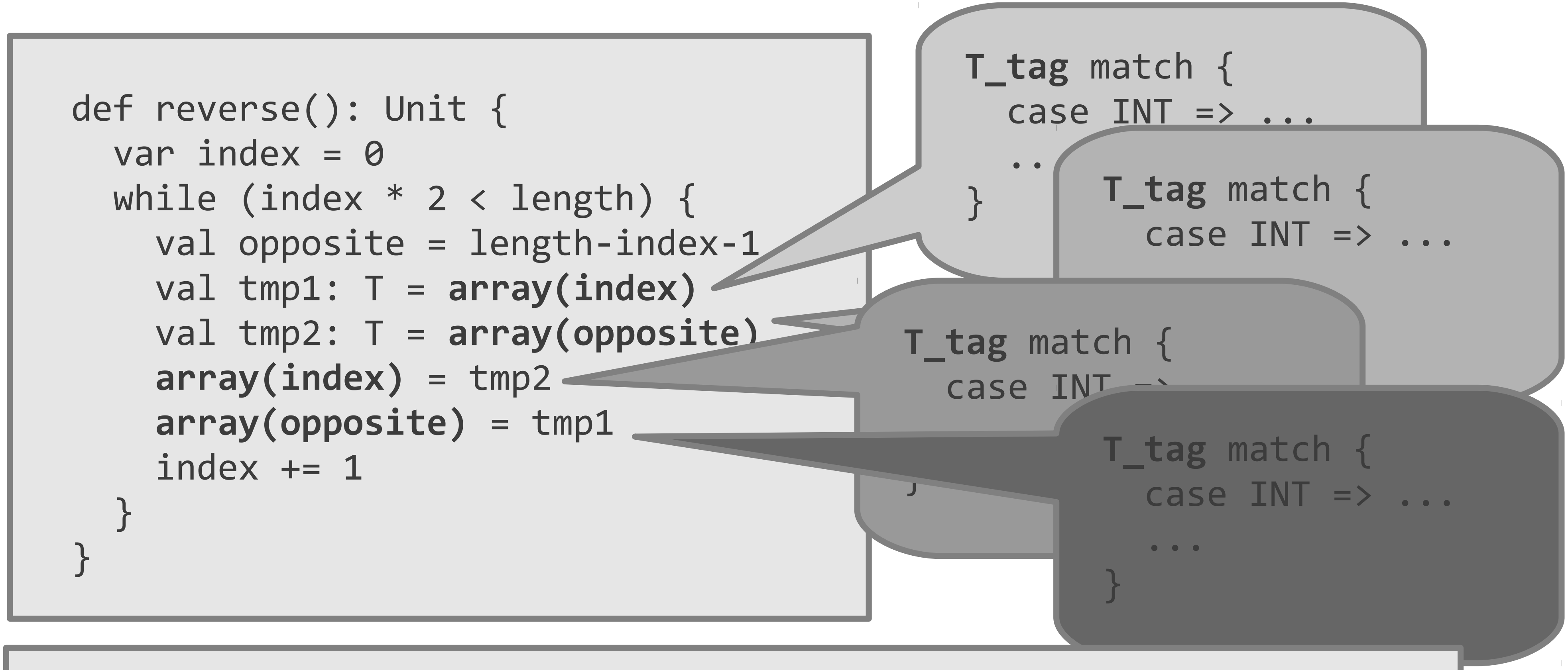
Switching

ArrayBuffer.reverse()



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Fuse the operations together?

Switching

`ArrayBuffer.reverse()`

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}
```

```
T_tag match {
  case INT =>
    val tmp1 = ...
    val tmp2 = ...
    array(.) = ...
    array(.) = ...
  ...
}
```

Switching

`ArrayBuffer.reverse()`

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def reverse(): Unit {
  var index = 0
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T_tag match {
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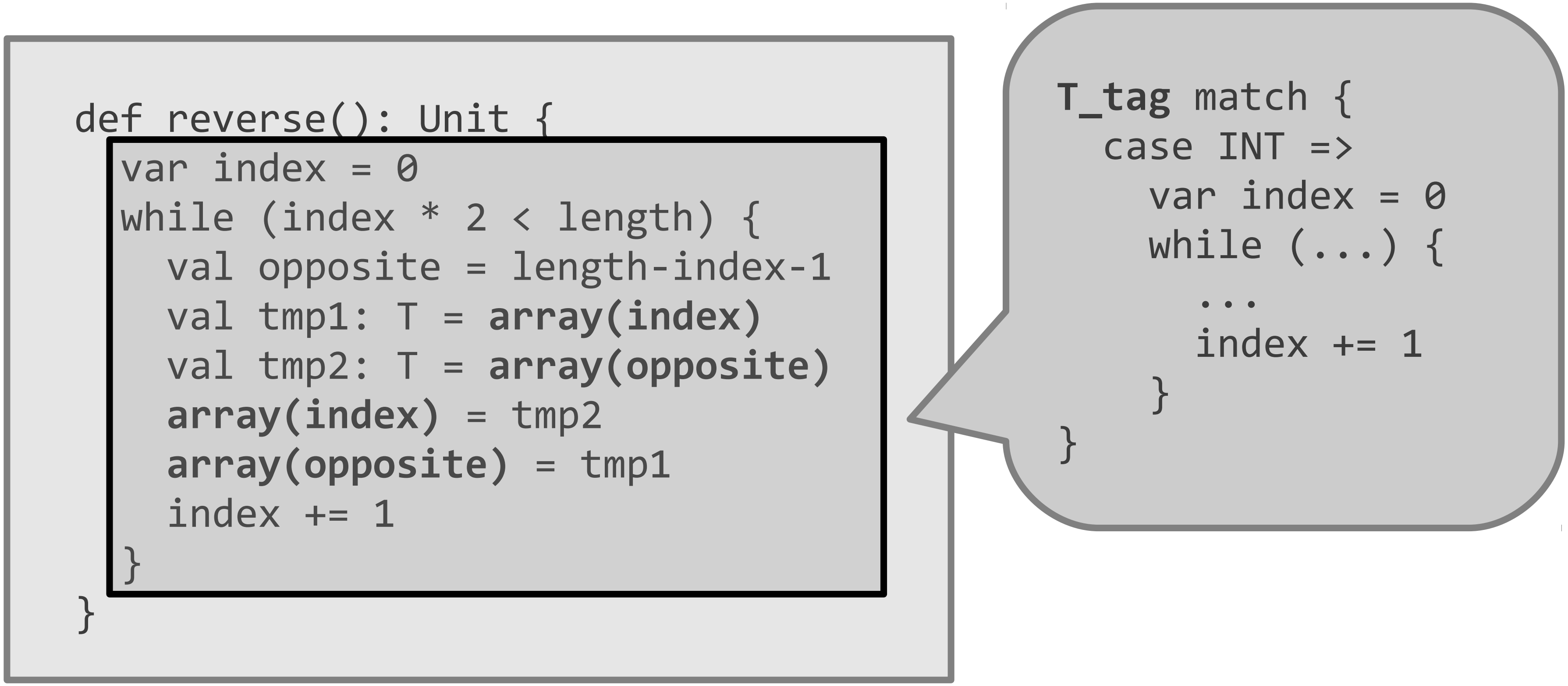
    val tmp2 = ...
    array(.) = ...
    array(.) = ...
  ...
}
```

Hoist the switch out of the loop?

Switching

ArrayBuffer.reverse()



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  }
}
```

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T_tag match {
  case INT =>
    var index = 0
    while (...) {
      ...
      index += 1
    }
}
```

Switching

ArrayBuffer.reverse()

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T_tag match {
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    while (...) {
      ...
      index += 1
    }
}
```
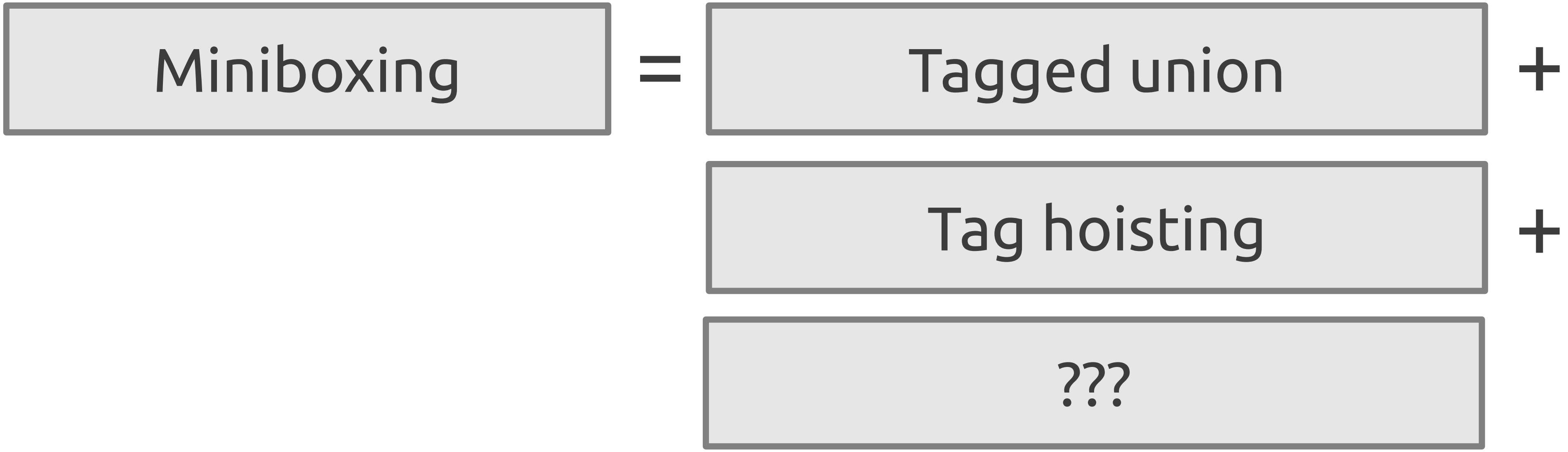

Is that enough? Method may be **called from a loop**

Performance

needs one more ingredient



Miniboxing = Tagged union + Tag hoisting + ???

Performance

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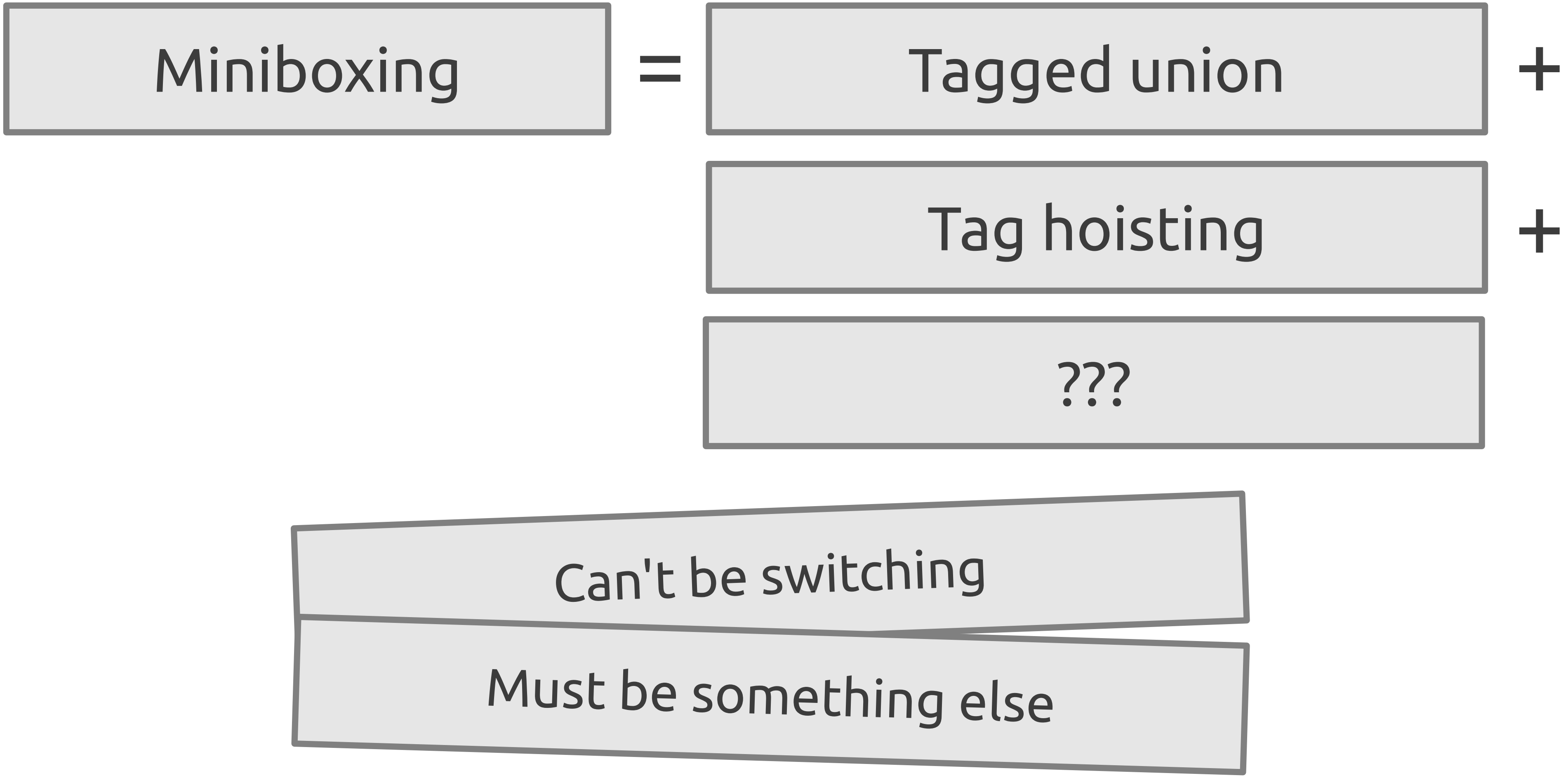
Miniboxing = Tagged union + Tag hoisting + ???

Can't be switching

Performance

needs one more ingredient



Miniboxing = Tagged union + Tag hoisting + ???

Can't be switching

Must be something else

Dispatching

- Dispatch object
  - Encodes array interactions

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  - Encodes array interactions

```
class Dispatcher[T] {
  def array_get(...): Long
  def array_set(...): Unit
}
```

Dispatching

- Dispatch object
  - Encodes array interactions

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class Dispatcher[T] {
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```
def identity_M(T_dispatcher: Dispatcher[T],
               t: Long): Long
```

Dispatching

- Dispatch object
  - Encodes array interactions

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class Dispatcher[T] {
  def array_get(...): Long
  def array_set(...): Unit
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```
def identity_M(T_dispatcher: Dispatcher[T],
                t: Long): Long
```

instead of tag

Dispatching

- Dispatch object
  - Encodes array interactions

```
object IntDispatcher extends Dispatcher[Int] {
  def array_get(...): Long = ...
  def array_set(...): Unit = ...
}
```

Dispatching

- Dispatch object
  - Encodes array interactions

```
object IntDispatcher extends Dispatcher[Int] {
  def array_get(...): Long = ...
  def array_set(...): Unit = ...
}
```

```
object LongDispatcher ...
object CharDispatcher ...
```

Dispatching

- Dispatch object
  - Encodes array interactions

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object IntDispatcher extends Dispatcher[Int] {
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  def array_set(...): Unit = ...
}
```

```
object LongDispatcher ...
object CharDispatcher ...
```

Passing a dispatcher = hoisted already

Dispatching

ArrayBuffer.reverse()

```
def reverse(): Unit {
  var index = 0
  while (index * 2 < length) {
    val opposite = length-index-1
    val tmp1: T = array(index)
    val tmp2: T = array(other)
    array(index) = tmp2
    array(opposite) = tmp1
    index += 1
  }
}
```

Dispatching

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T_dispatcher.array_get

Dispatching

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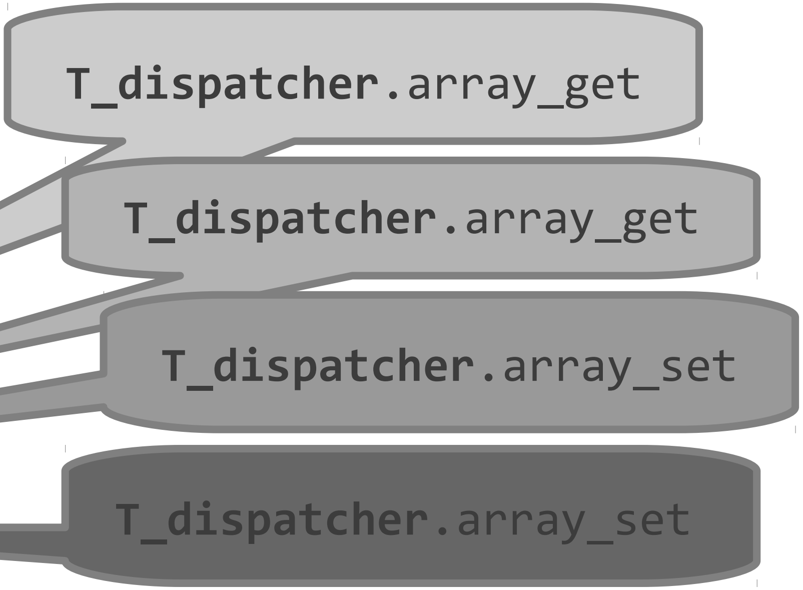


T_dispatcher.array_get

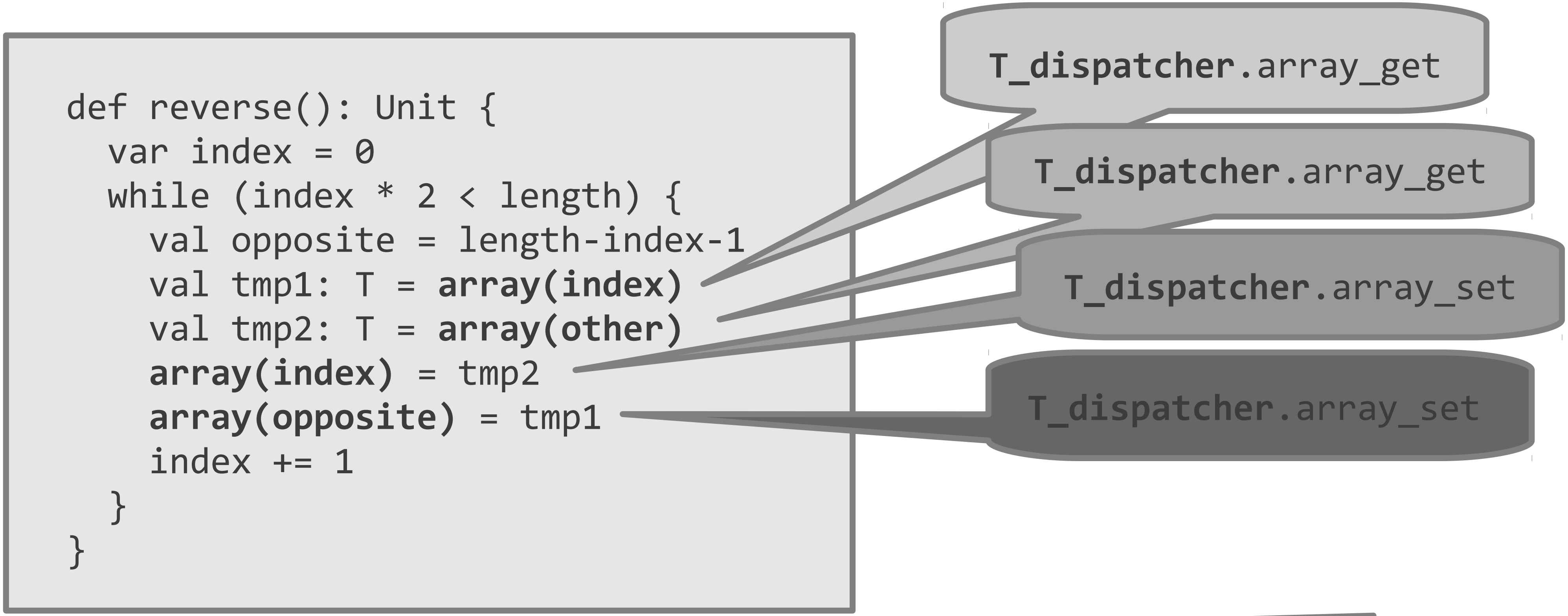
T_dispatcher.array_get

T_dispatcher.array_set

T_dispatcher.array_set

Dispatching

`ArrayBuffer.reverse()`



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  }
}
```

With inlining, we get good performance

Dispatching

```
ArrayBuffer.reverse()
```

```
T_dispatcher.array_get
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Dispatching

```
ArrayBuffer.reverse()
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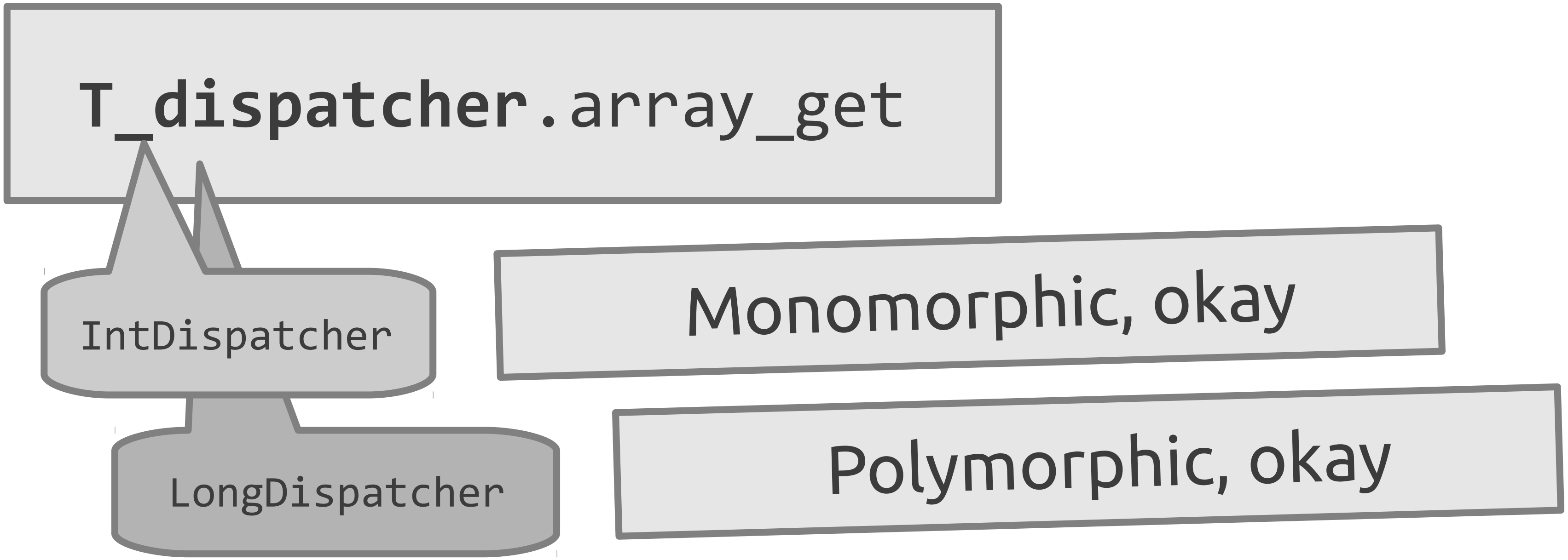
```
T_dispatcher.array_get
```

```
IntDispatcher
```

Monomorphic, okay

Dispatching

```
ArrayBuffer.reverse()
```



T_dispatcher.array_get

IntDispatcher

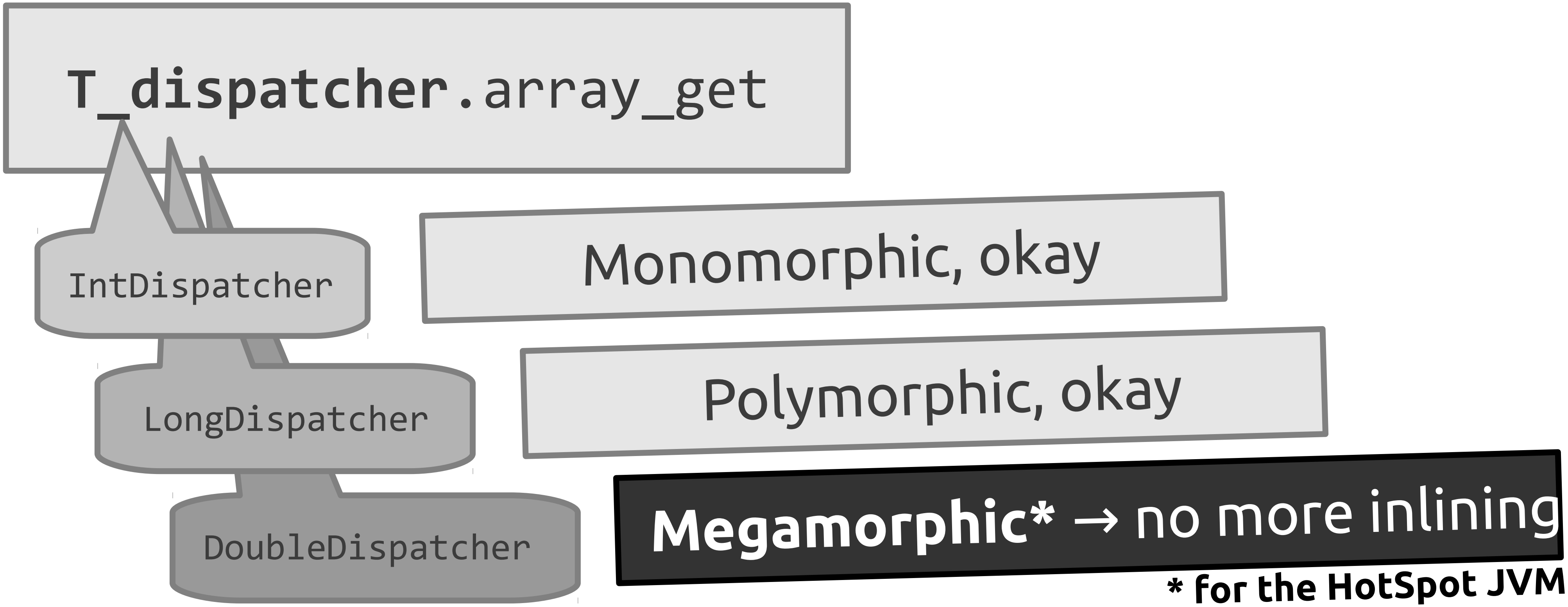
LongDispatcher

Monomorphic, okay

Polymorphic, okay

Dispatching

`ArrayBuffer.reverse()`



T_dispatcher.array_get

IntDispatcher

LongDispatcher

DoubleDispatcher

Monomorphic, okay

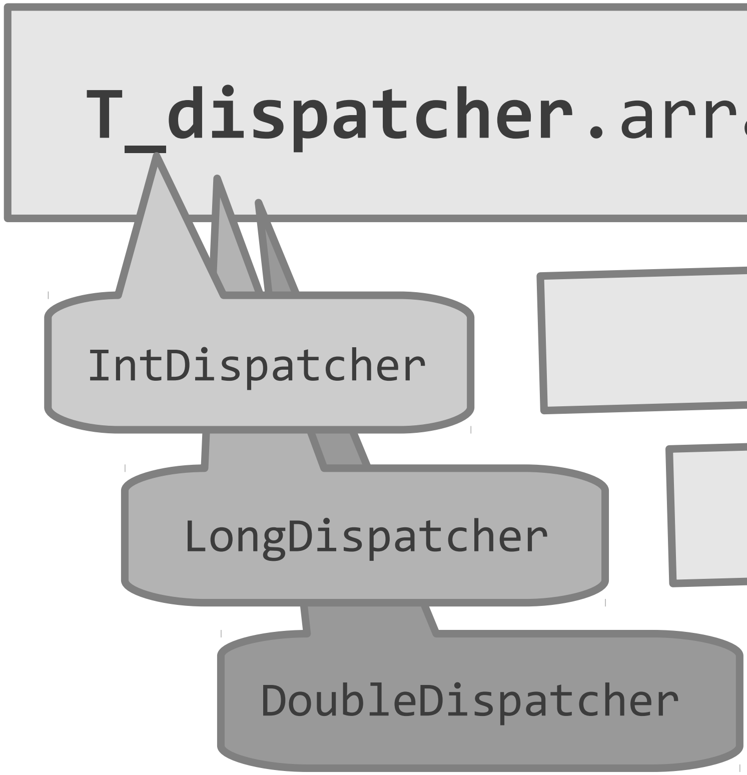
Polymorphic, okay

Megamorphic* → no more inlining

*** for the HotSpot JVM**

Dispatching

`ArrayBuffer.reverse()`



`T_dispatcher.array_get`

`IntDispatcher`

`LongDispatcher`

`DoubleDispatcher`

Monomorphic, okay

Polymorphic, okay

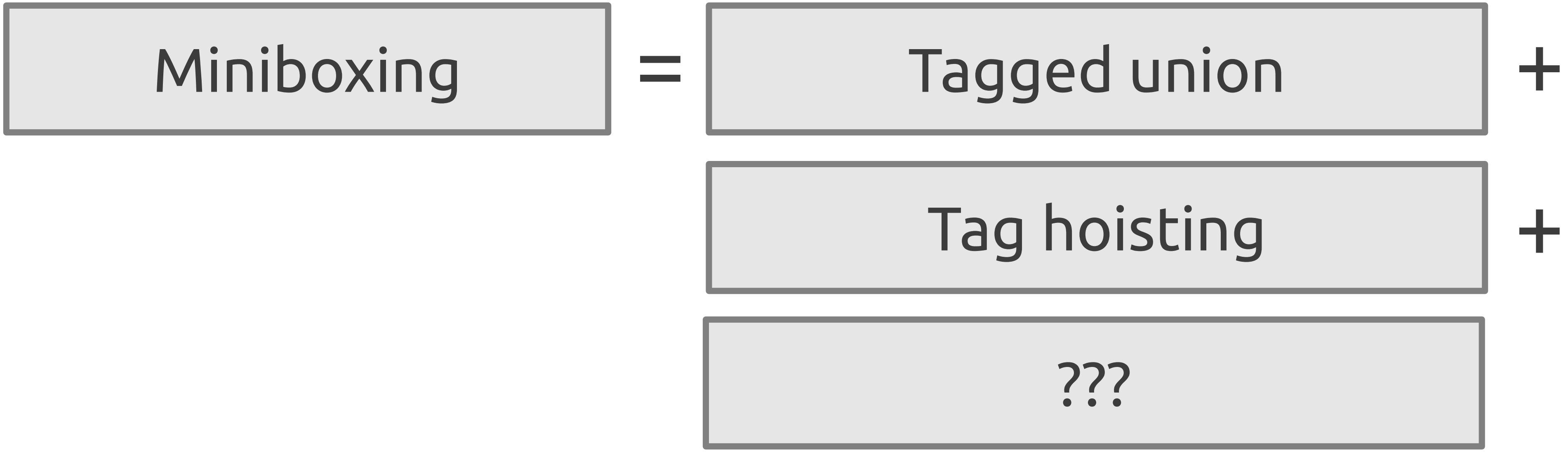
Megamorphic* → no more inlining

*** for the HotSpot JVM**

No more inlining → bad performance

Performance

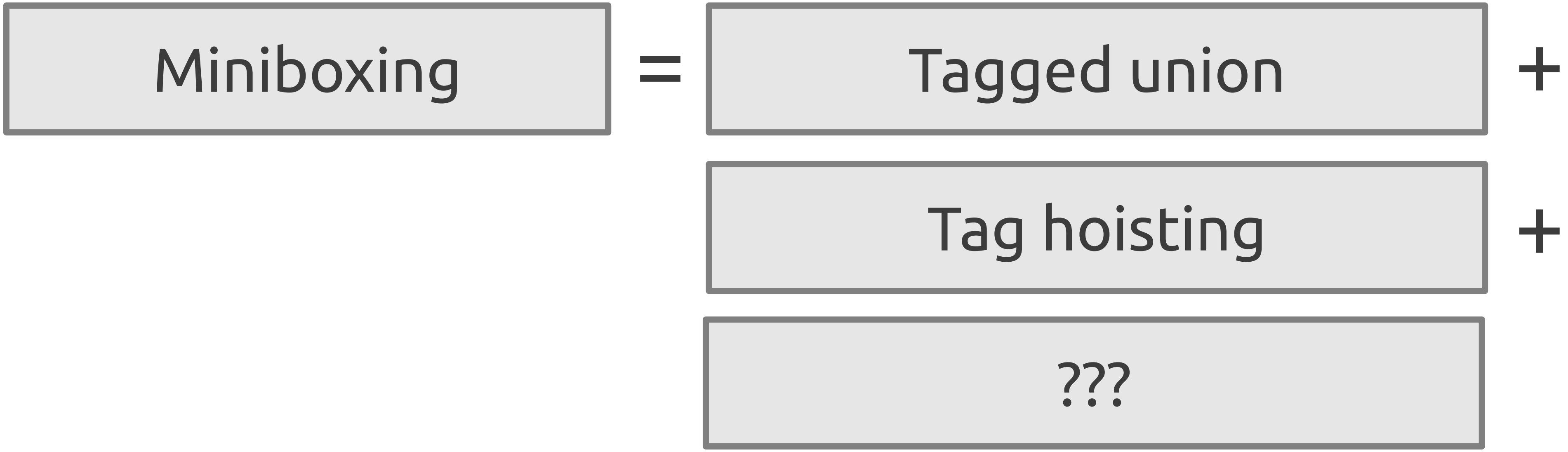
needs one more ingredient



Miniboxing = Tagged union + Tag hoisting + ???

Performance

needs one more ingredient



Miniboxing = Tagged union + Tag hoisting + ???

Object oriented dispatch isn't that

The secret ingredient

The secret ingredient

- **Switch-based** dispatching

```
T_tag match {
  case INT => ...
  ...
}
```

The secret ingredient

- **Switch-based** dispatching
- When instantiating the class
  - **T_tag** is **known**

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The secret ingredient

- **Switch-based** dispatching
- When instantiating the class
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  - **T_tag** is a **constant**

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The secret ingredient

- **Switch-based** dispatching
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Encode T_tag in the class name?

The secret ingredient

- **Switch-based** dispatching
- When instantiating the class
  - **T_tag** is **known**
  - **T_tag** is a **constant**

```
T_tag match {
  case INT => ...
  ...
}
```

Encode T_tag in the class name?

Staticly? Code explosion!

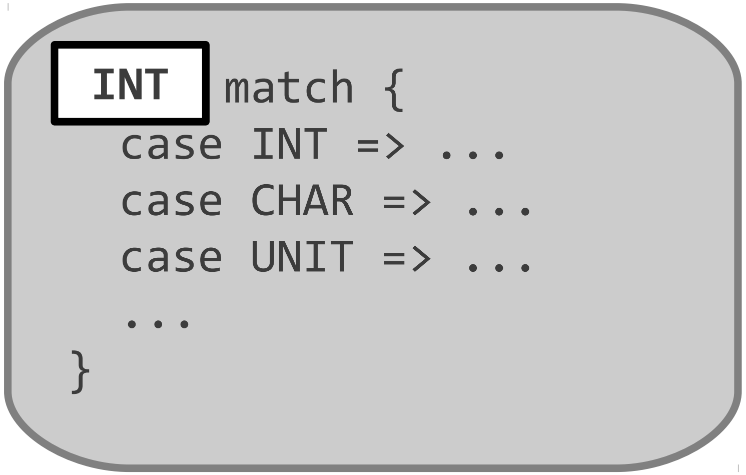
Load-time specialization

- Load-time transformation

```
T_tag match {
  case INT => ...
  case CHAR => ...
  case UNIT => ...
  ...
}
```

Load-time specialization

- Load-time transformation
  - set **T_tag** statically



```
INT match {
  case INT => ...
  case CHAR => ...
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  ...
}
```
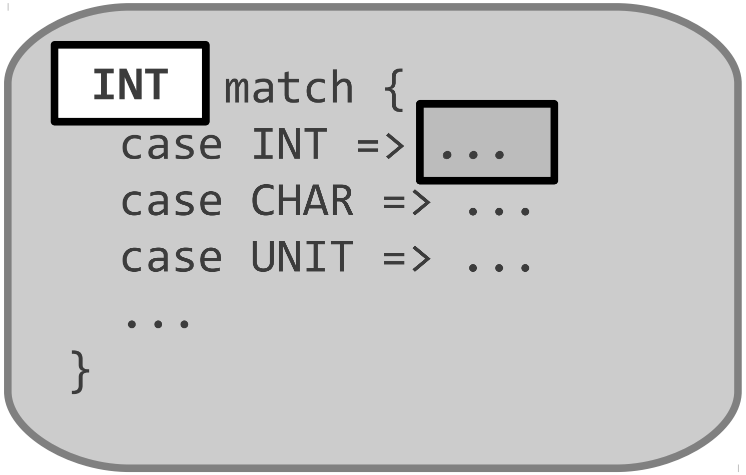

Load-time specialization

- Load-time transformation
  - set **`T_tag`** statically
  - perform **constant folding**



```
INT  match {
  case INT =>  ...
  case CHAR =>  ...
  case UNIT =>  ...
  ...
}
```

Load-time specialization

- Load-time transformation
  - set **`T_tag`** statically
  - perform **constant folding**
  - perform **dead code elimination**

```
...
```

Load-time specialization

- Load-time transformation
  - set `T_tag` statically
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...

Only the useful code

Load-time specialization

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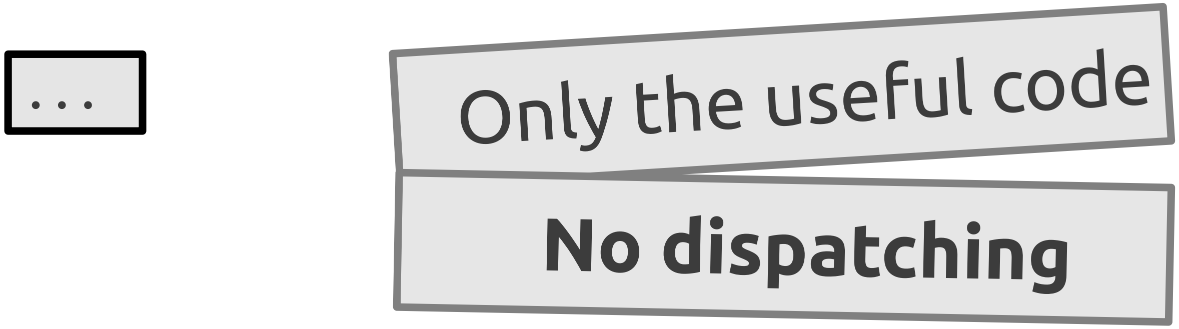


...

Only the useful code

No dispatching

Load-time specialization

- Load-time transformation
  - set `T_tag` statically
  - perform **constant folding**
  - perform **dead code elimination**

...

Only the useful code

No dispatching

Is this the secret ingredient? **Yes!**

Performance

needs one more ingredient

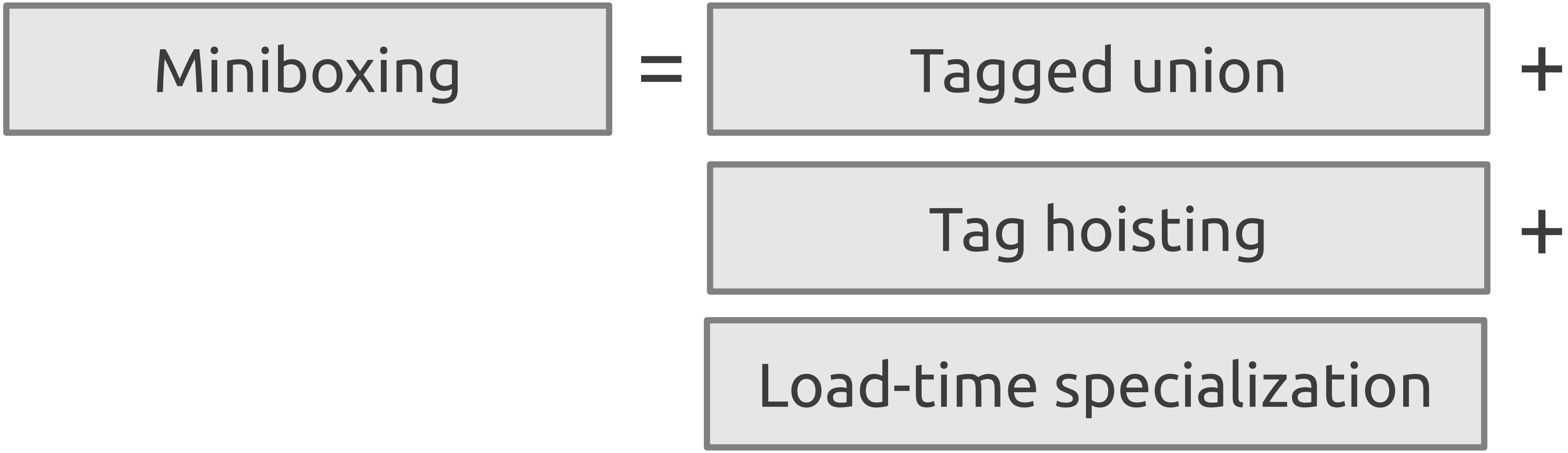
Miniboxing = Tagged union +

Tag hoisting +

Load-time specialization

Performance

needs one more ingredient



Miniboxing = Tagged union + Tag hoisting + Load-time specialization

Attaching tags to code enables load-time specialization

Generics

Specialization

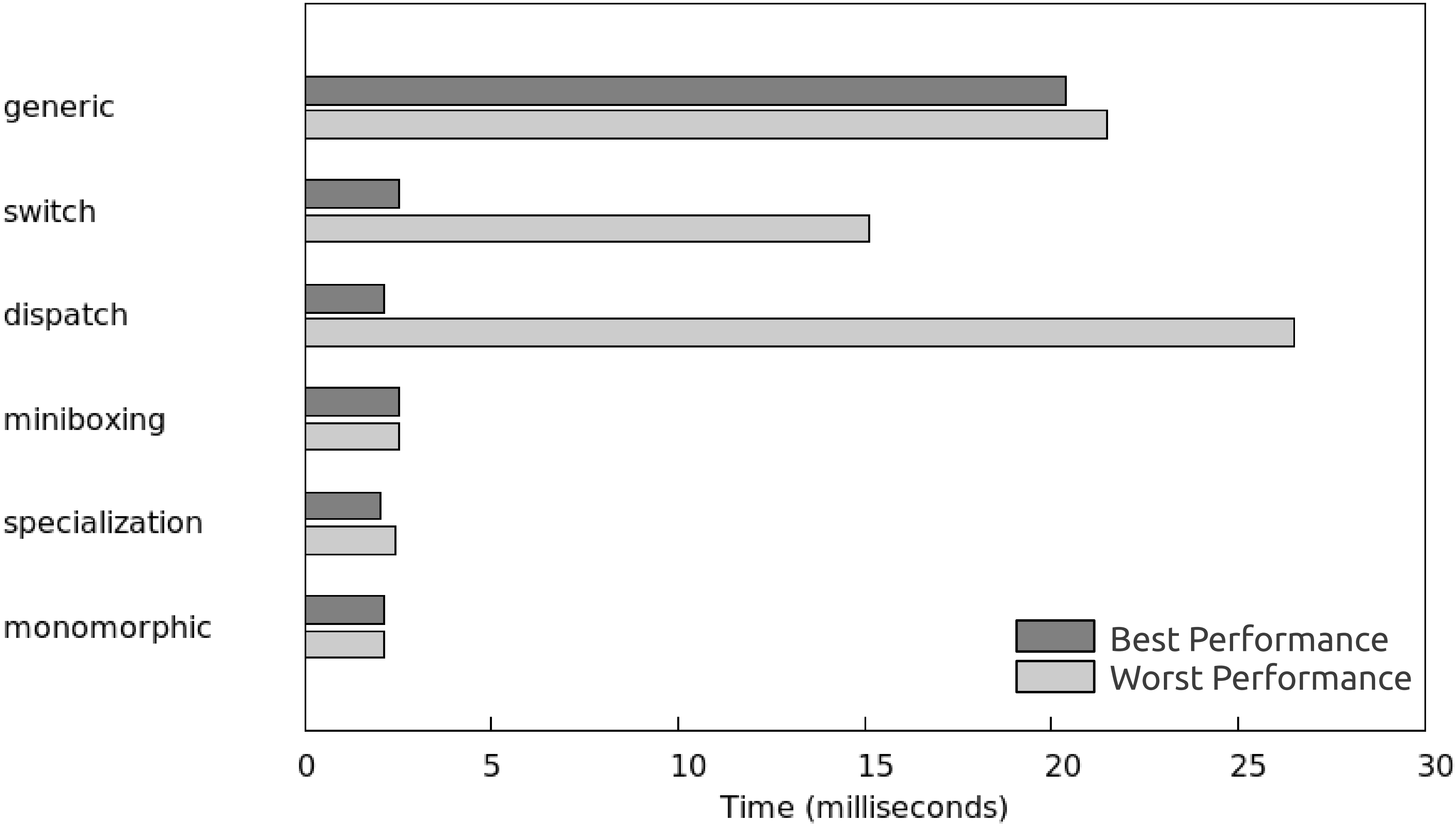
Miniboxing

Performance

Evaluation

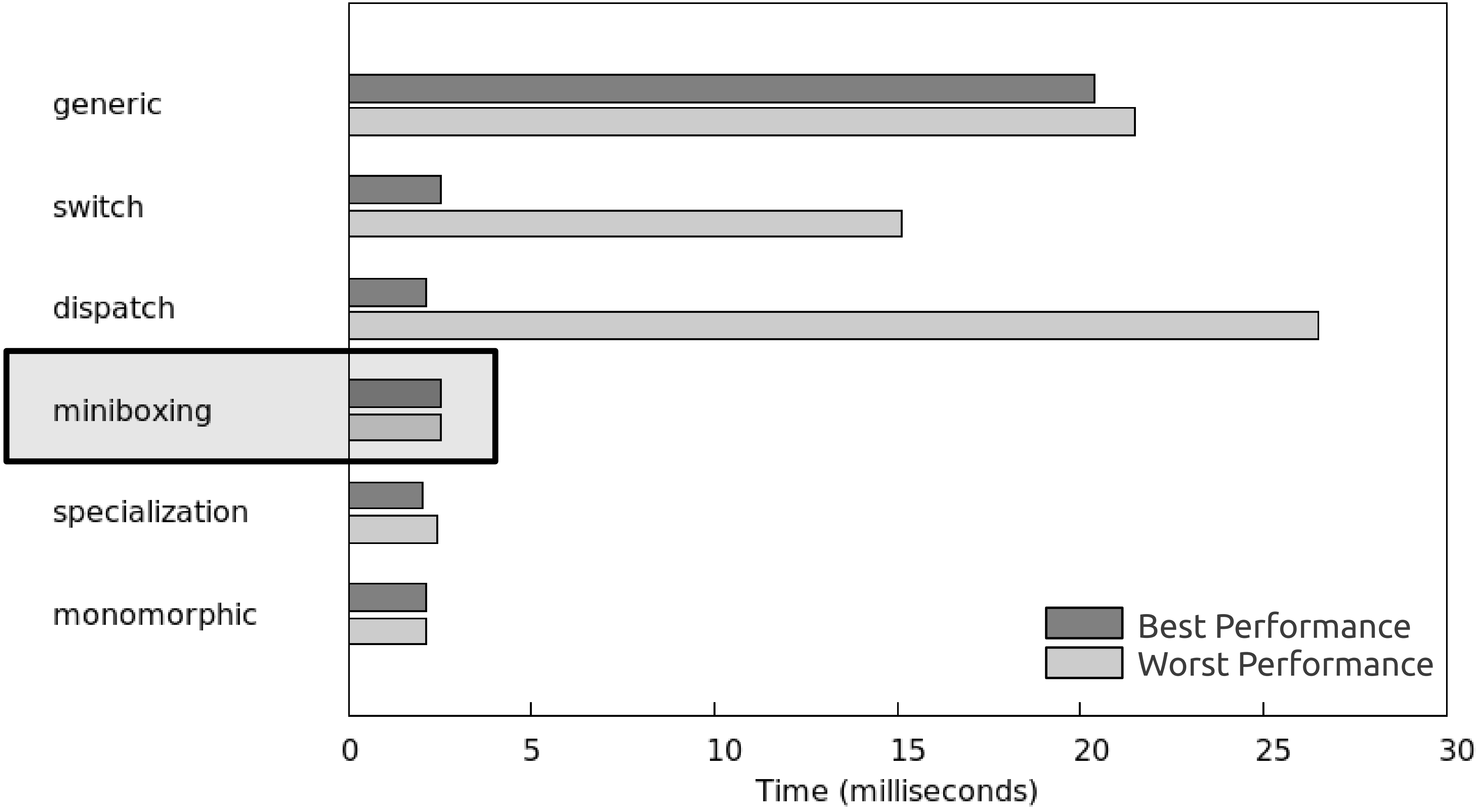
WE ARE HERE

Evaluation - Performance



(less is better)

Evaluation - Performance



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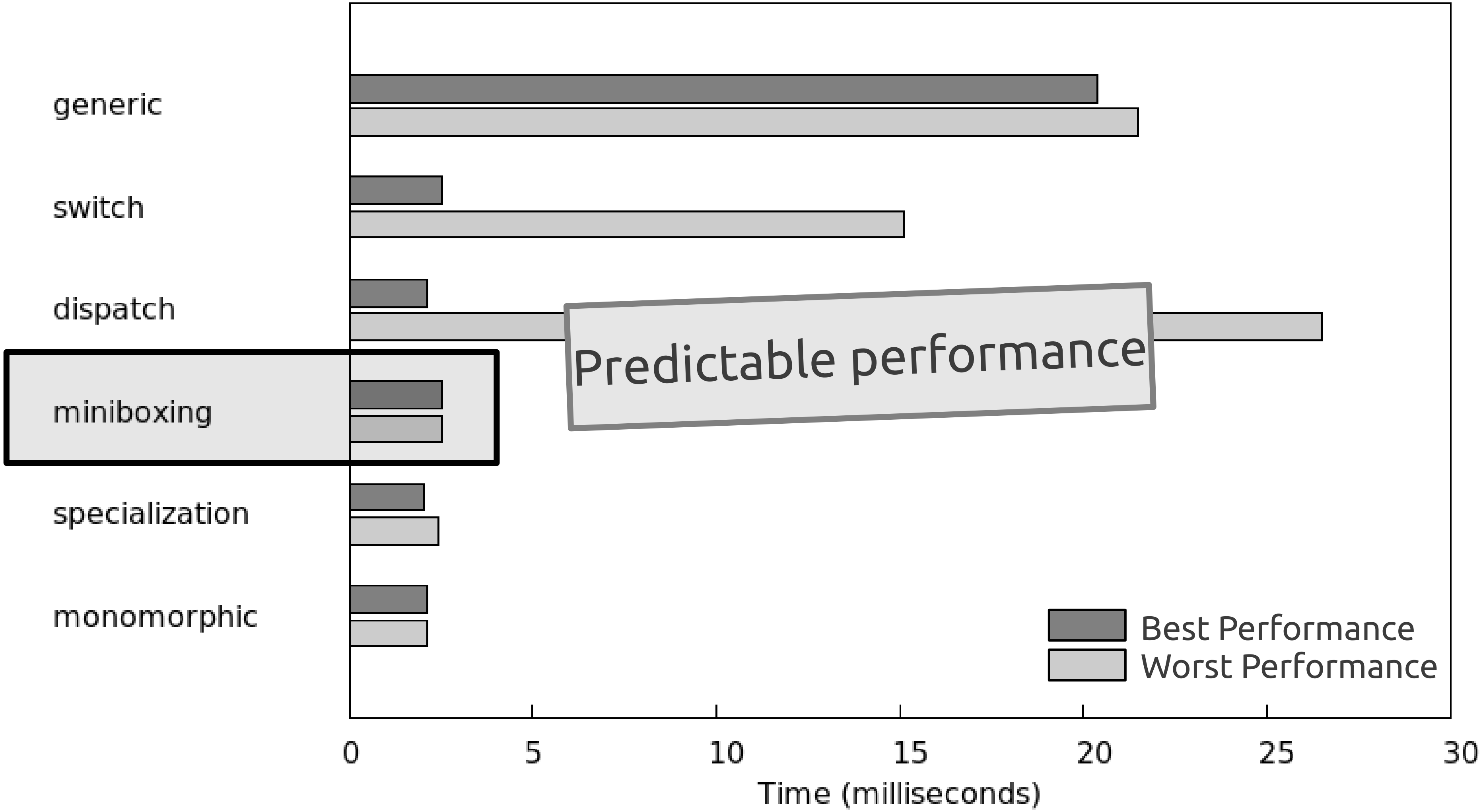
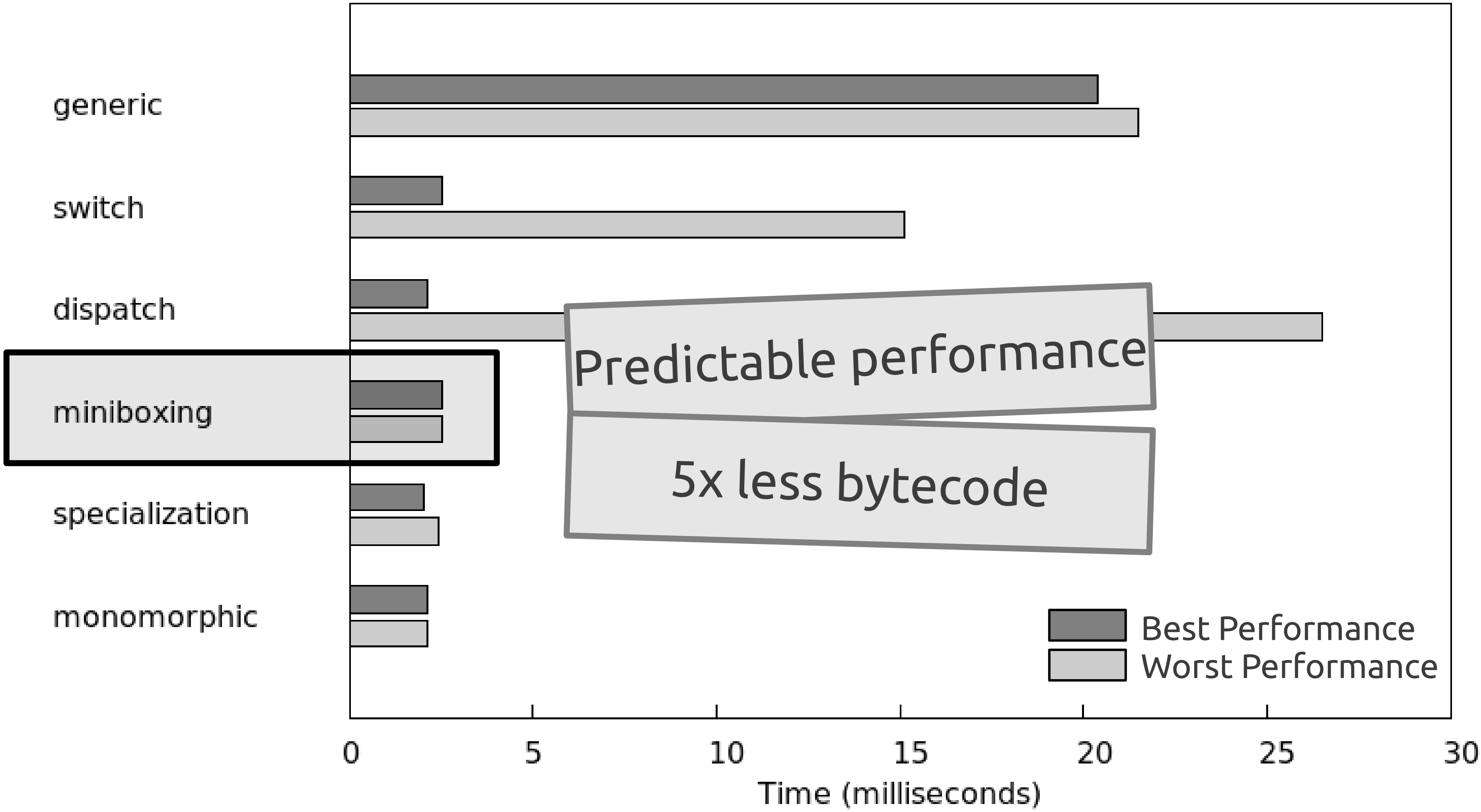
Evaluation - Performance



Predictable performance

(less is better)

Evaluation - Performance

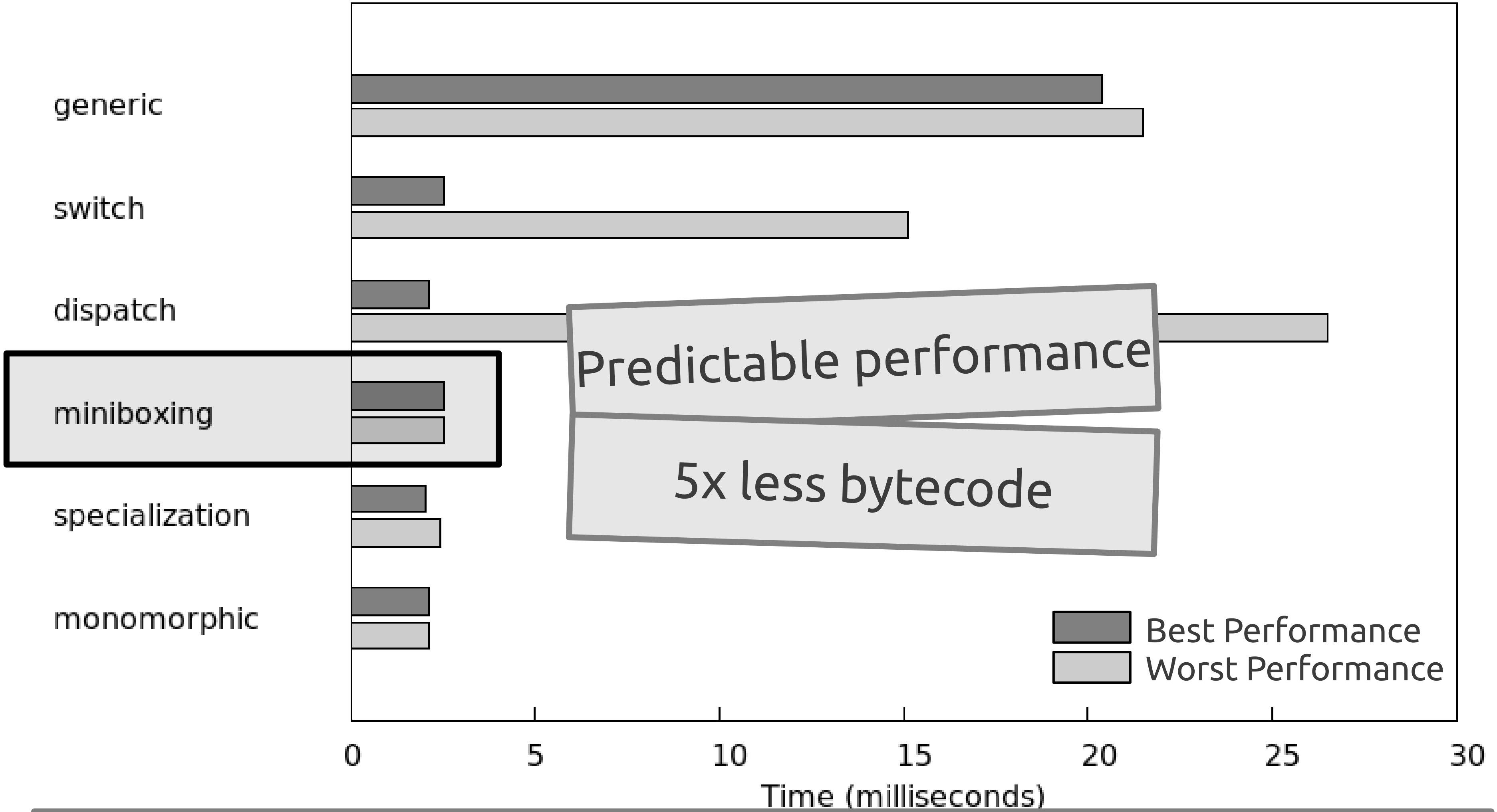


Predictable performance

5x less bytecode

(less is better)

Evaluation - Performance



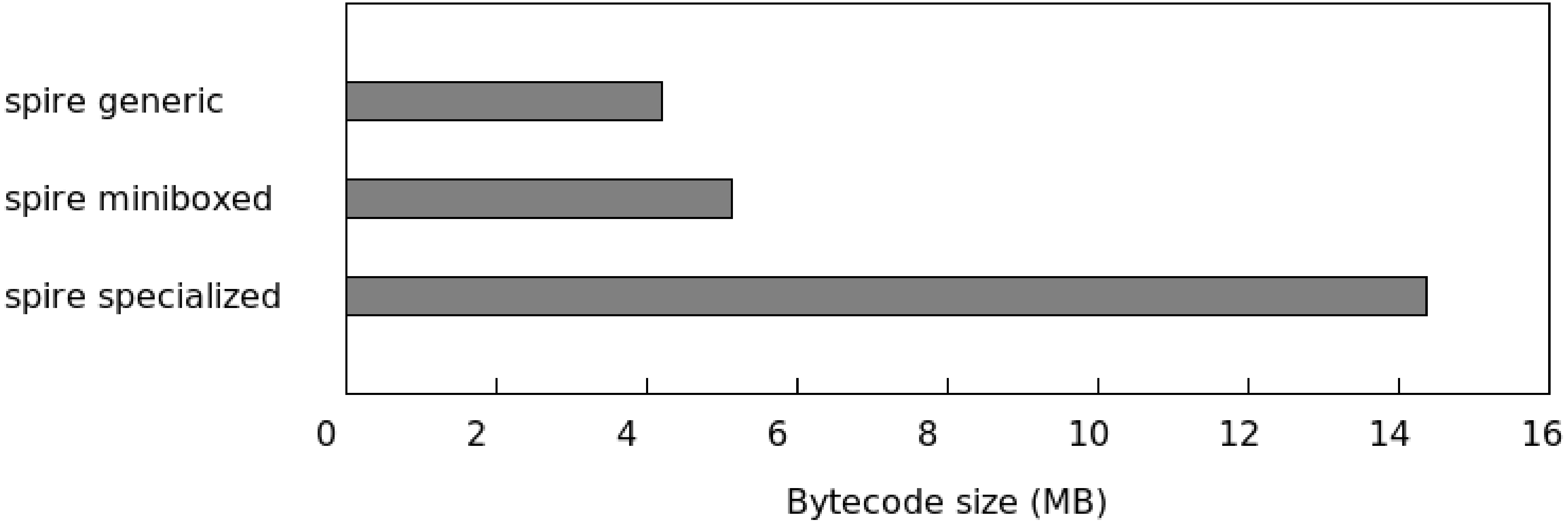
Predictable performance

5x less bytecode

Similar results on other benchmarks

Evaluation - Code size

Spire – numeric abstractions library (12KLOC)



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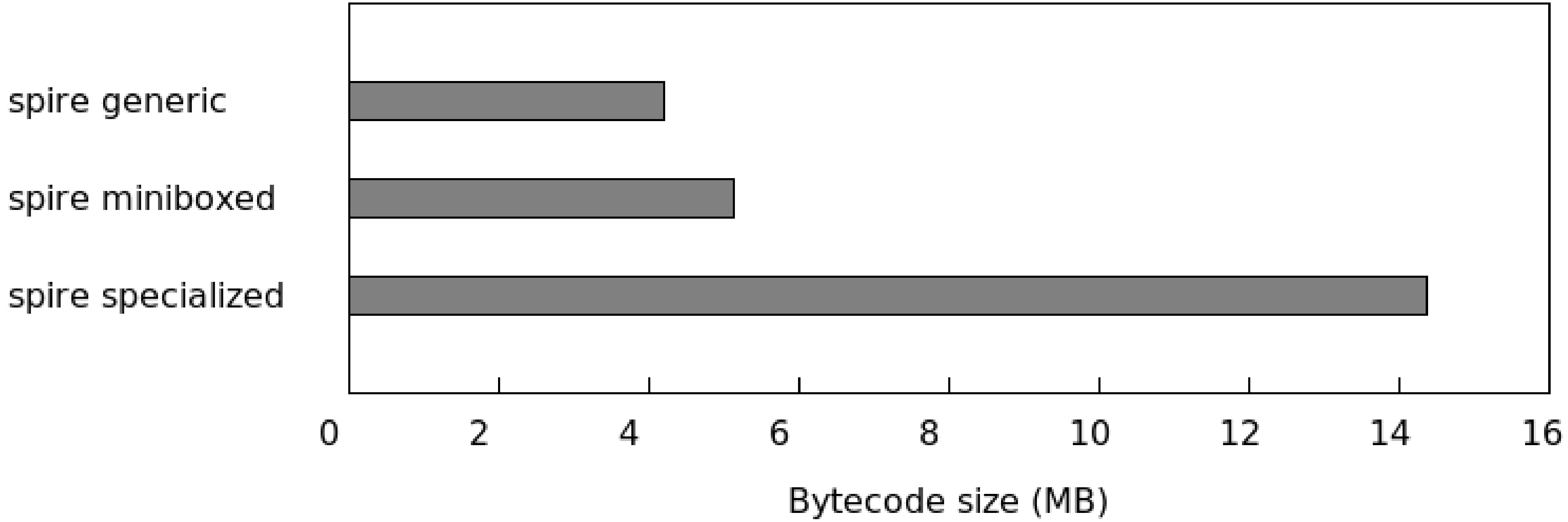
Evaluation - Code size

Spire – numeric abstractions library (12KLOC)



(less is better)

2.8x bytecode reduction (4.7x for `Vector` in std. lib)

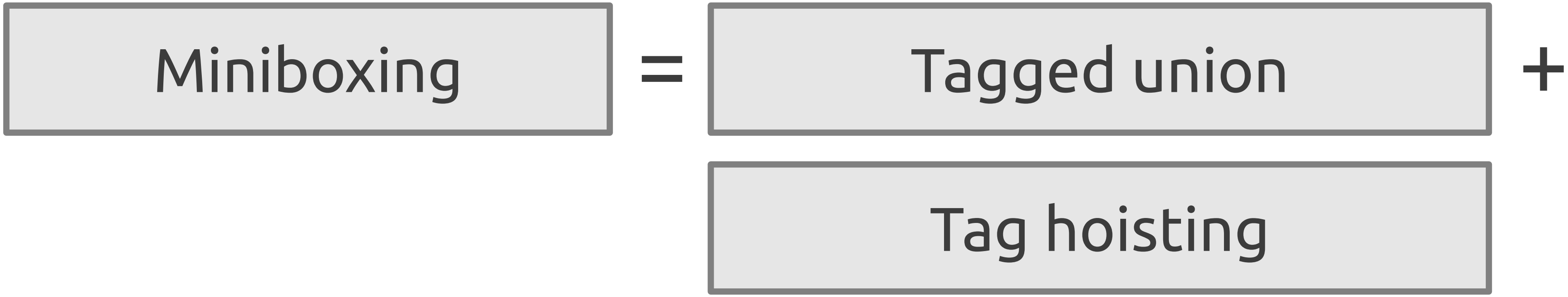
Contributions

Miniboxing

Contributions

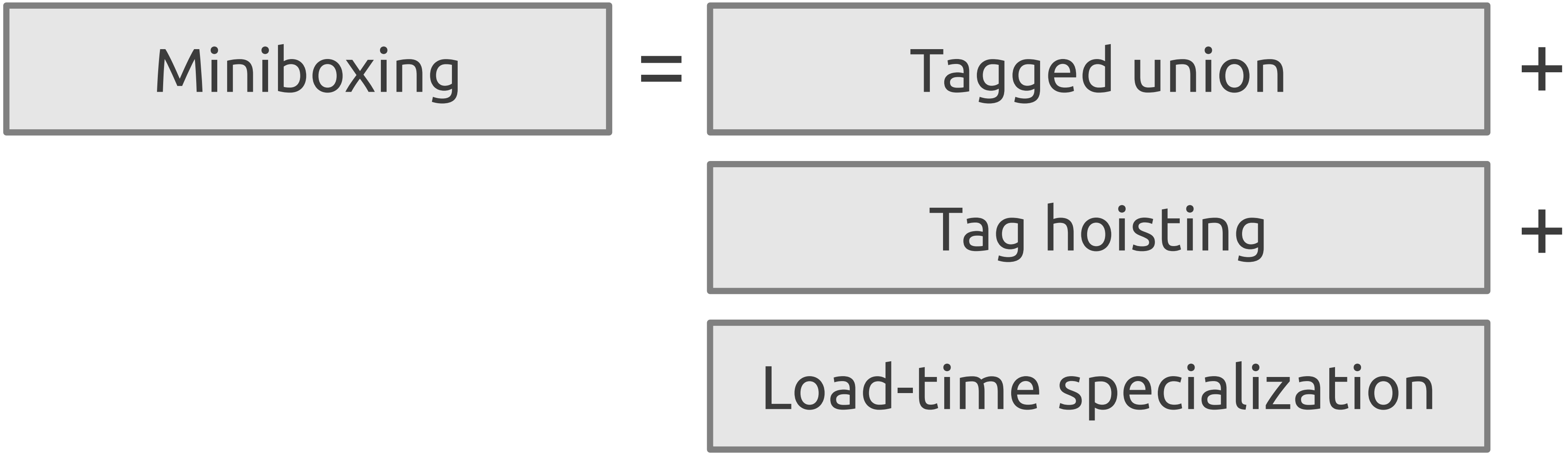
Miniboxing = Tagged union

Contributions



Miniboxing = Tagged union + Tag hoisting

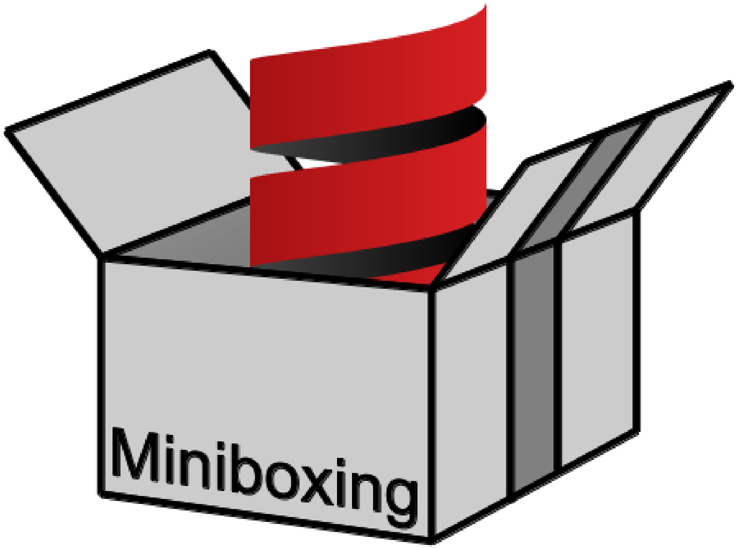
Contributions



Miniboxing = Tagged union + Tag hoisting + Load-time specialization

Conclusions

OOPSLA * Artifact * AEC * Evaluated *
Consistent * Complete * Well Documented * Easy to Reuse *



- improves performance
- reduces bytecode size

visit scala-miniboxing.org!