Size Optimizations for Java Programs

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Our Goal

Reduce the memory consumption of object-oriented programs

By

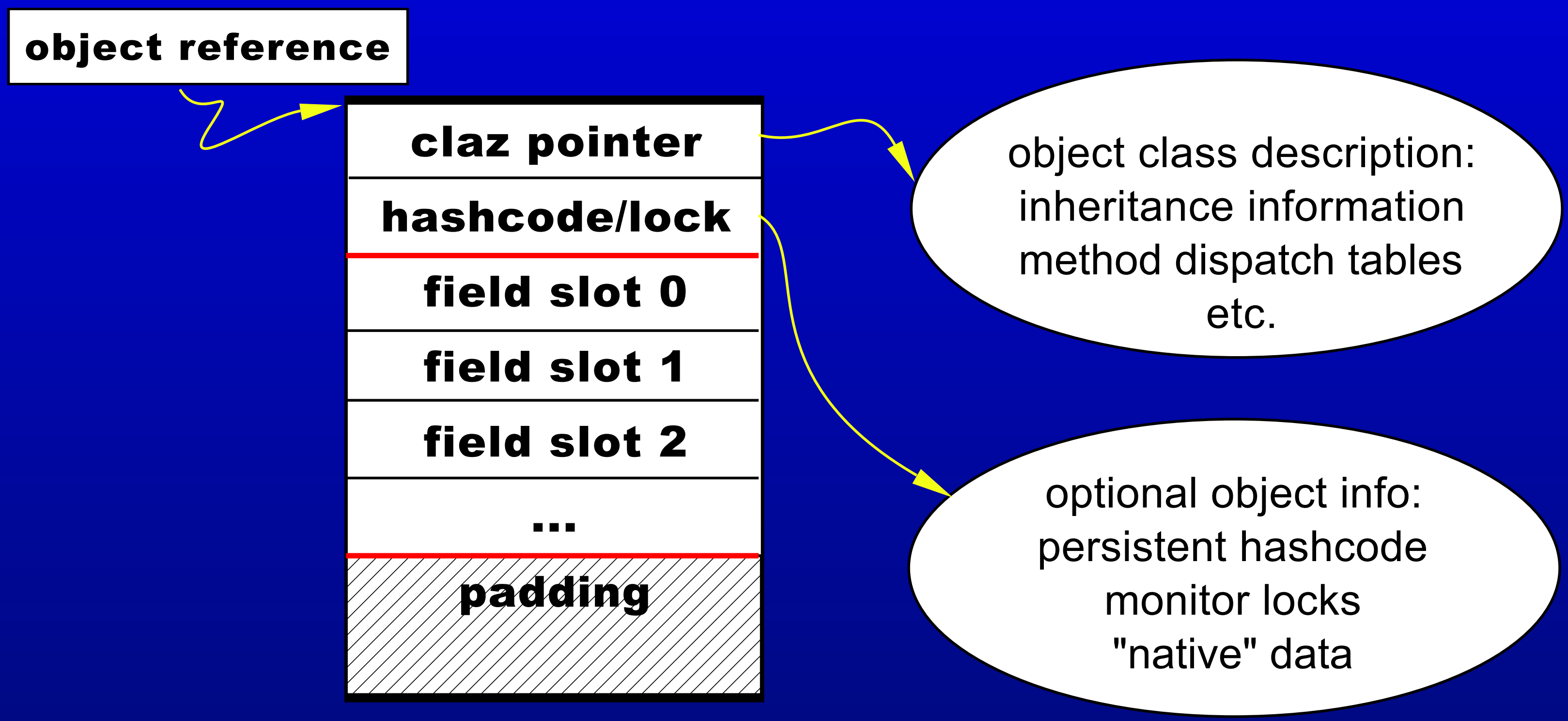
Using program analysis to identify opportunities to reduce the space required to store objects,

Then

Applying transformations to reduce the memory consumption of the program.

Structure of a Java Object

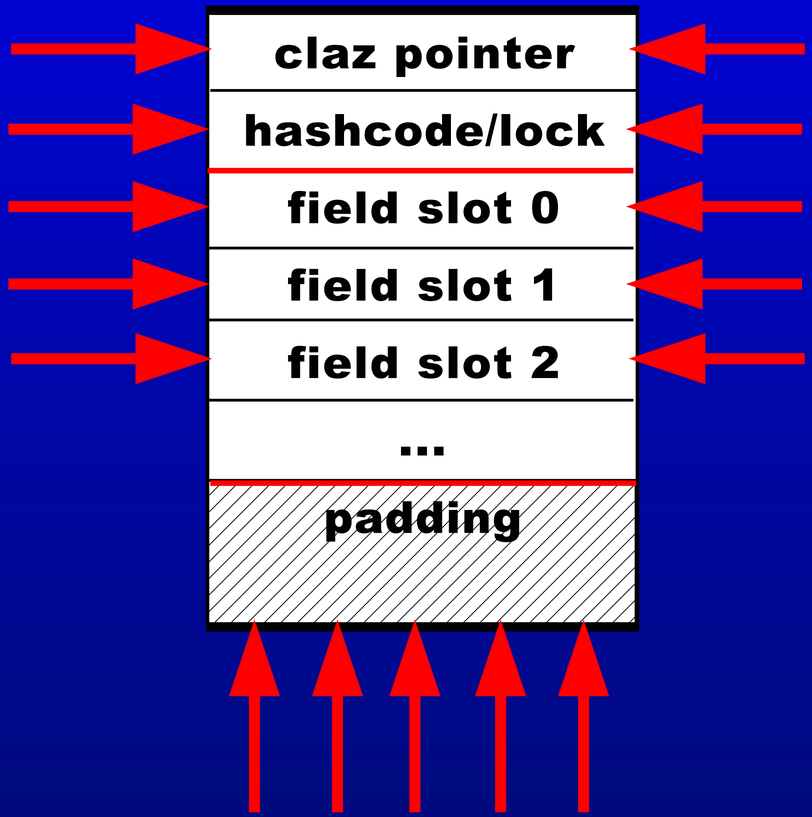
- Typical of many O-O languages.



Strategy

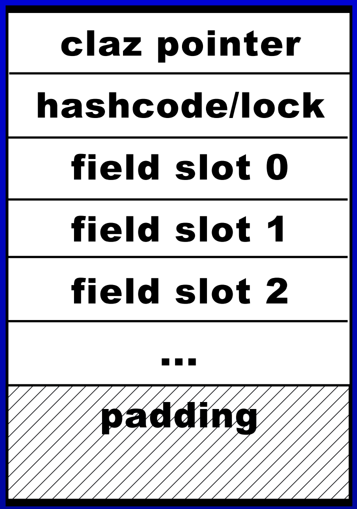
Strategy

Push hard on all the bits.



How to compress objects

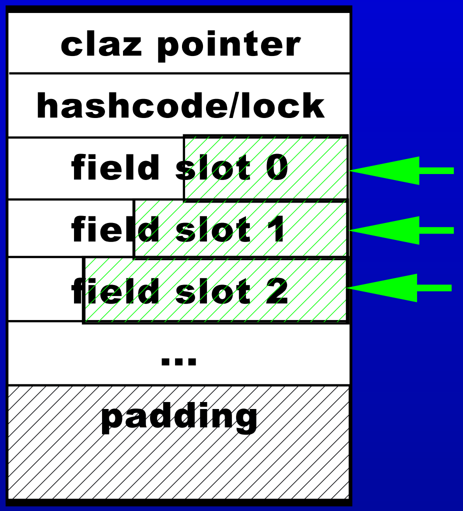
Three broad techniques:



How to compress objects

Three broad techniques:

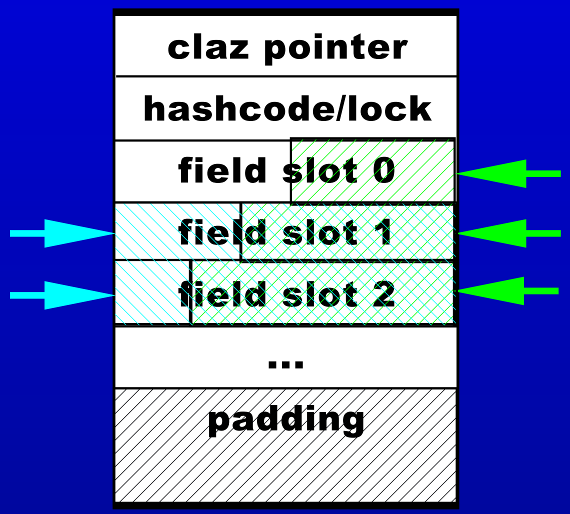
- Field compression



How to compress objects

Three broad techniques:

- Field compression
- Mostly-constant field elimination



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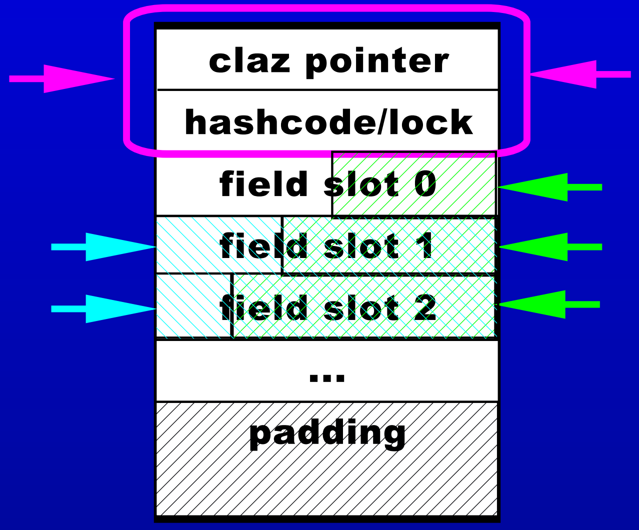
- Header optimizations



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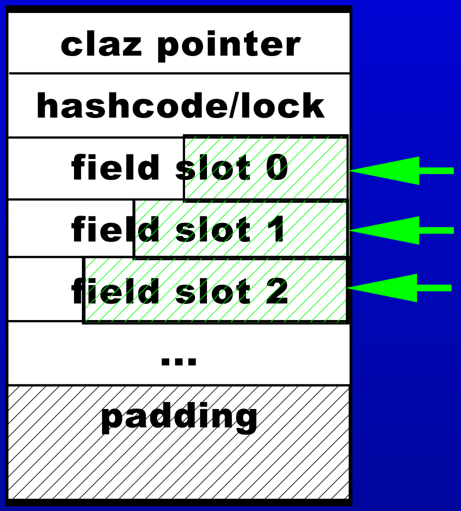

Field Compression

Reduce the space taken up by an object's fields.

```
class Car {
    int color;
    ...
}
```

Field Compression

Reduce the space taken up by an object's fields.

- Sparse Predicated Typed Constant analysis to discover unread/unused/constant fields.

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BLACK=0

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Reduce the space taken up by an object's fields.

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- Bitwidth analysis to discover tight upper bounds on field size.

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BLACK=0 RED=1 BLUE=2

Field Compression

Reduce the space taken up by an object's fields.

- Sparse Predicated Typed Constant analysis to discover unread/unused/constant fields.
- Bitwidth analysis to discover tight upper bounds on field size.
- Field packing into bytes or bits.

```
class Car {
    int color;
    ...
}
```

BLACK=0 RED=1 BLUE=2

How are these analyses performed?

Intraprocedural Analysis

```
int foo() {
    if (...)
        i=1;
    else
        i=2;
    if (i>0)
        ⋮
}
```

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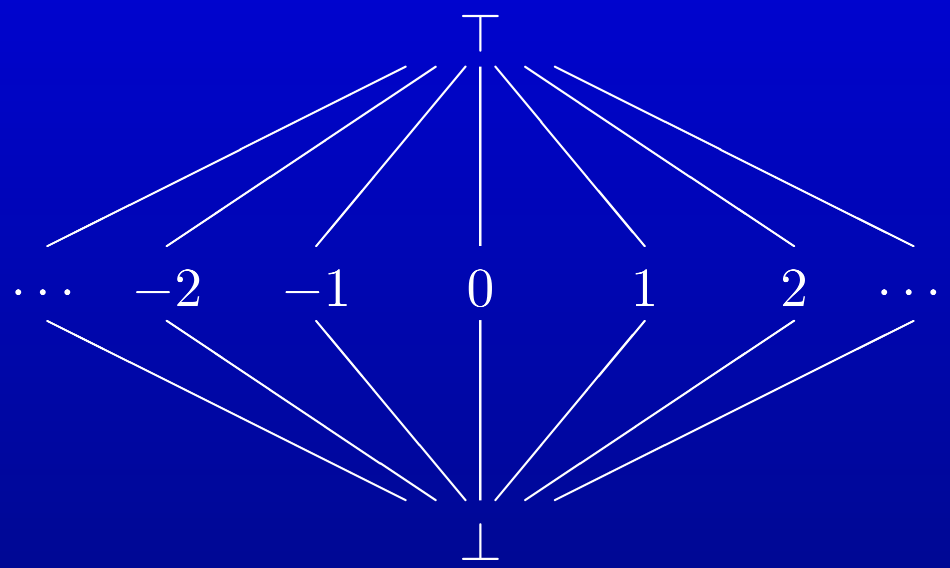

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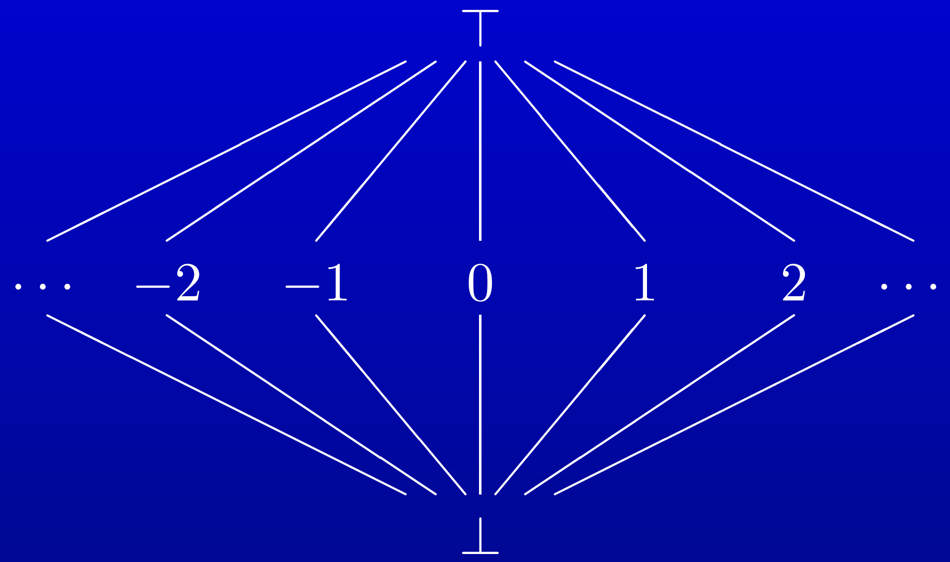

$\mathtt{i} = \bot$

Intraprocedural Analysis

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        i=1;
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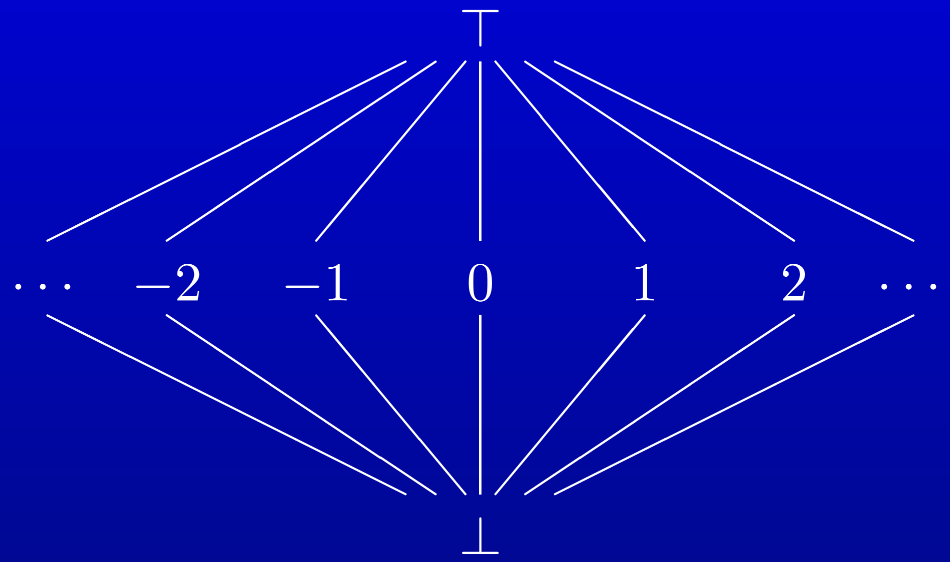

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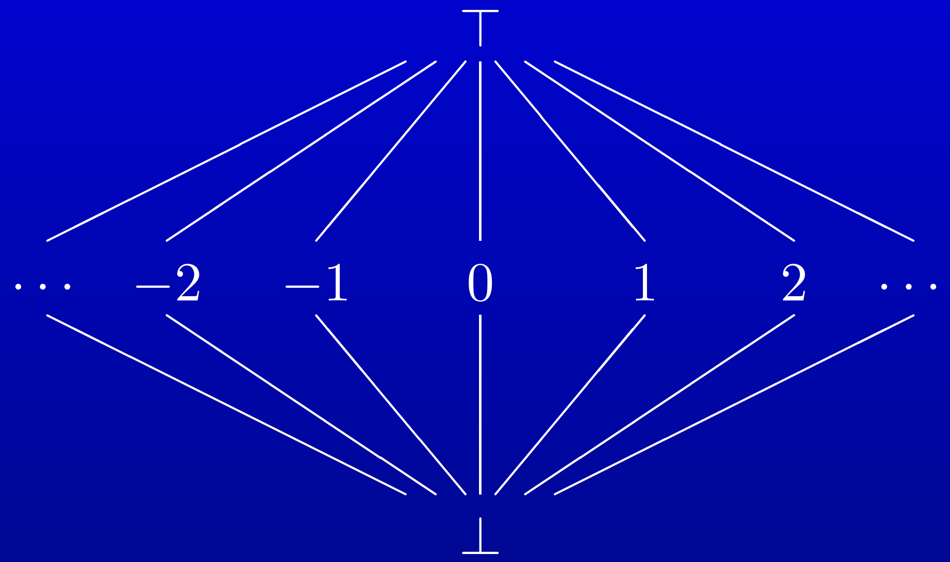

$$\mathtt{i} = \bot \sqcap 1$$

Intraprocedural Analysis

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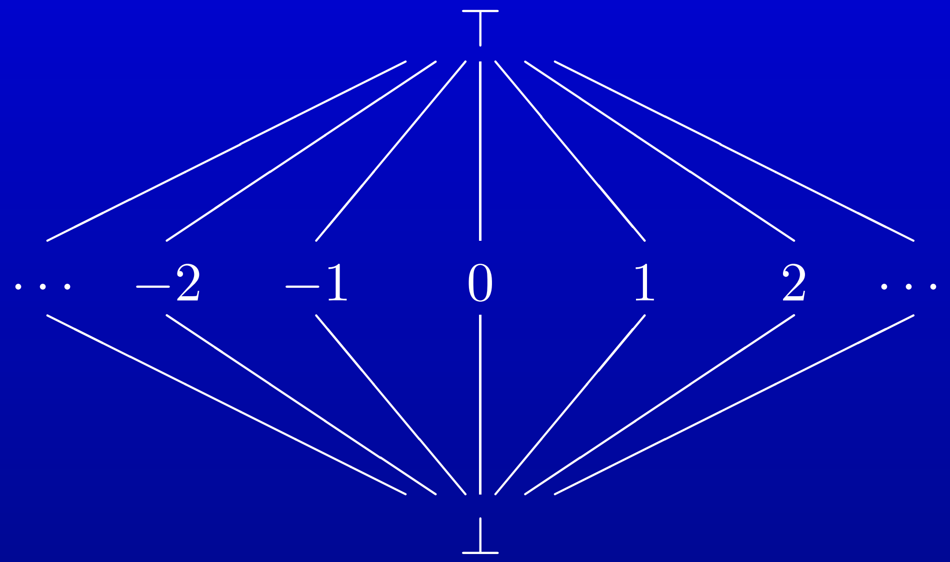
int foo() {
    if (...)
        i=1;
    else
        i=2;
    if (i>0)
        ⋮
}
```



$\mathbf{i} = 1$

[Because $\bot \sqsubseteq 1$ and $1 \sqsubseteq 1$]

Intraprocedural Analysis

```
int foo() {
    if (...)
        i=1;
    else
        i=2;
    if (i>0)
        ⋮
}
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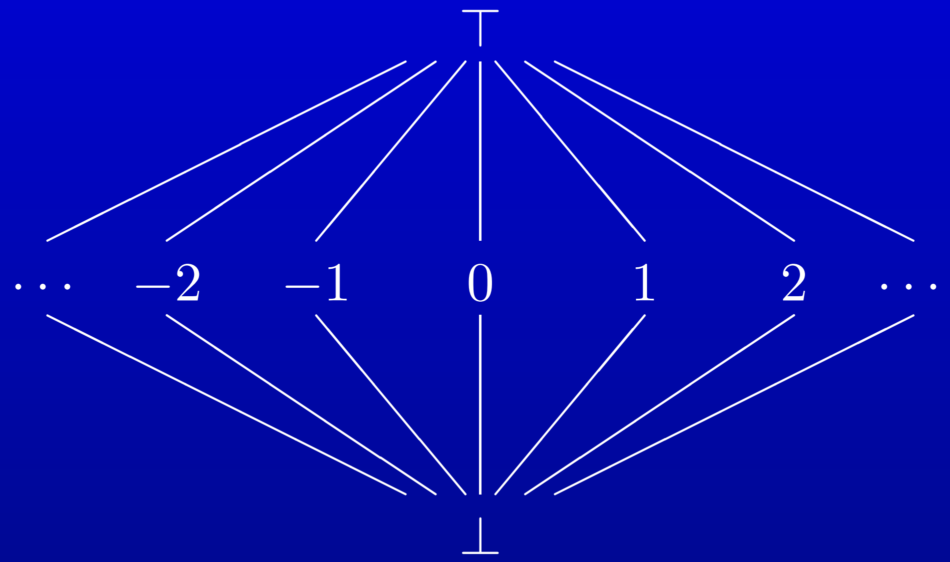

$\boxed{\mathtt{i} = 1}$

Intraprocedural Analysis

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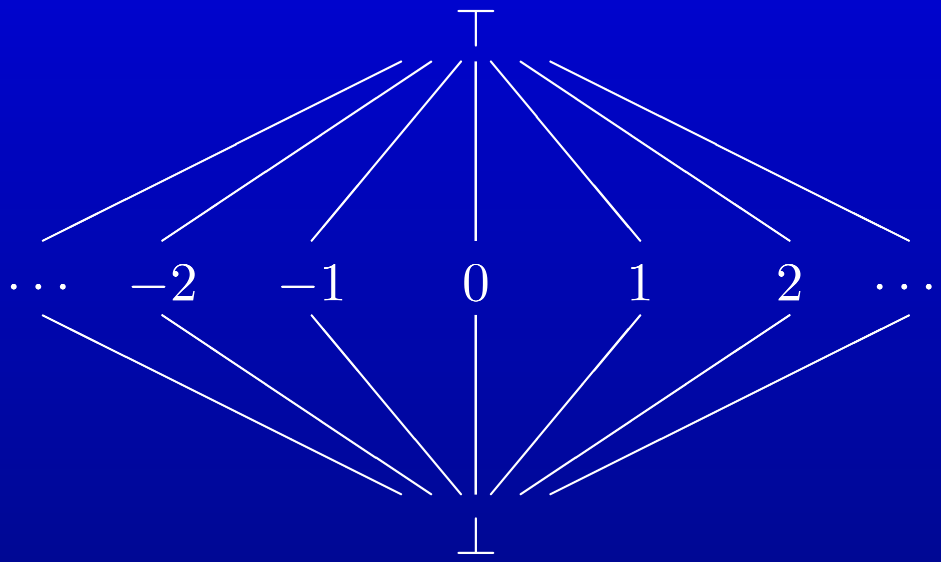

$$\mathtt{i} = 1 \sqcap 2$$

Intraprocedural Analysis

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int foo() {
    if (...)
        i=1;
    else
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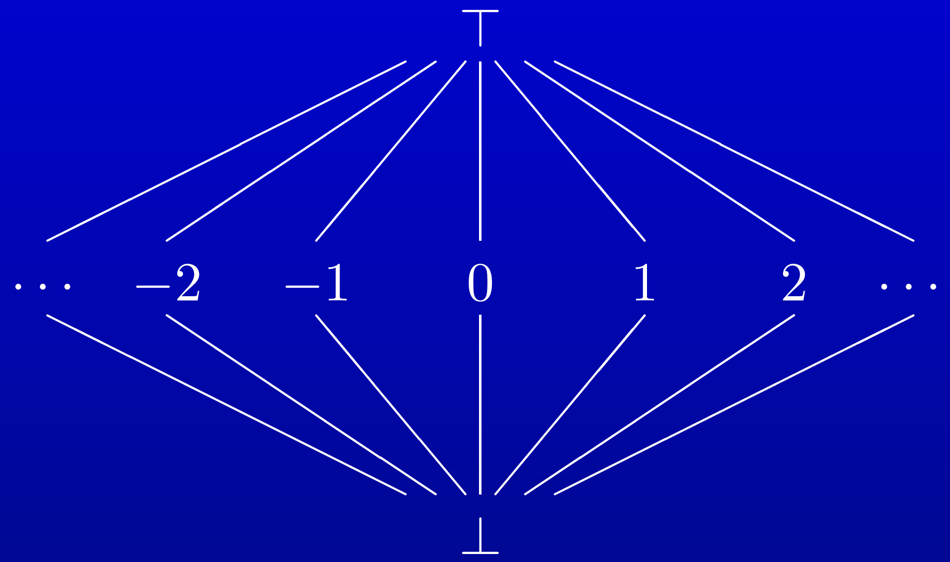
        ⋮
}
```



$$\mathbf{i} = 1 \sqcap 2 = \top$$

[Because $1 \sqsubseteq \top$ and $2 \sqsubseteq \top$]

Intraprocedural Analysis

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int foo() {
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        i=1;
    else
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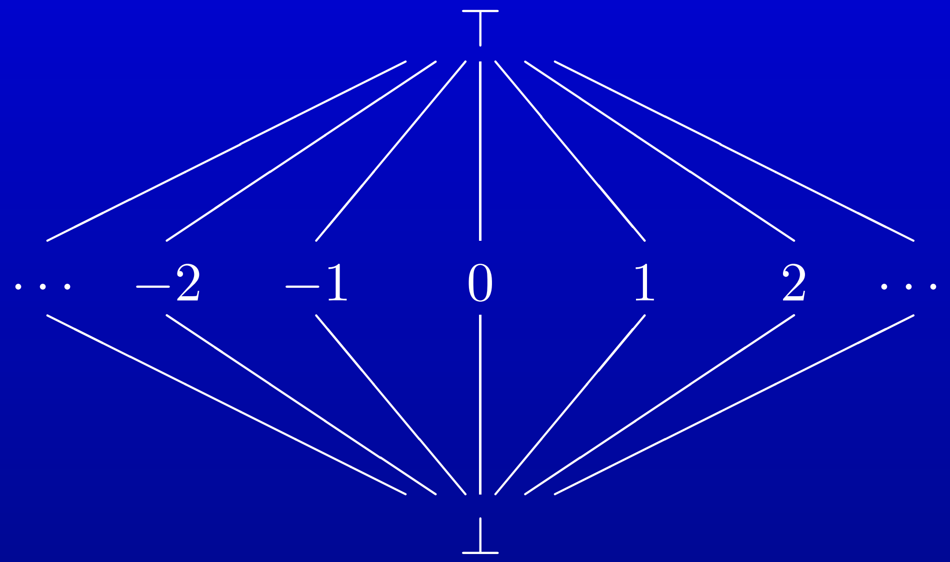
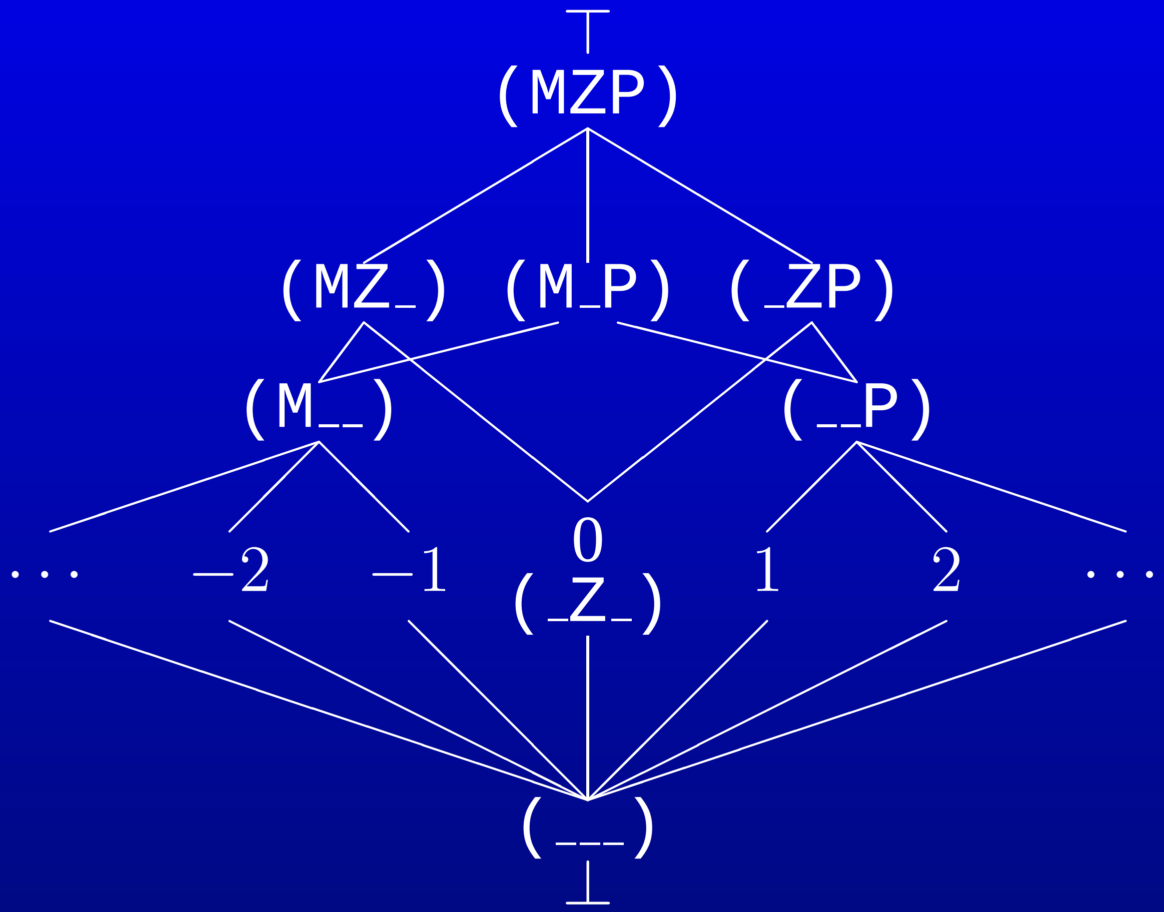


$$\mathbf{i} = 1 \sqcap 2 = \top$$

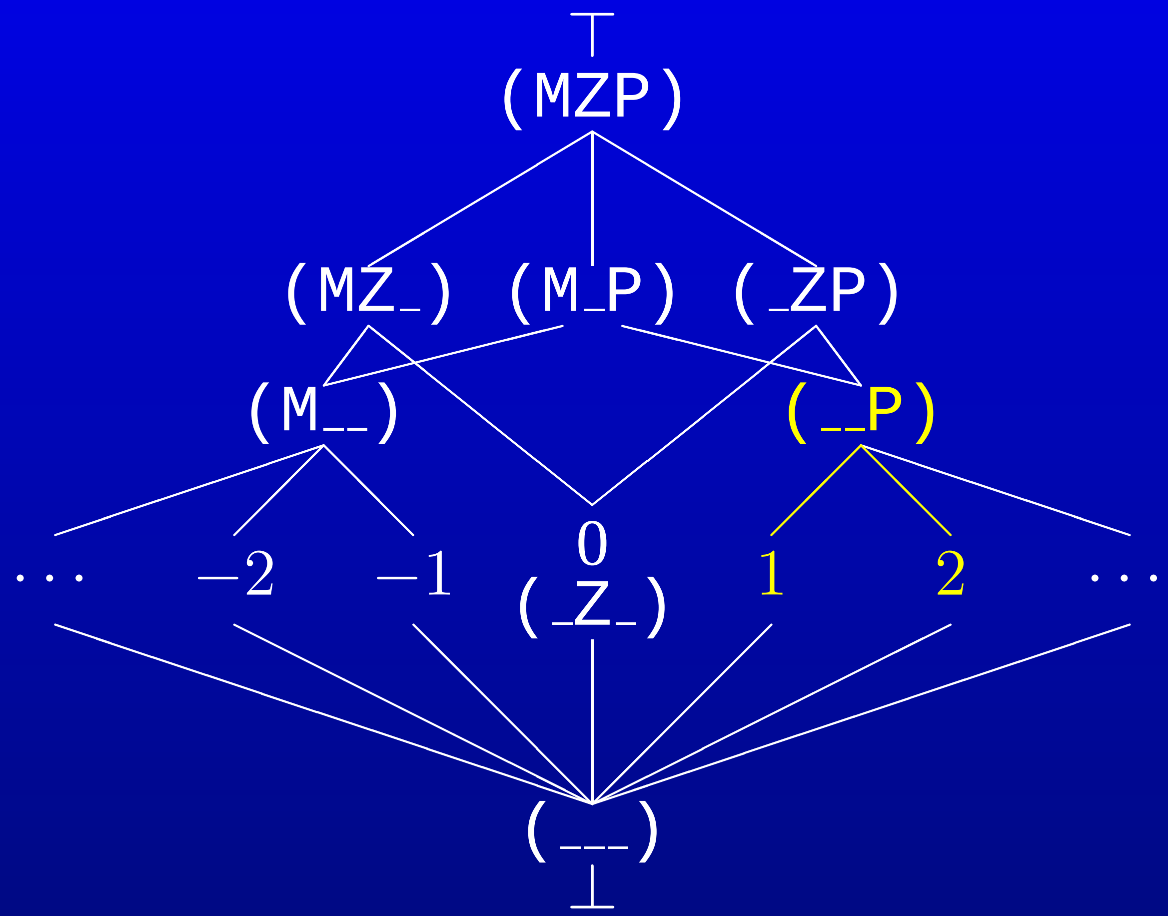
[Because $1 \sqsubseteq \top$ and $2 \sqsubseteq \top$]

A signed integer lattice



An integer lattice for signed integers. A classification into negative (M), positive (P), or zero (Z) is grafted onto the standard flat integer constant domain.

A signed integer lattice



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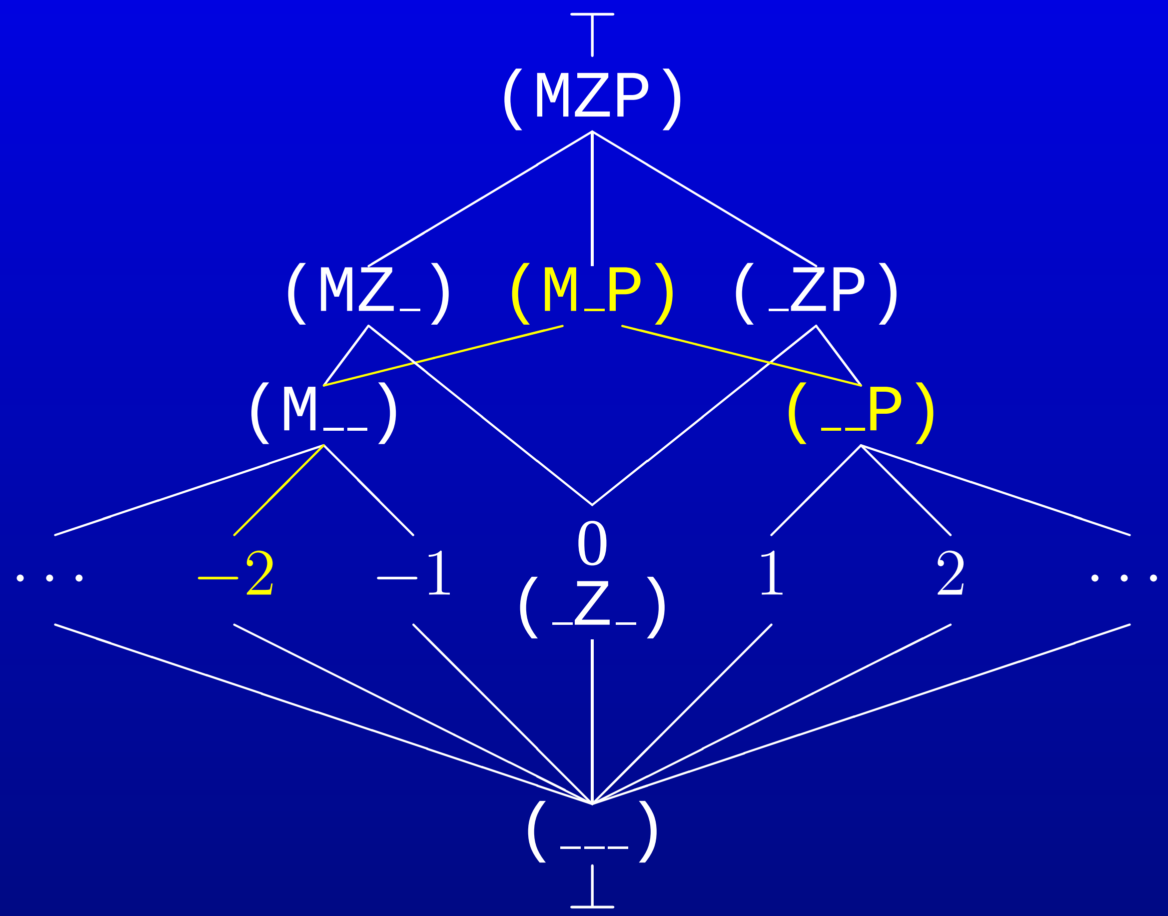

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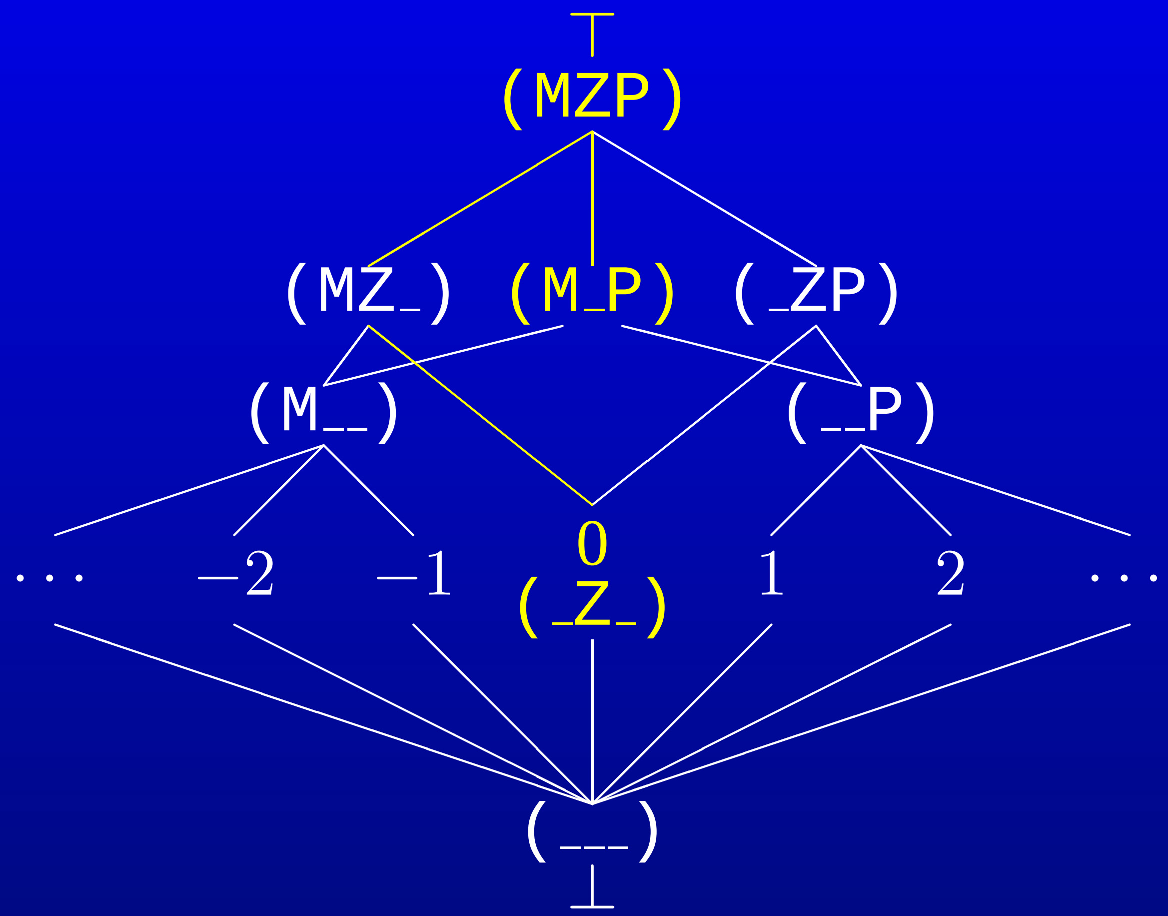

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Example, redux

```
int foo() {
    if (...)
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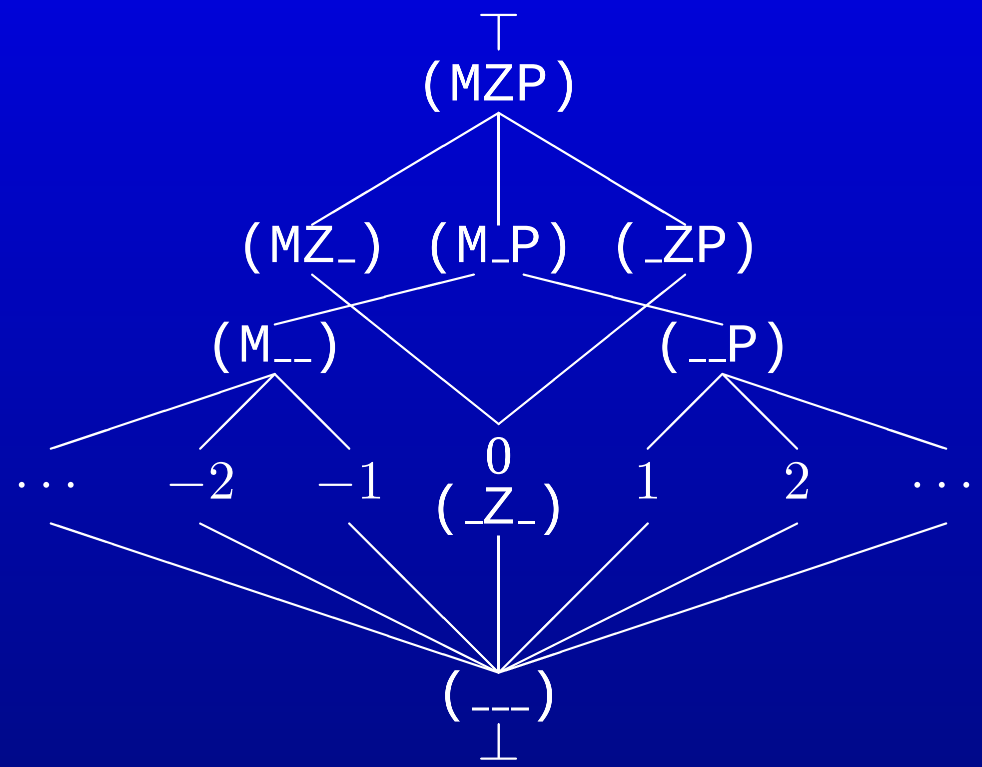

$\mathtt{i} = \bot$

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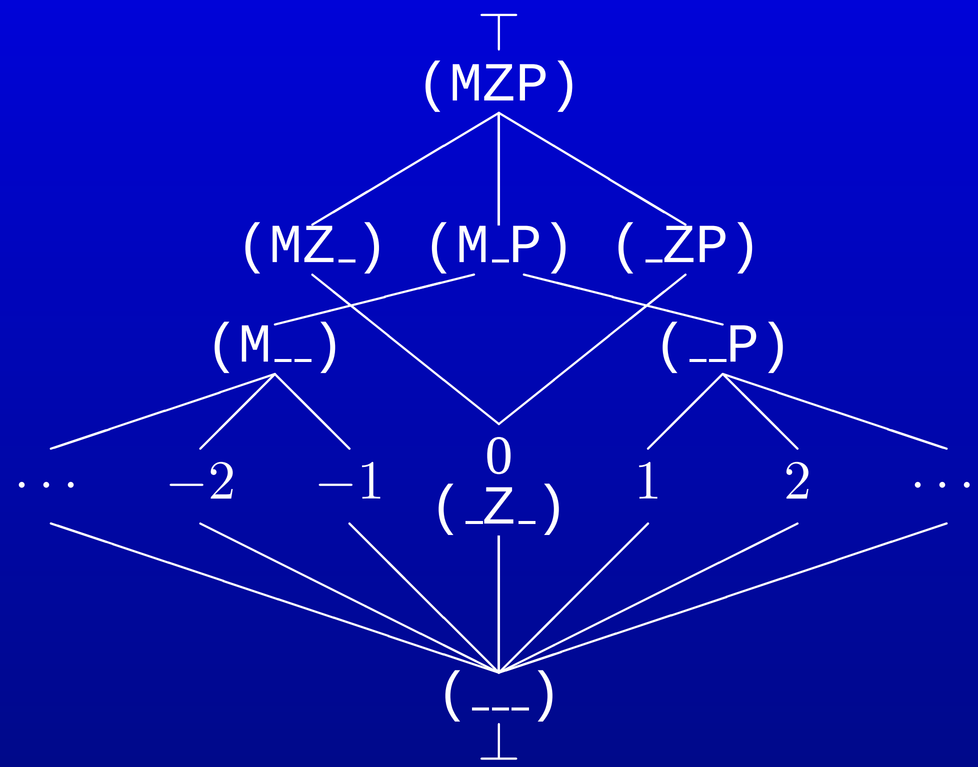

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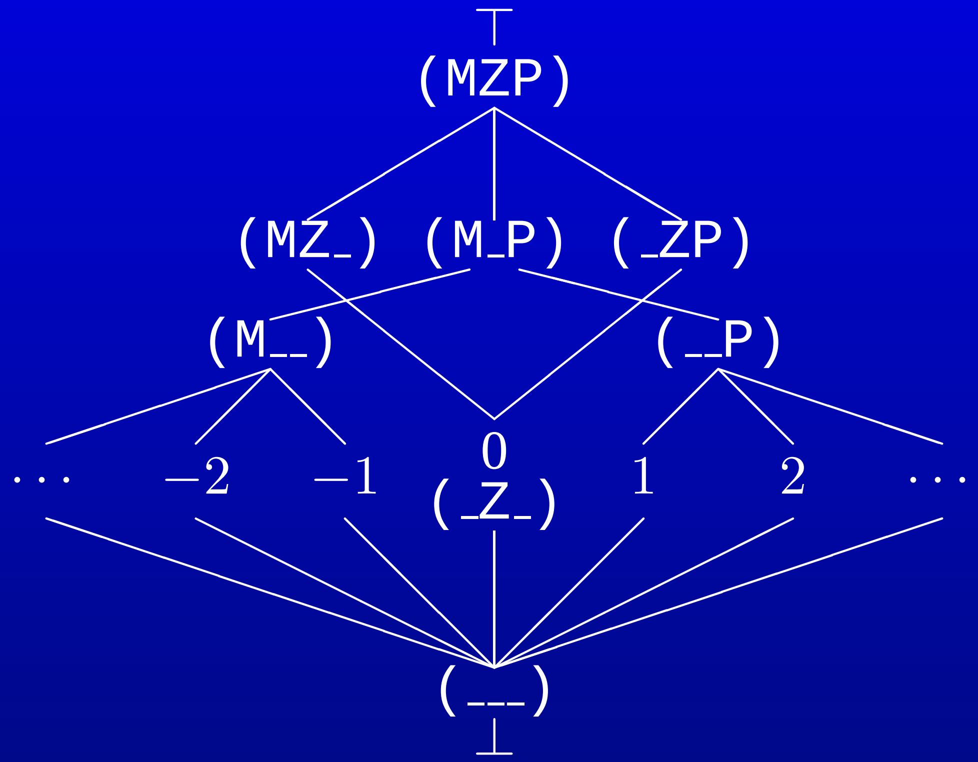

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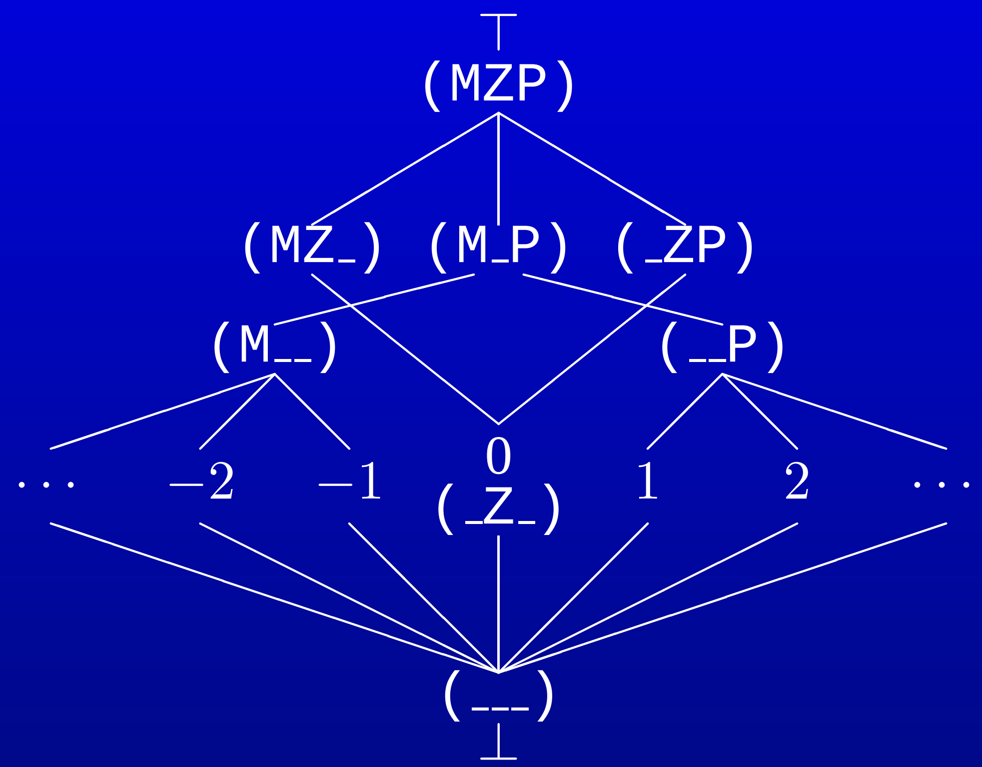

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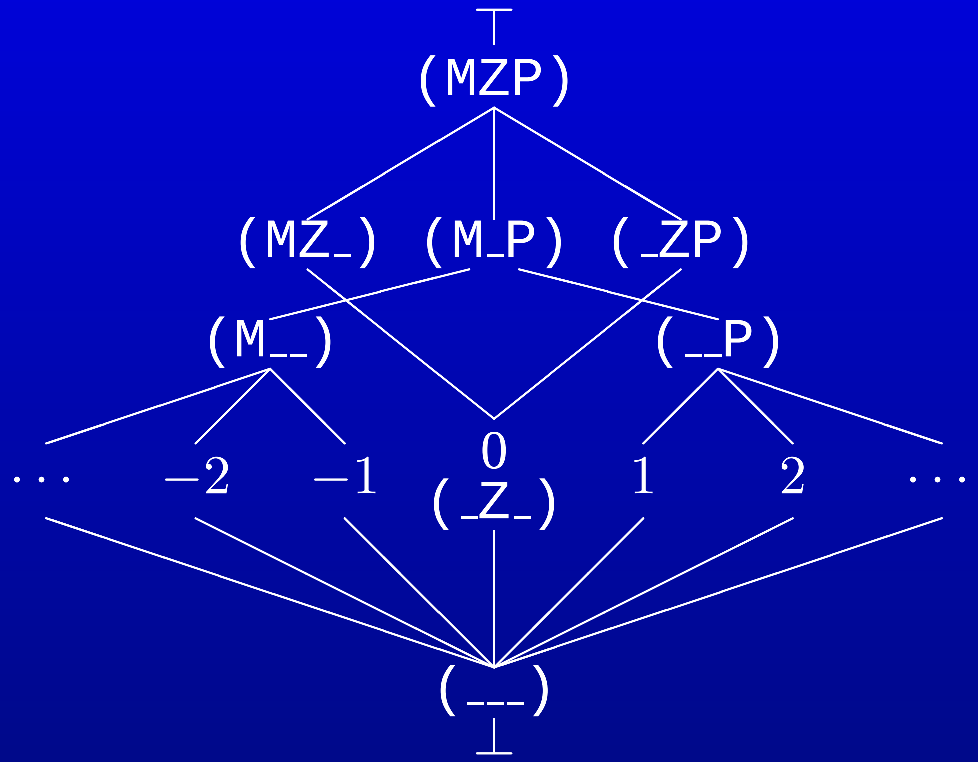

i = 1

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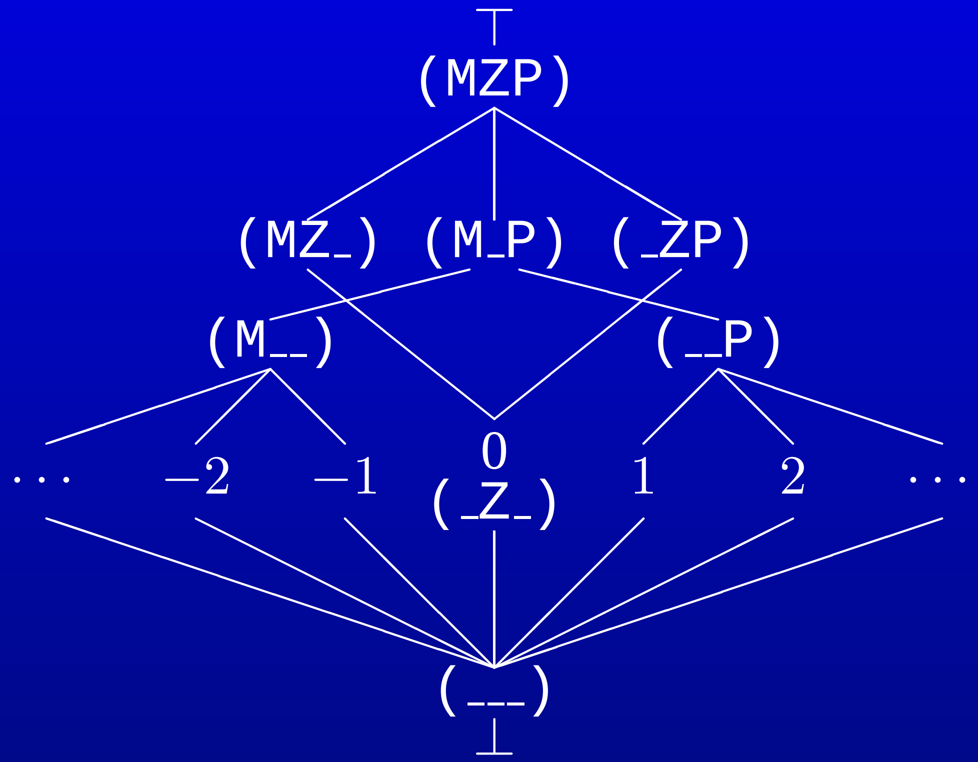

$$\mathbf{i} = 1 \sqcap 2$$

Example, redux

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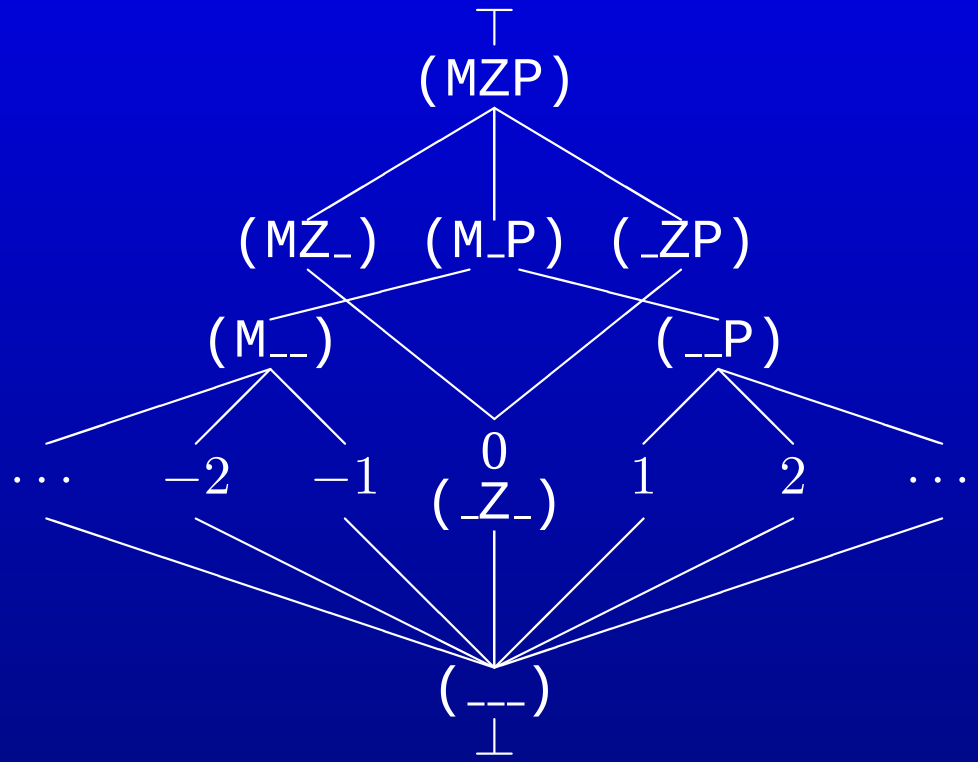
    if (i>0)
        ⋮
}
```



$$\mathtt{i} = 1 \sqcap 2 = \mathtt{(\_\_P)}$$

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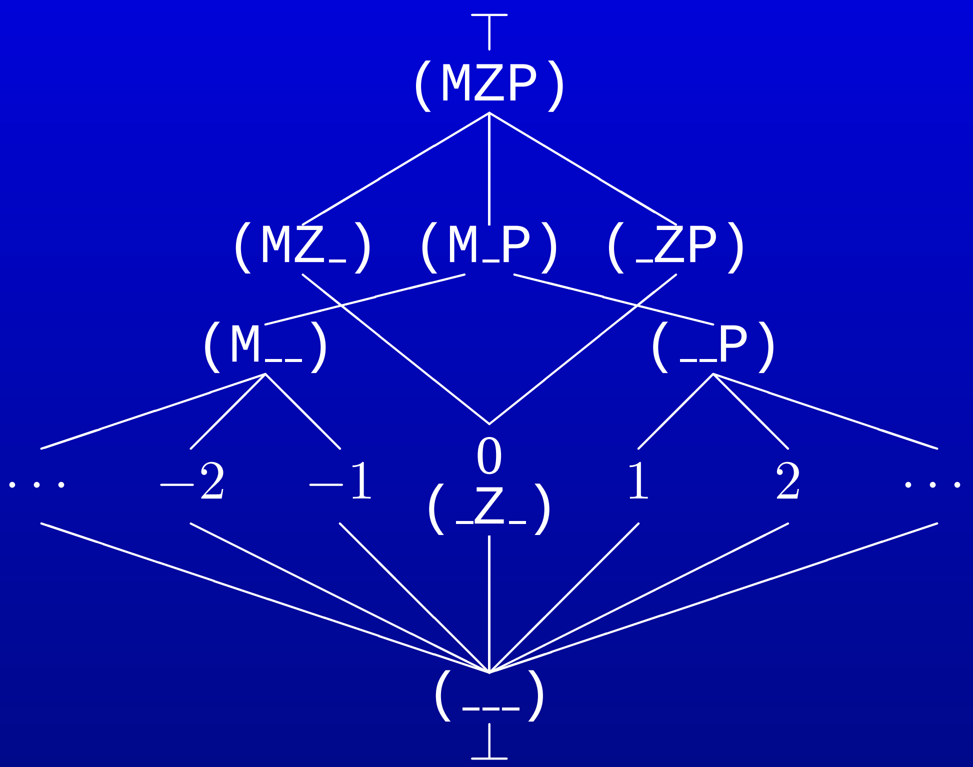

$\mathbf{i} = 1 \sqcap 2 = \mathbf{(\_\_P)}$

Extending the lattice

Replace **`M`** and **`P`** in previous lattice entries with positive integers m and p. Encode zero as $m = p = 0$.

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$$\texttt{(\_\_P)} \Rightarrow \langle 0, p \rangle$$
$$\texttt{(M\_\_)} \Rightarrow \langle m, 0 \rangle$$
$$\texttt{(\_Z\_)} \Rightarrow \langle 0, 0 \rangle$$

Extending the lattice

Replace **M** and **P** in previous lattice entries with positive integers m and p. Encode zero as $m = p = 0$.

(__P) $\Rightarrow \langle 0, p \rangle$

(M__) $\Rightarrow \langle m, 0 \rangle$

(_Z_) $\Rightarrow \langle 0, 0 \rangle$

In lattice context: **(__P)** $\Rightarrow$

$\langle 0, 31 \rangle$

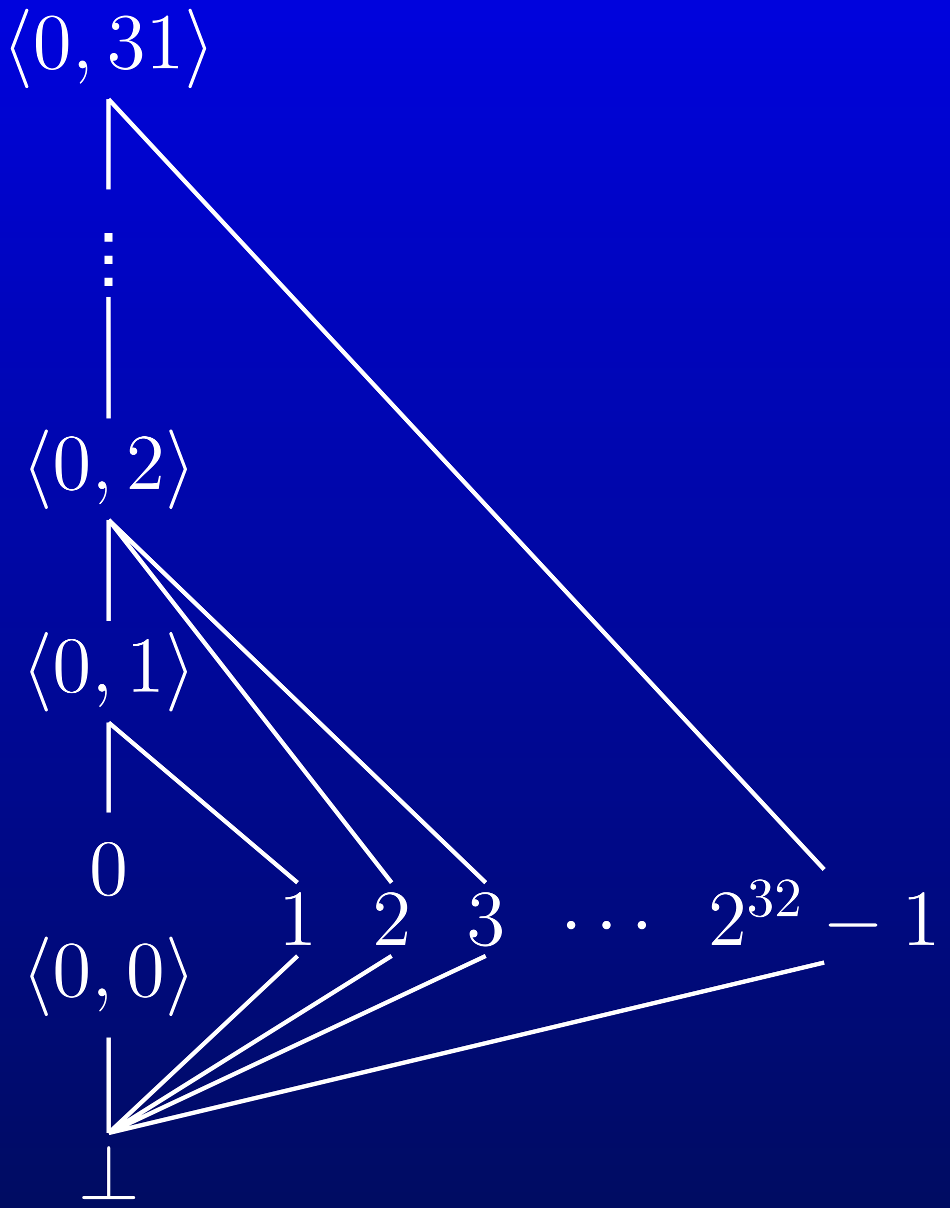
$\vdots$

$\langle 0, 3 \rangle$

$\langle 0, 2 \rangle$

$\langle 0, 1 \rangle$

Bitwidth lattice detail



Example, redux redux

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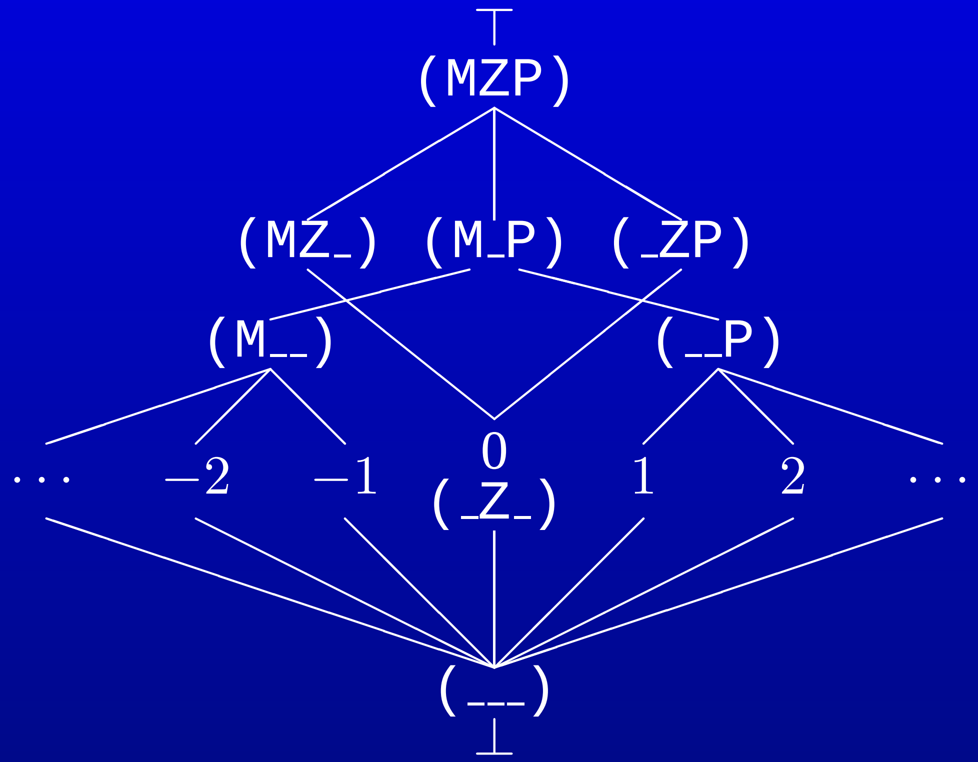

$\mathbf{i} = \bot$

Example, redux redux

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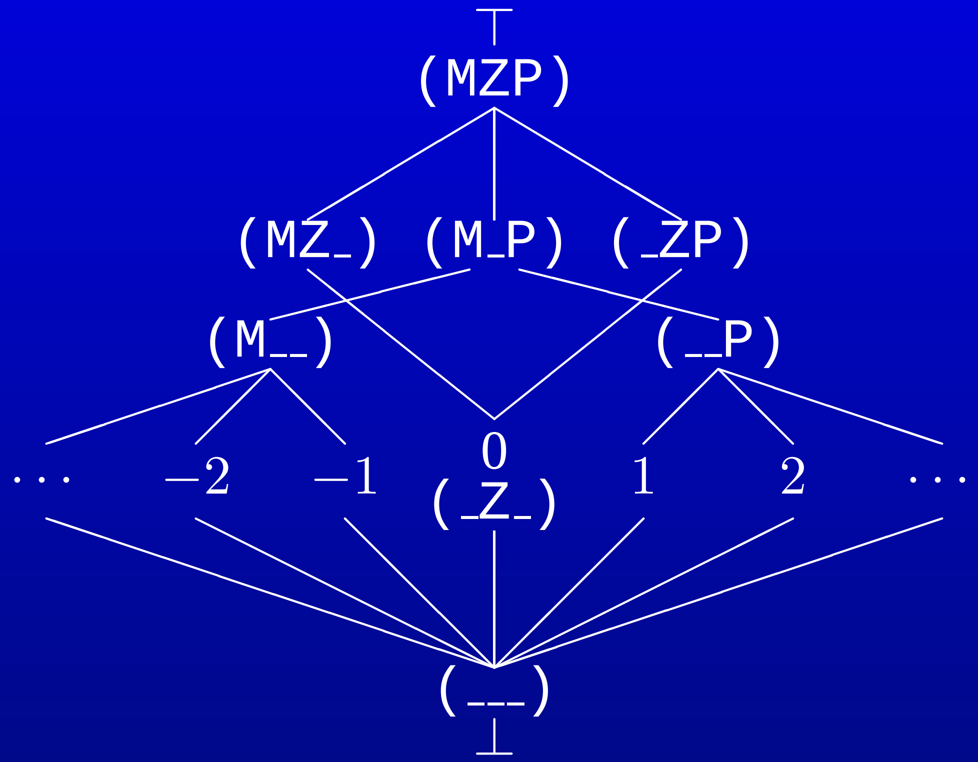

$$\mathbf{i} = \bot$$

Example, redux redux

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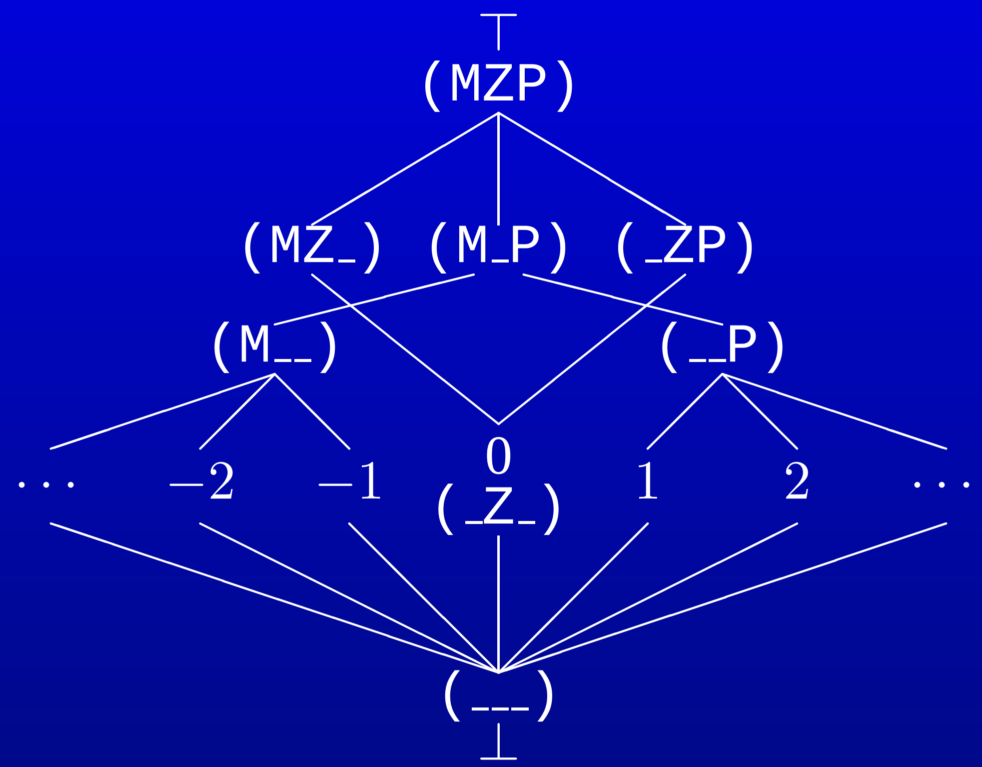

$$\mathbf{i} = \bot \sqcap 1$$

Example, redux redux

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int foo() {
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    else
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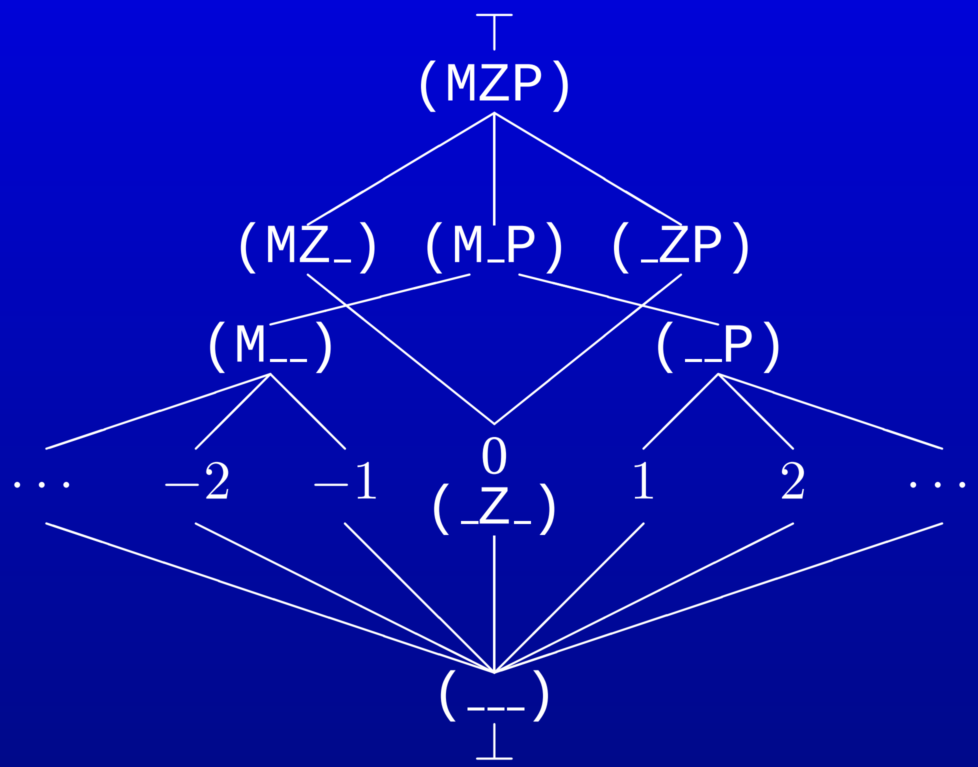
    if (i>0)
        ⋮
}
```



i $= 1$

Example, redux redux

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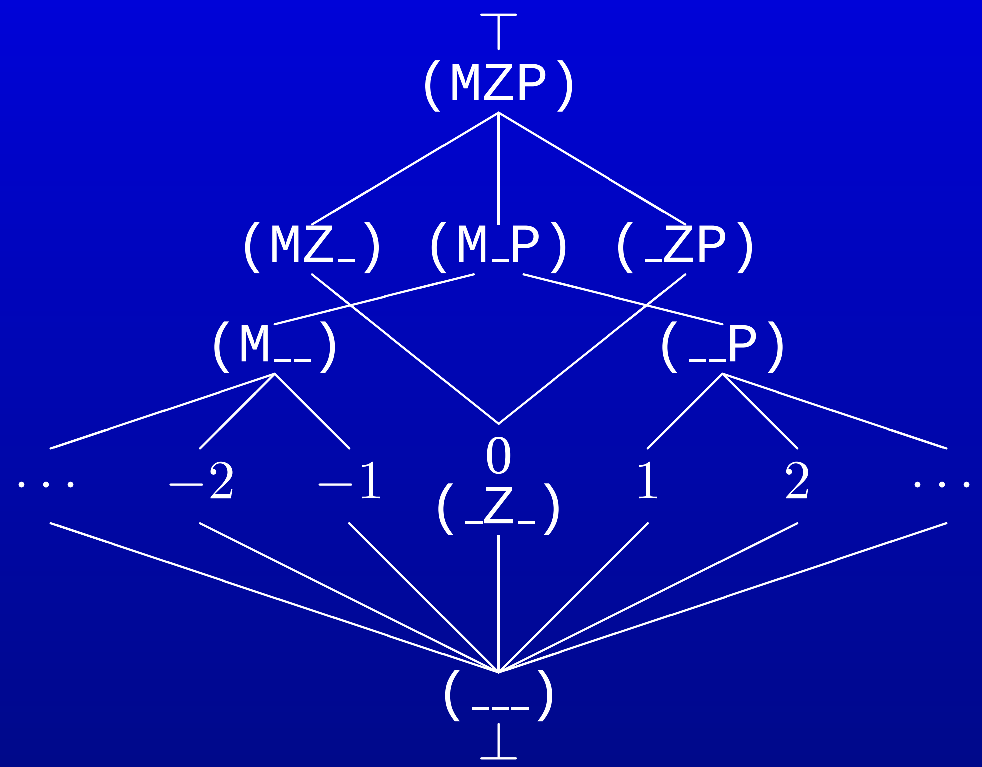
int foo() {
    if (...)
        i=1;
    else
        i=2;
    if (i>0)
        ⋮
}
```



$$\boxed{\mathtt{i} = 1}$$

Example, redux redux

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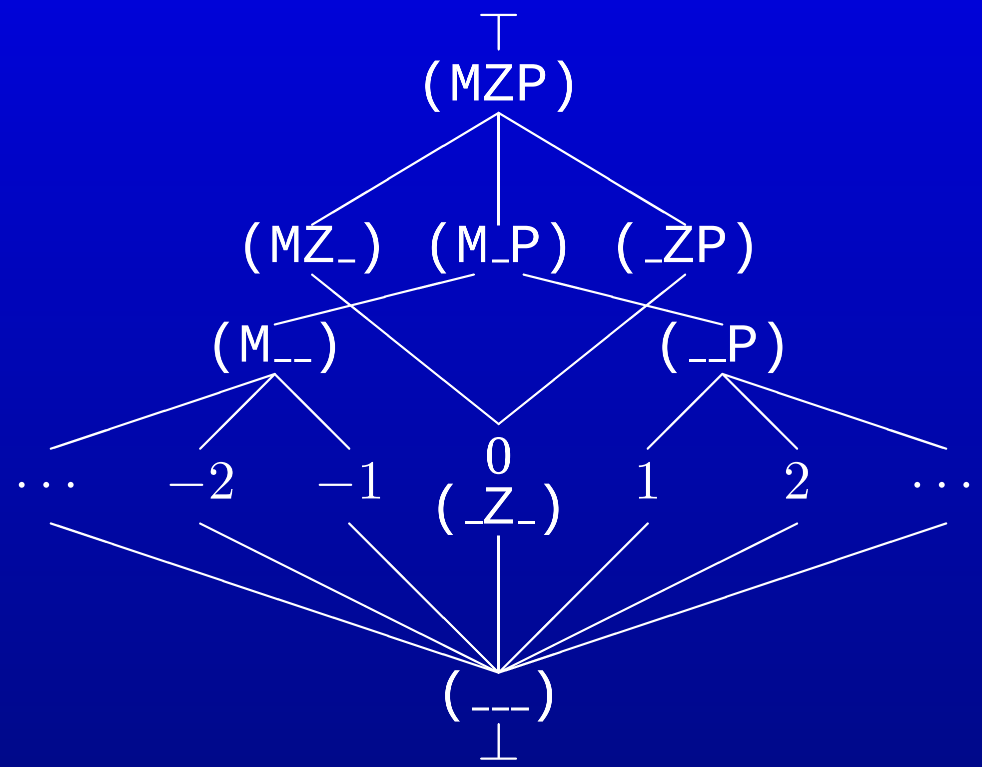

$\mathbf{i} = 1 \sqcap 2$

Example, redux redux

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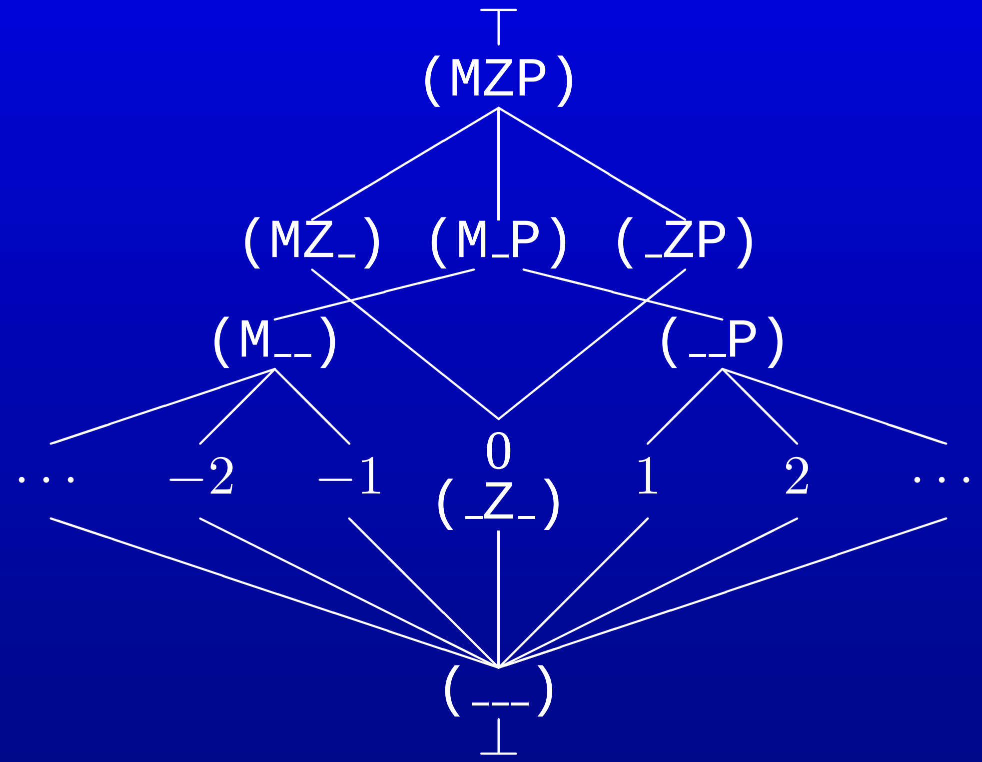

$$\mathbf{i} = 1 \sqcap 2 = \langle 0, 2 \rangle$$

Example, redux redux

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int foo() {
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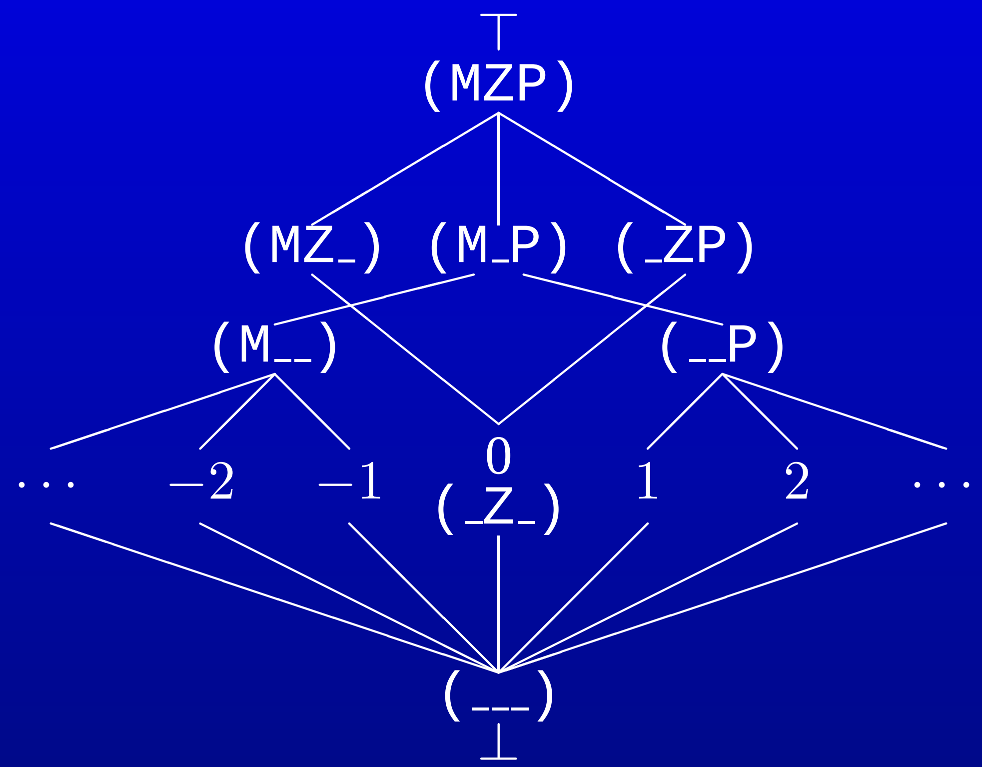


$$\mathbf{i} = 1 \sqcap 2 = \langle 0, 2 \rangle$$

Bitwidth combination rules

$$
\begin{aligned}
-\langle m, p\rangle &= \langle p, m\rangle \\
\langle m_l, p_l\rangle + \langle m_r, p_r\rangle &= \langle 1+\max(m_l, m_r), 1+\max(p_l, p_r)\rangle \\
\langle m_l, p_l\rangle \times \langle m_r, p_r\rangle &= \left\langle \begin{array}{l} \max(m_l+p_r, p_l+m_r), \\ \max(m_l+m_r, p_l+p_r) \end{array} \right\rangle \\
\langle 0, p_l\rangle \wedge \langle 0, p_r\rangle &= \langle 0, \min(p_l, p_r)\rangle \\
\langle m_l, p_l\rangle \wedge \langle m_r, p_r\rangle &= \langle \max(m_l, m_r), \max(p_l, p_r)\rangle
\end{aligned}
$$

Some combination rules for bit-width analysis.

Interprocedural analysis

```
int foo() {
    if (...)
        i=1;
    else
        i=2;
    if (i>0)
        ⋮
}
```

Interprocedural analysis

```
int foo() {
    if (...)
        this.f=1;
    else
        this.f=2;
    if (this.f>0)
        ⋮
}
```

Interprocedural analysis

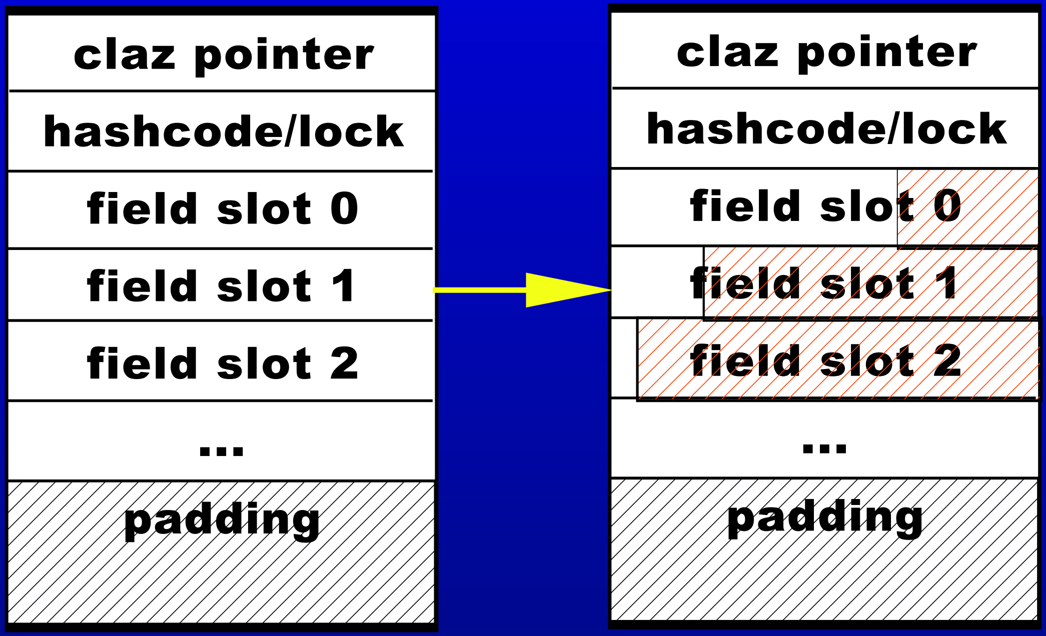
```
int foo() {
    if (...)
        this.f=1;
    else
        this.f=2;
    if (this.f>0)
        ⋮
}
```

```
int foo() {
    this.f=1;
}
int bar() {
    this.f=2;
}
int bar() {
    if (this.f>0)
        ...
}
```

All cars are black

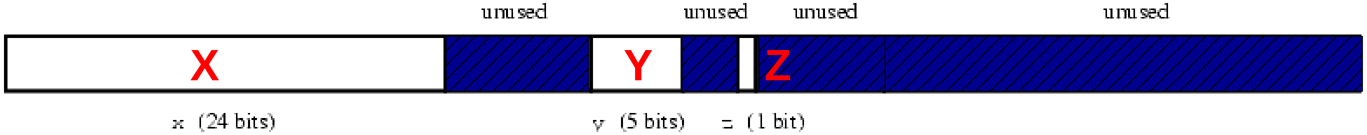
```
void paint(int color) {
    if (this.model == FORD)
        color = BLACK;
    this.color = color;
}
```

Field compression using bitwidths

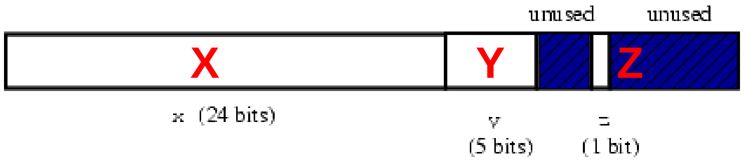


Field packing

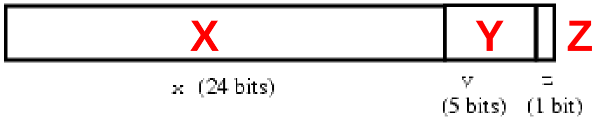
Standard packing word-aligns the object and aligns each field to the width of its type (4-byte data is 4-byte aligned):



"Byte" alignment byte-aligns the object and all fields:



"Bit" alignment requires no alignment of objects or fields:



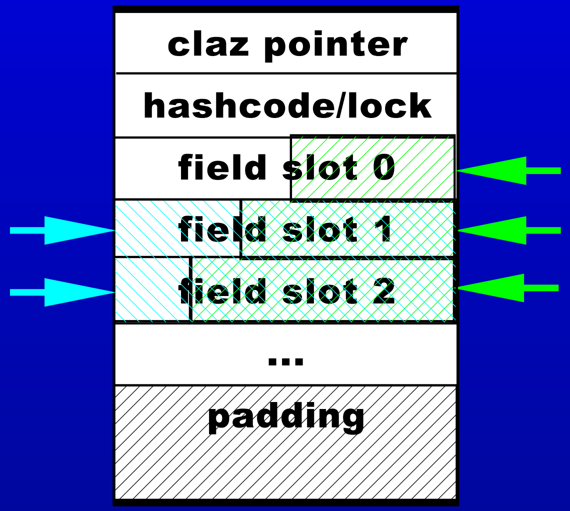

```
class A {
    int x; /* actual width 24 bits */
    byte y; /* actual width 5 bits */
    boolean z; /* actual width 1 bit */
}
```

Object header omitted.

How to compress objects

Three broad techniques:

- Field compression
- Mostly-constant field elimination
- Header optimizations



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  - Identify fields which have a certain value "most of the time."
    - Static analysis/profiling.
  - Transform objects to remove fields w/ the common value.
    - Static specialization/externalization.

Specialization example:

java.lang.String

```
public final class String {
    private final char value[];
    private final int offset;
    private final int count;
    ...
    public char charAt(int i) {
        return value[offset+1];
    }
    public String substring(int start) {
        int noff = offset + start;
        int ncnt = count - start;
        return new String(value, noff, ncnt);
    }
}
```

Key properties

To use static specialization we need:

- A field with a frequently-occuring value.
  - **`String.offset`** is almost always zero.
- The value of the field must never be modified after the object is created.

Transforming the class

We will split String into two classes:

- **`SmallString`** without the field.
- **`BigString`** with the field.

We will use **`SmallString`** for all instances where the offset field is zero (our “mostly-constant” value).

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Problems:

- The code could directly access the to-be-removed field.
- Allocation sites directly instantiate the old class.

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```

Specialization example:

java.lang.String

```
public final class SmallString {
    private final char value[];
    private final int offset;
    private final int count;
    protected int getOffset() { return 0; }
    ...
    public char charAt(int i) {
        return value[getOffset()+1];
    }
    public String substring(int start) {
        int noff = getOffset() + start;
        int ncnt = count - start;
        return new String(value, noff, ncnt);
    }
}
```

Specialization example:

java.lang.String

```
public final class SmallString {
    private final char value[];

    private final int count;
    protected int getOffset() { return 0; }
    ...
    public char charAt(int i) {
        return value[getOffset()+i];
    }
    ...
}
public final class BigString extends SmallString {
    private final int offset;
    protected int getOffset() { return offset; }
}
```

Transforming allocation sites

Case 1: field is constant in constructor.

```
String s = new String     (new char[] {’a’, ’b’, ’c’});

String     (char[] val) {
    this.value = (char[]) val.clone();
    this.offset = 0;
    this.count = val.length;
}
```

Transforming allocation sites

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```
SmallString s = new SmallString(new char[] {'a', 'b', 'c'});

SmallString(char[] val) {
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}
```

Transforming allocation sites

Case 2: field is simple function of constructor parameter.

```
String s = new String(new char[] {'a', 'b', 'c'},
                      x, 1);

String(char[] val, int offset, int length) {
    this.value = (char[]) val.clone();
    this.offset = offset;
    this.count = length;
}
```

Transforming allocation sites

Case 2: field is simple function of constructor parameter.

```
SmallString s;

if (x==0)
    s = new SmallString(new char[] {'a', 'b', 'c'}, x, 1);
else
    s = new BigString(new char[] {'a', 'b', 'c'}, x, 1);
```

Transforming allocation sites

Case 3: assignment to field is unknown.

```
String    s = new String   (s, o, l);

String   (char[] val, int offset, int length) {
    this.value = (char[]) val.clone();
    while (length>0 && value[offset]==' ') {
        offset++; length-;
    }
    this.offset = offset;
    this.count = length;
}
```

Transforming allocation sites

Case 3: assignment to field is unknown.

```
BigString s = new BigString(s, o, l);

BigString(char[] val, int offset, int length) {
    this.value = (char[]) val.clone();
    while (length>0 && value[offset]==’ ’) {
        offset++; length-;
    }
    this.offset = offset;
    this.count = length;
}
```

Static specialization

- Split class implementations into “field-less” and “field-ful” versions.
- Use virtual accessor functions to hide this split from users of the class.
- Done at compile time, on fields which can be shown to be compile-time constants, thus “static.”
  - Fields can not be mutated after the constructor completes.
- Can be done recursively on multiple fields.
  - Profiling guides splitting order if there are multiple candidates.

Key properties (revisited)

To use static specialization we need:

- A field with a frequently-occuring value.
  - **`String.offset`** is almost always zero.
- The value of the field must never be modified after the object is created.

Key properties (revisited)

To use static specialization we need:

- A field with a frequently-occuring value.
  - **`String.offset`** is almost always zero.
- ~~The value of the field must never be modified after the object is created.~~

Creating external fields

- Sometimes fields are *run-time* constants (or nearly so) but not *compile-time* constants.

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Creating external fields

- Sometimes fields are *run-time* constants (or nearly so) but not *compile-time* constants.
  - Examples: sparse matrices, “two-input nodes” in Jess expert system, the “next” field in short linked lists.
- Exploit field→map duality to reduce memory overhead in the common case.

Fields and Maps

- Accessing an object field `a.b` (where a is the object reference and b is the field name) is equivalent to evaluating a map from $\langle a, b \rangle$ to the value type.

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- The mapping we will implement will be *incomplete*. We define the result of accessing a non-existing mapping to be $\perp$.
- To achieve our storage savings, we map $\perp$ to the frequent “mostly-constant” value.

Externalization example:

java.lang.String

```
public final class String {
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public final class String {
    private final char value[];
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    public char charAt(int i) {
        return value[getOffset()+1];
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    public String substring(int start) {
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        return new String(value, noff, ncnt);
    }
    protected int getOffset() {
        Integer i = External.map.get(this, "offset");
        if (i==null) return 0;
        else return i.intValue();
    }
}
```

External map implementation

Open−addressed Hashtable

Object	Field	Value
Object	Field	Value
Object	Field	Value
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Key **Value**

- "open addressed" for low overhead.

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- two-word key and one-word values means break-even point is 82%

  (i.e. field may not differ from the “mostly-constant” value in more than 18% of objects.)

We can do better!

Open−addressed Hashtable

Key	Value
Object + Field	Value
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- Use small integers to enumerate fields.

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- Use small integers to enumerate fields.
- Offset the object pointer by the field index to get a 1-word key.
- Limits the number of fields which may be externalized, based on the size of the object.
- One-word key and one-word value lowers break-even point to 66%.

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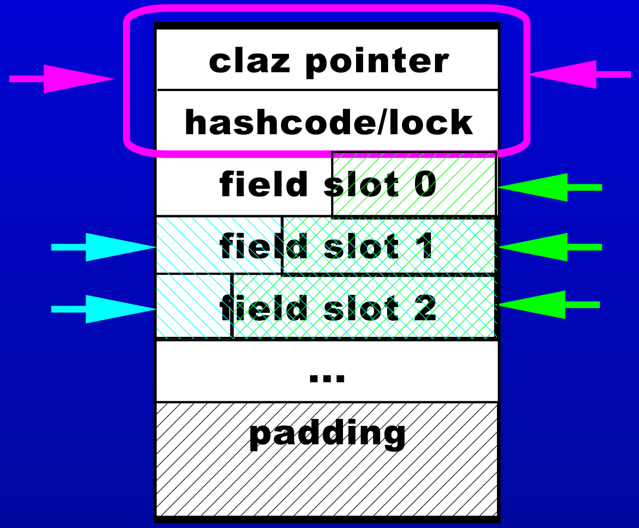
- Use value profiling to identify classes where field externalization will be worthwhile.
- In our experiments, looked for integer “mostly-constant” values in the range $[-5, 5]$ for numeric types. Only looked at `null` as a candidate for pointer types.
- 0 and 1 by far the most common.

How to compress objects

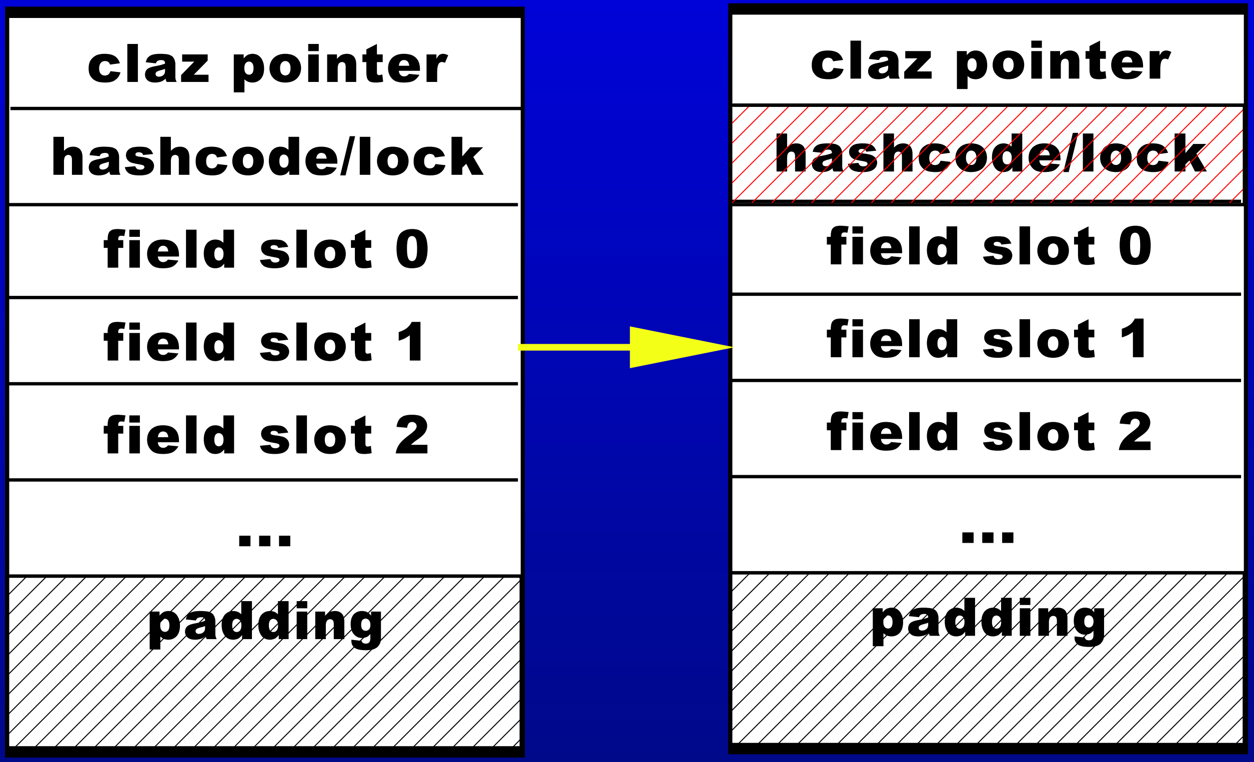
Three broad techniques:

- Field compression
- Mostly-constant field elimination
- Header optimizations



Header optimizations:

Hashcode/Lock compression



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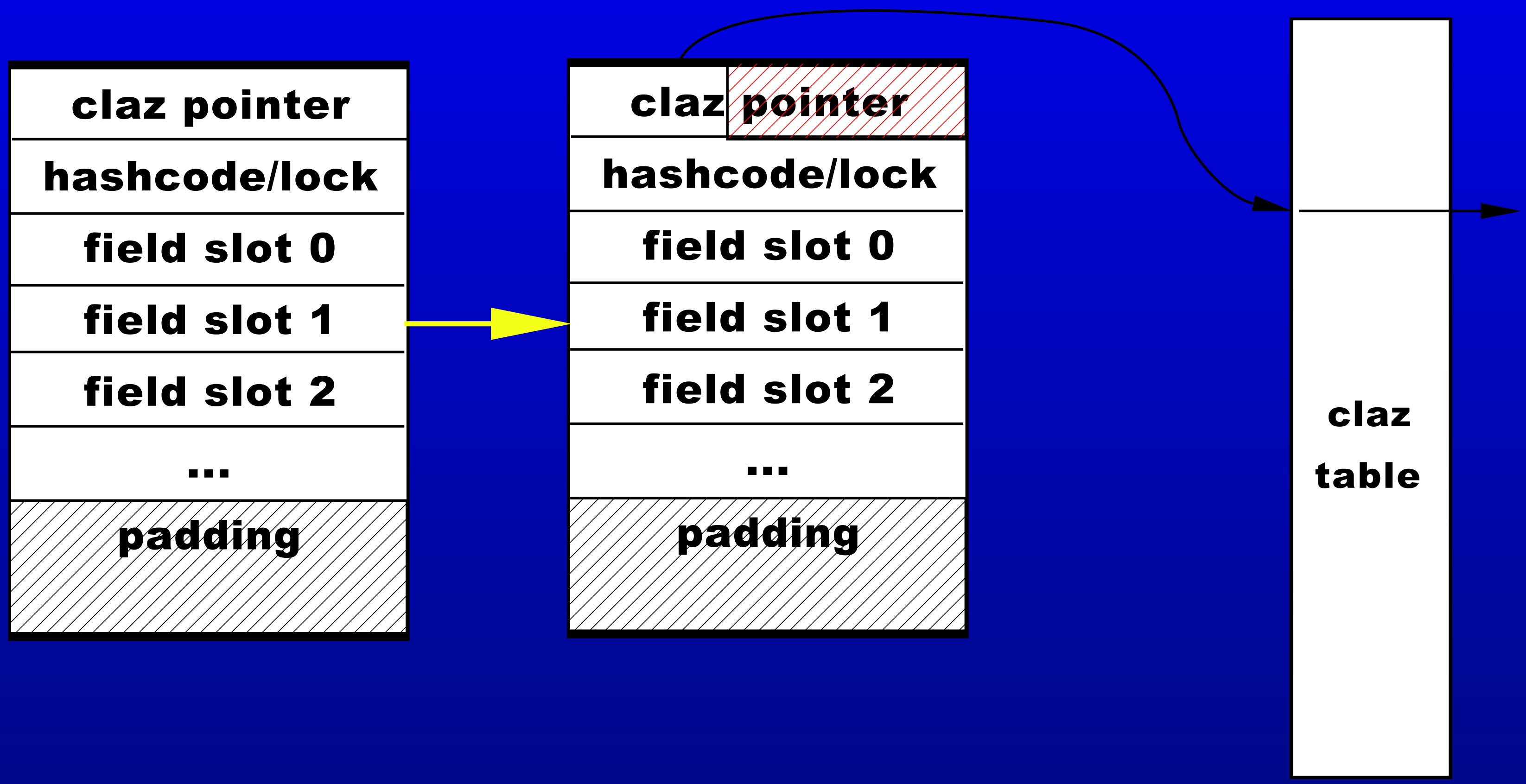
Header optimizations:

Hashcode/Lock compression

- Implemented as a special case of field externalization.
- The hashcode/lock field often unused because:
  - Most objects do not use their built-in hashcode.
  - Most objects are not synchronization targets.
- Could also use a static pointer analysis.

Header optimizations:

claz compression



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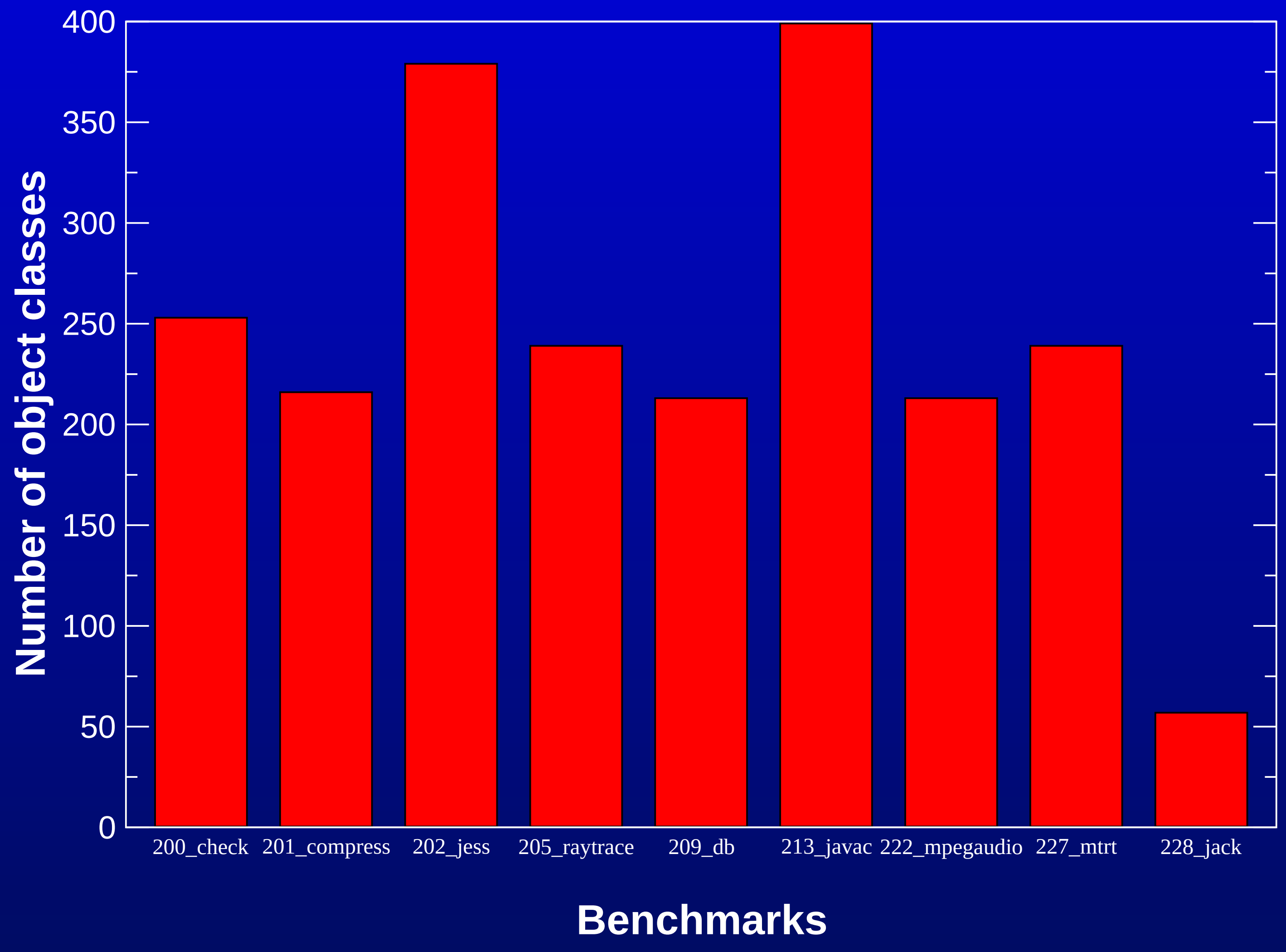
- With co-operation of GC, works in dynamic environments.
- Many applications use less than 256 object types.

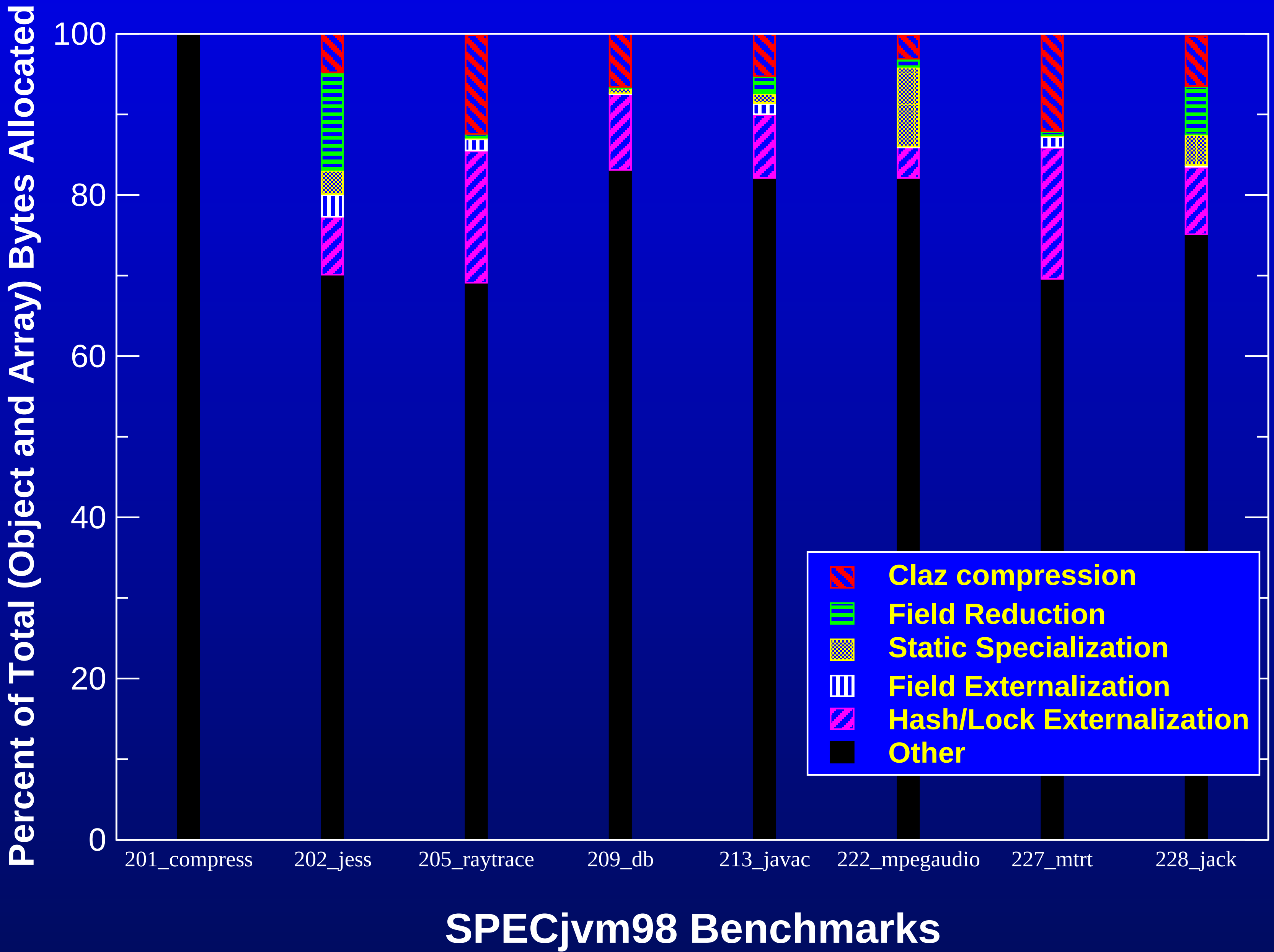
Class statistics

Class statistics for applications in SPECjvm98 benchmark suite:

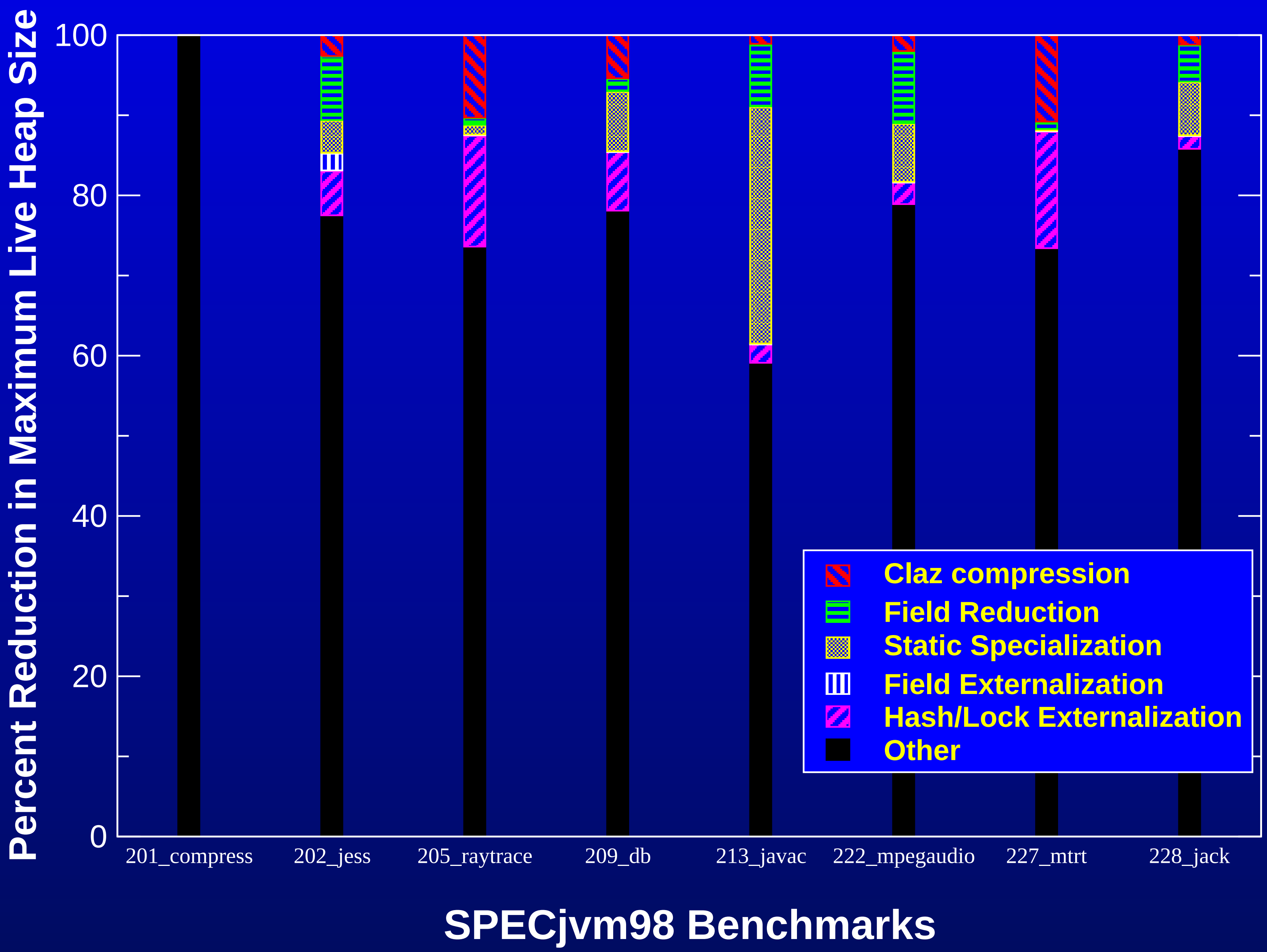


How well does it work?

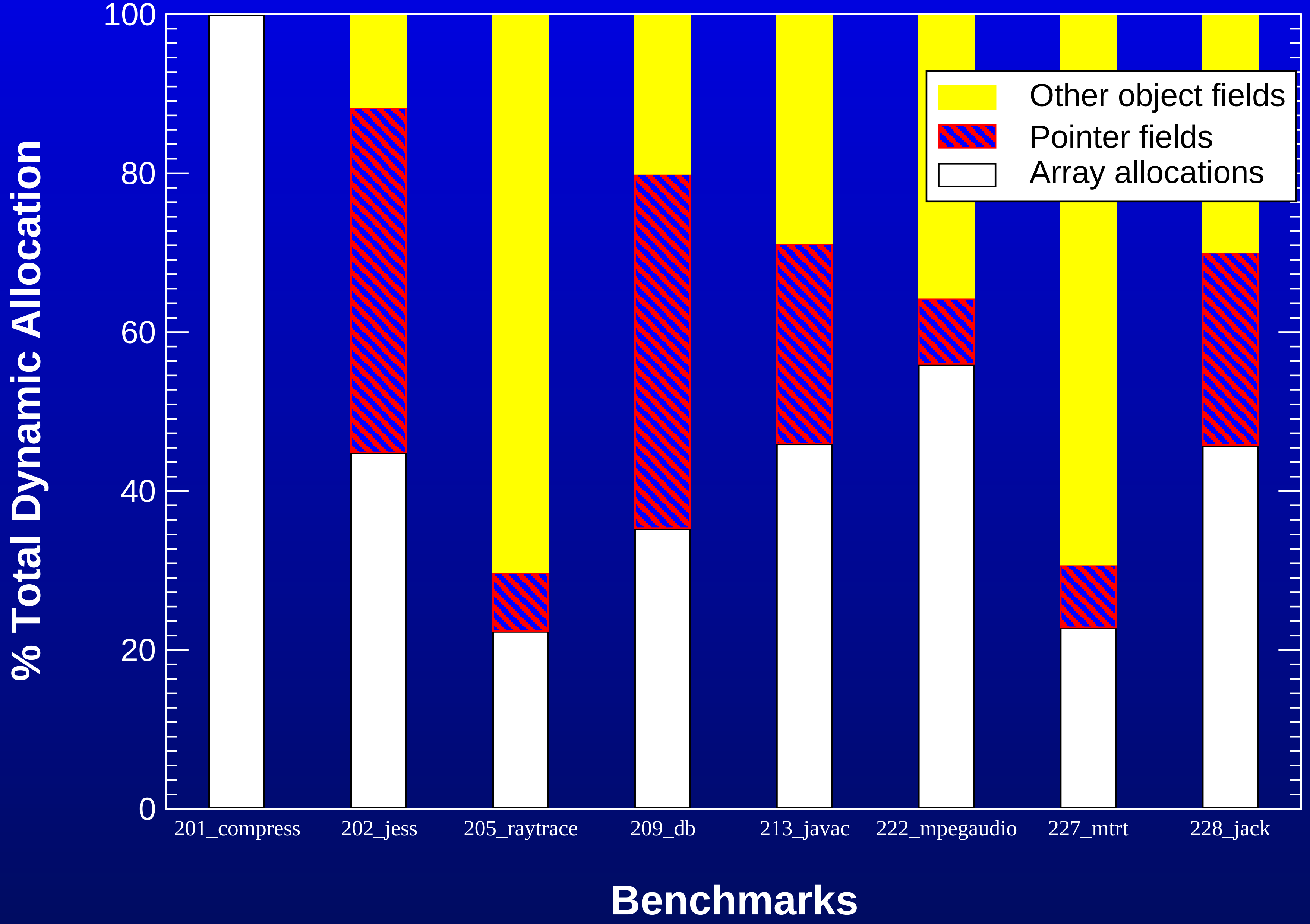
Reduction in total allocations



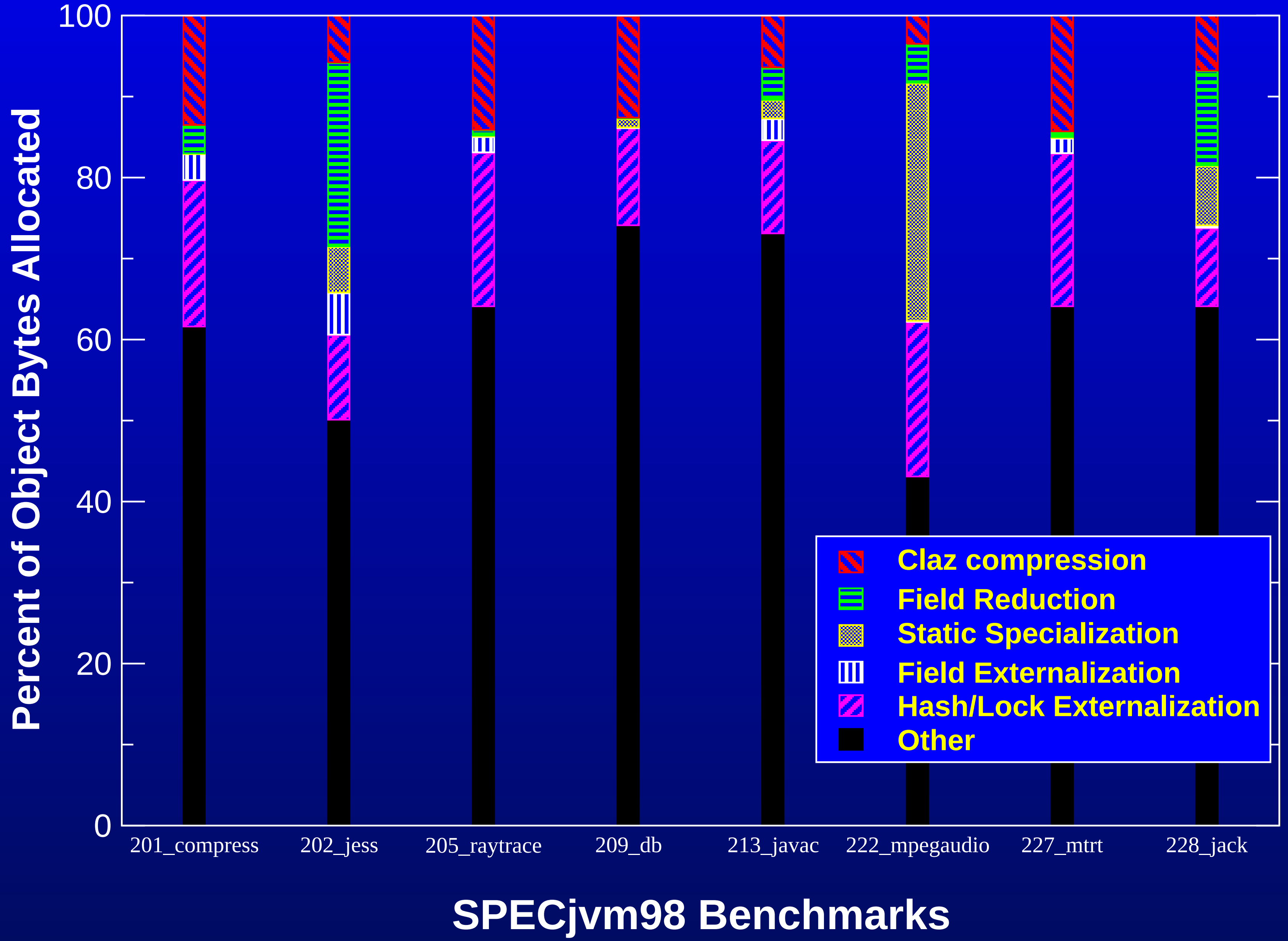
Reduction in total live data



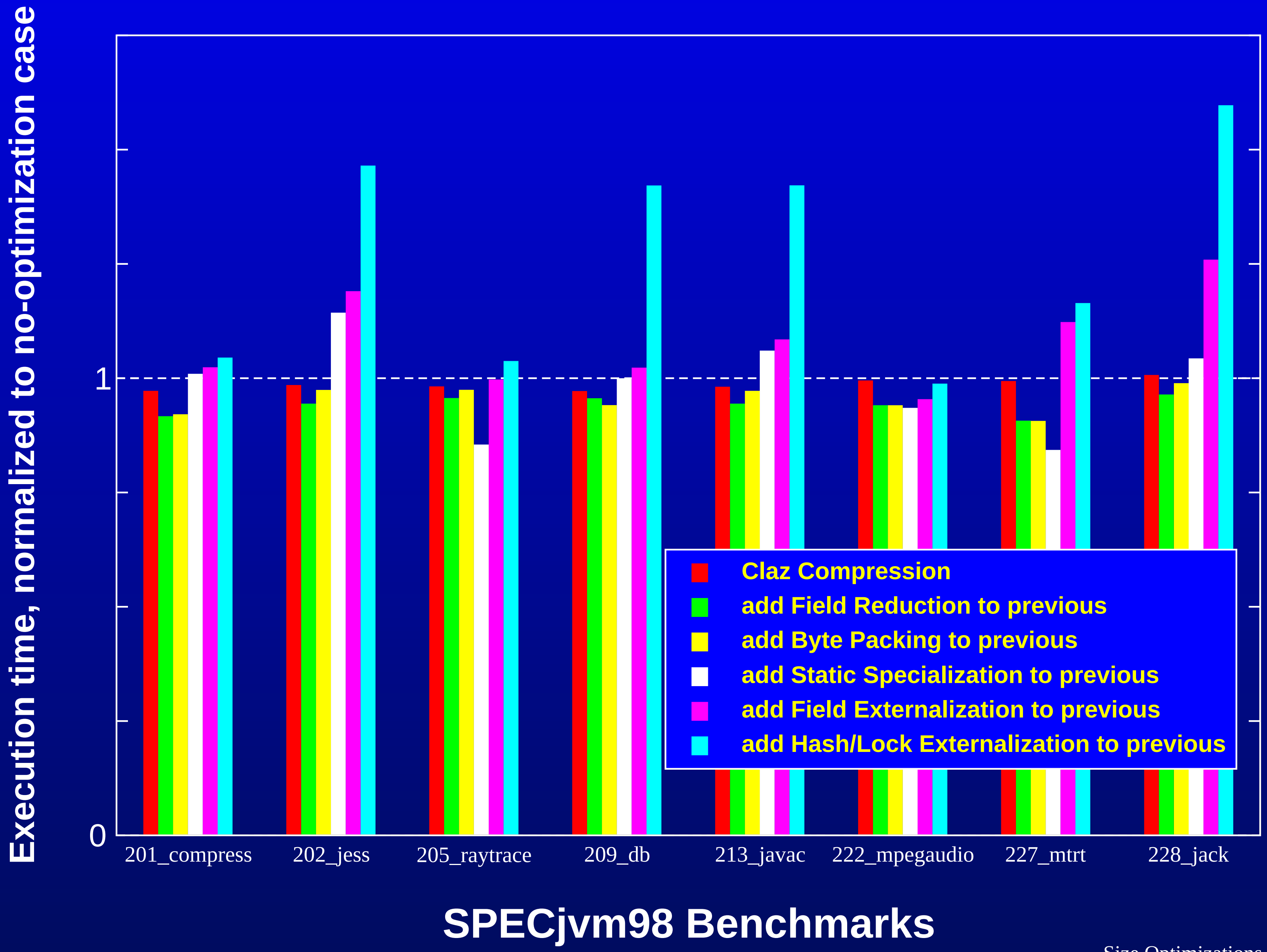
Available reduction opportunities



Reduction in object allocations



Moderate performance impact



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- We know nothing about "field-like" maps.
  - Enable *internalization*.

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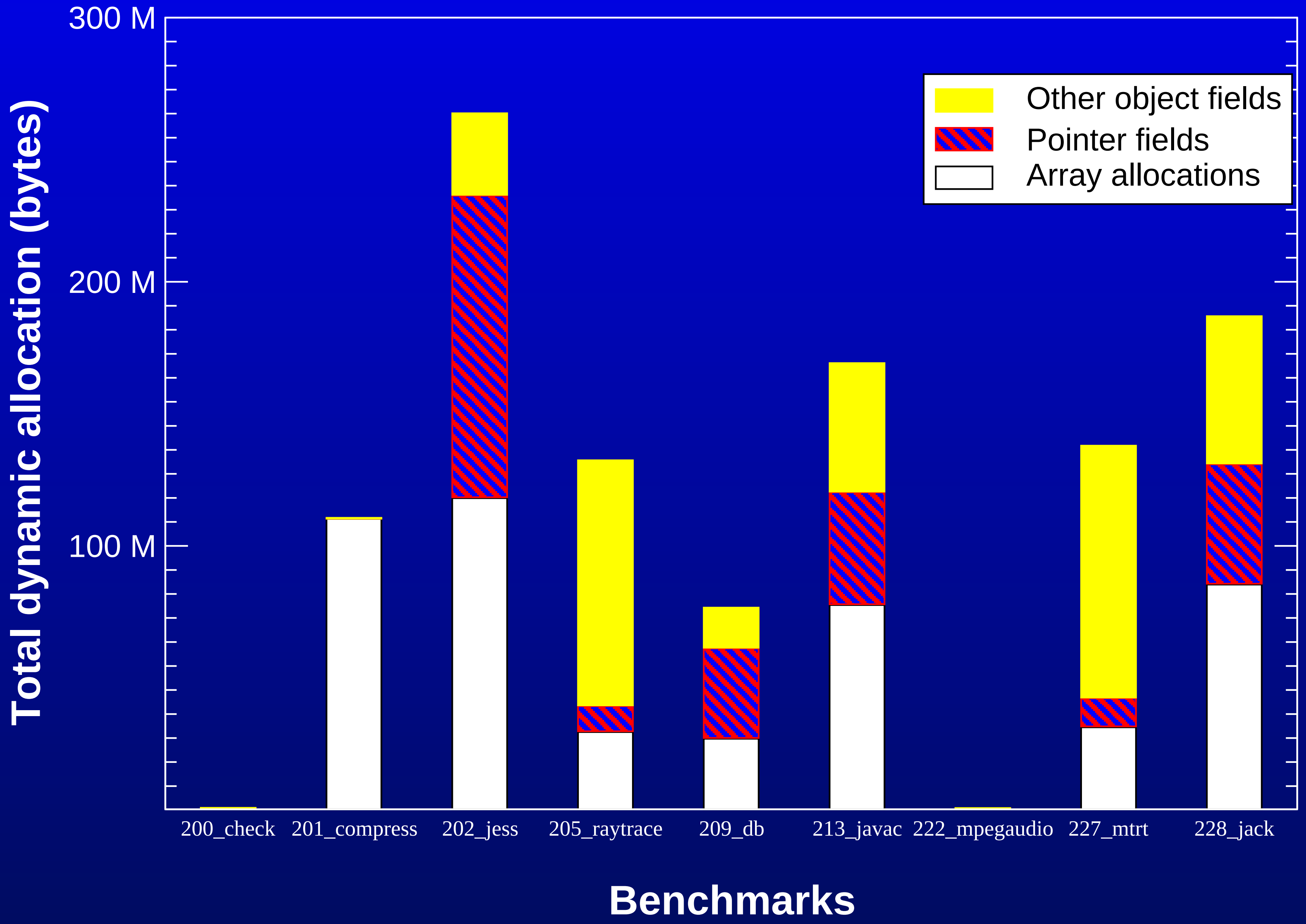
- We achieved substantial space savings on typical object-oriented applications.
  - In one case, over 40% reduction in total live data.
- Even more space reduction is possible!
- Performance impact was acceptable.

The Graveyard Of Unused Slides follows this point.

Available reduction opportunities



Bitwidth analysis

Motivation:

- Tedious and error-prone for programmer to manually specify widths.

```
struct foo {
    int x:24;
    int y:5;
    int z:1;
};
```

Bitwidth analysis

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struct foo {          void foo() {
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};                        ...
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};
```

```
void foo() {
    int x:24;
    int y:5;
    int z:1;
    ...
}
```

```
void foo() {
    int x, y, z;
    ...
}
```

- The compiler can do it for us!