Size Optimizations for Java Programs

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Our Goal

Reduce the memory consumption of object-oriented programs

By

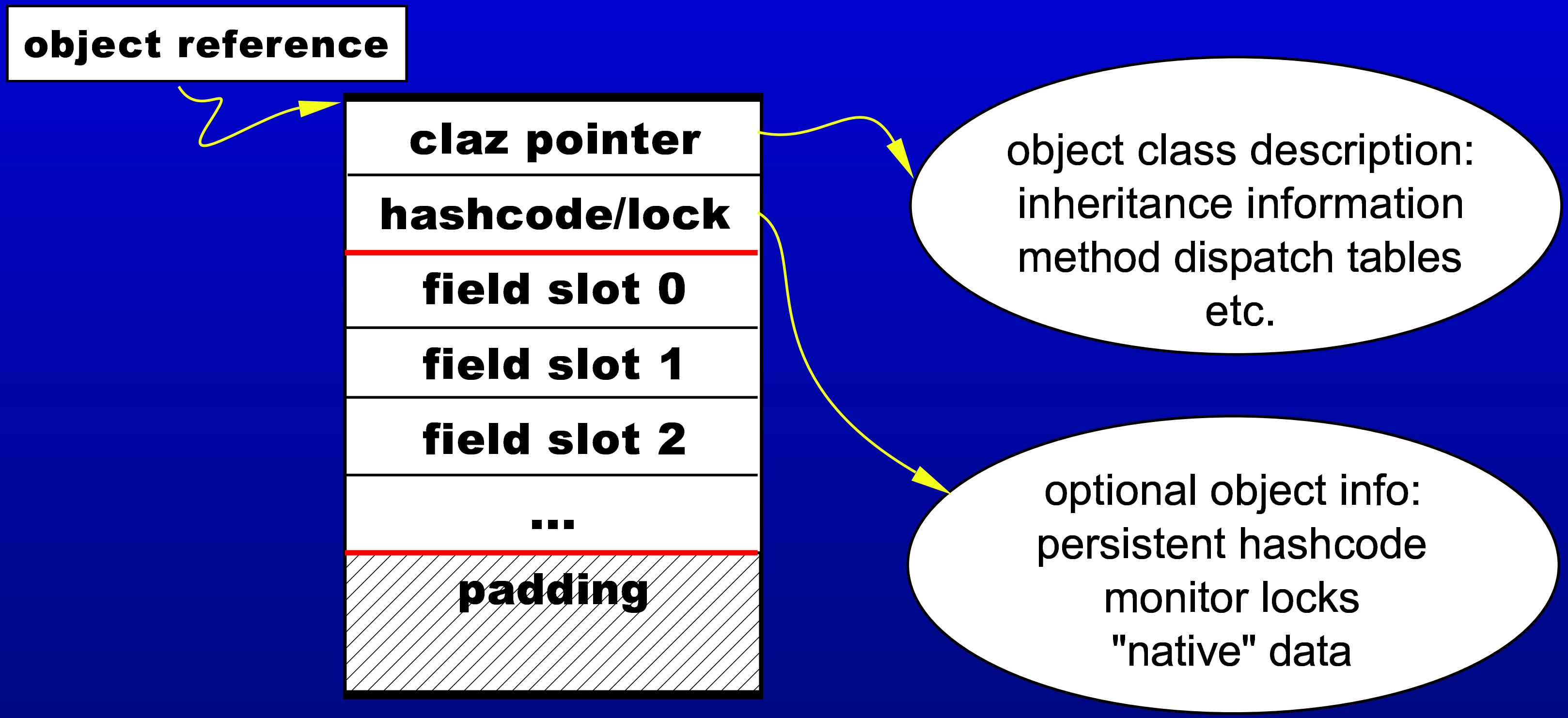
Using program analysis to identify opportunities to reduce the space required to store objects,

Then

Applying transformations to reduce the memory consumption of the program.

Structure of a Java Object

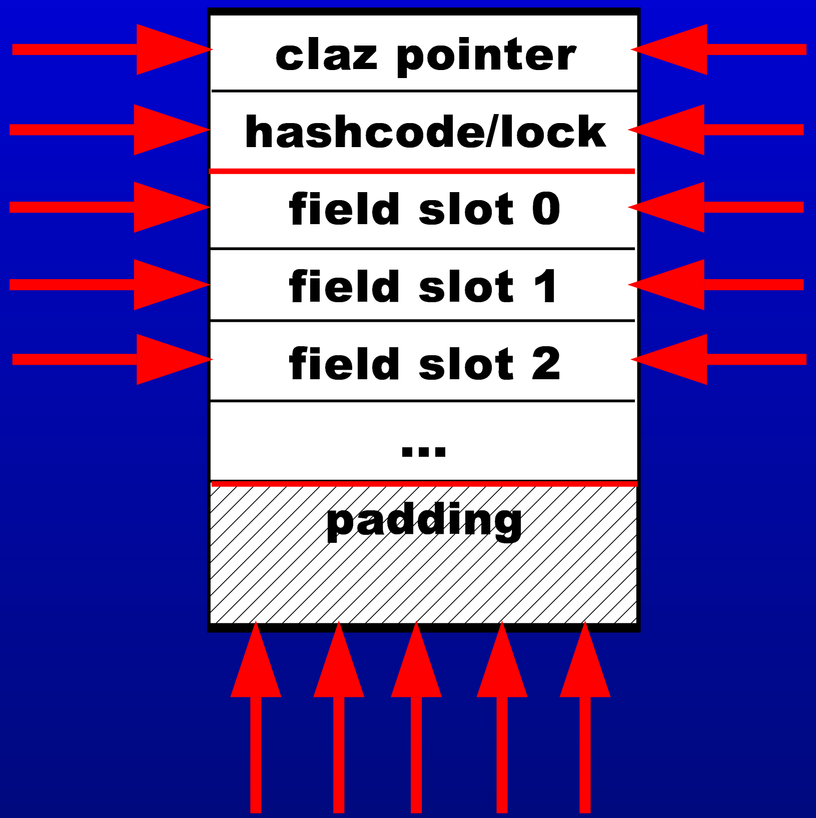
- Typical of many O-O languages.



Strategy

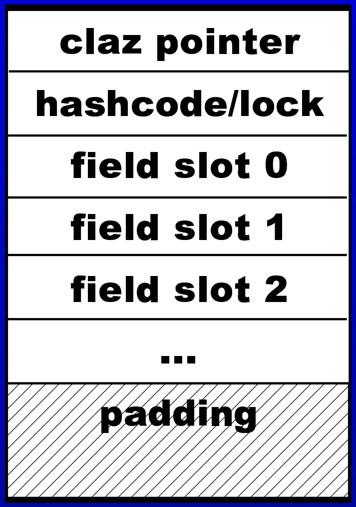
Strategy

Push hard on all the bits.



How to compress objects

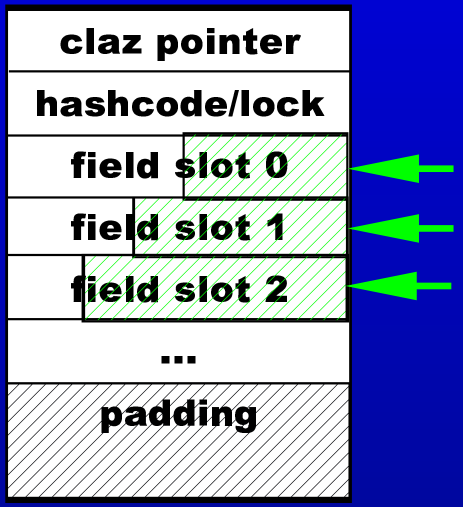
Three broad techniques:



How to compress objects

Three broad techniques:

- Field compression



How to compress objects

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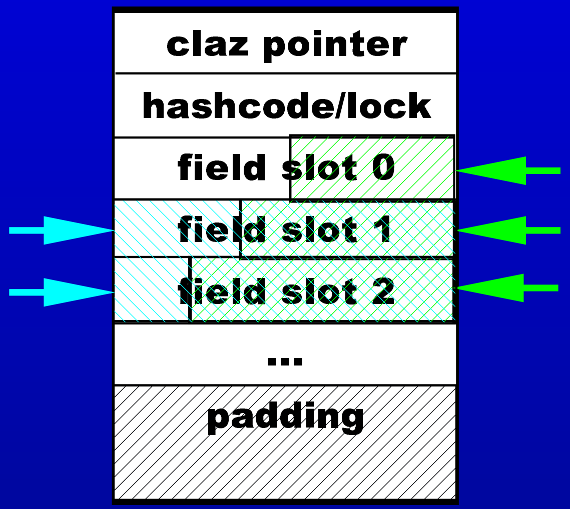
- Field compression
- Mostly-constant field elimination



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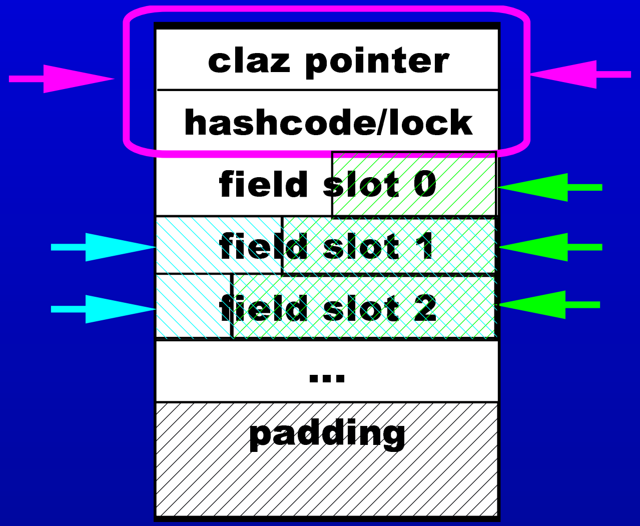

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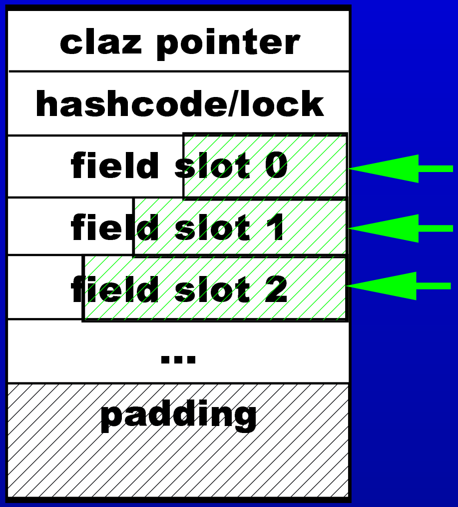

Field Compression

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

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

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

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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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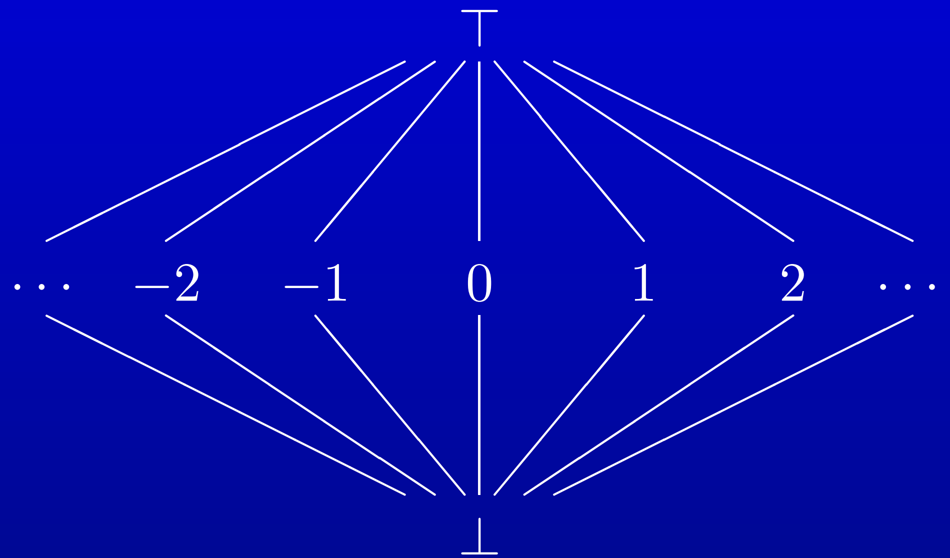

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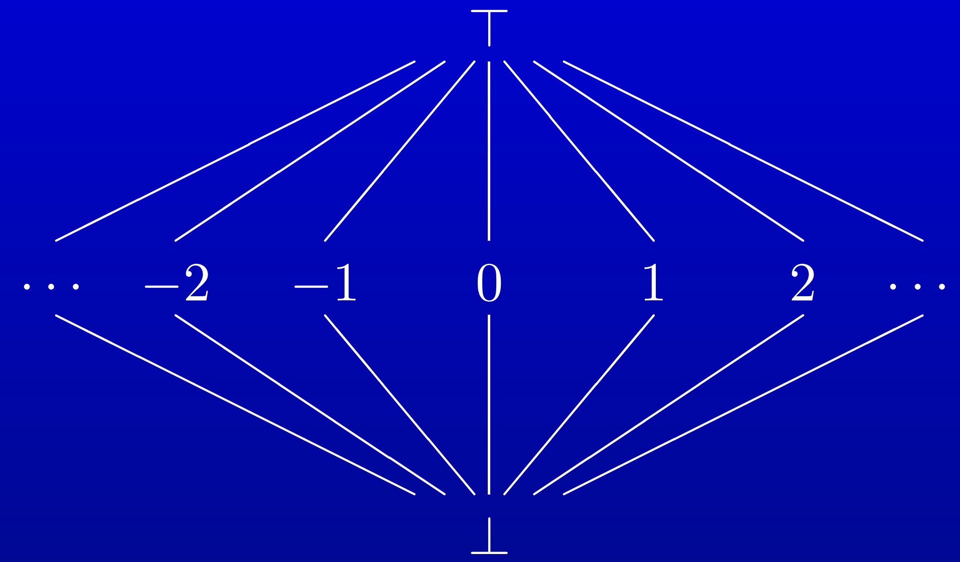

$\boxed{\mathtt{i} = \perp}$

Intraprocedural Analysis

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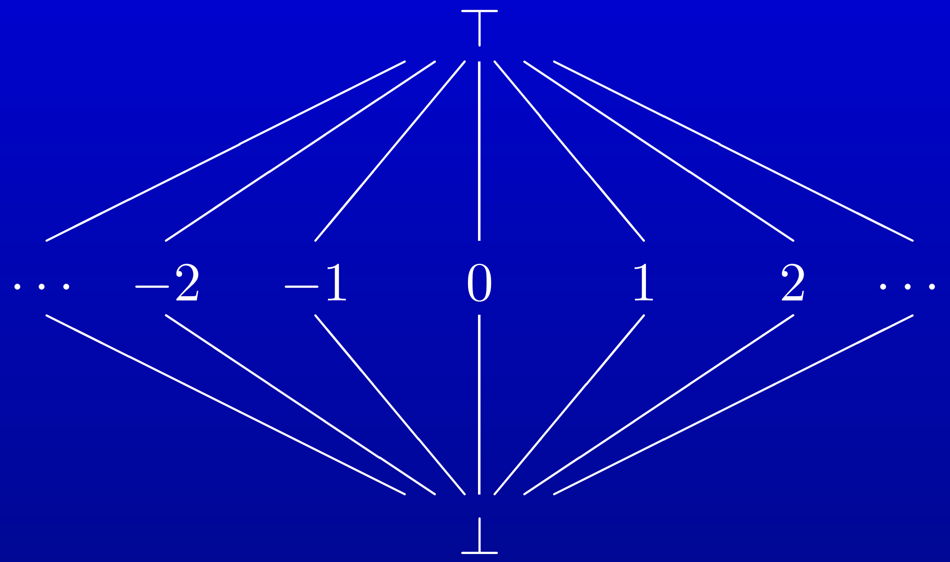

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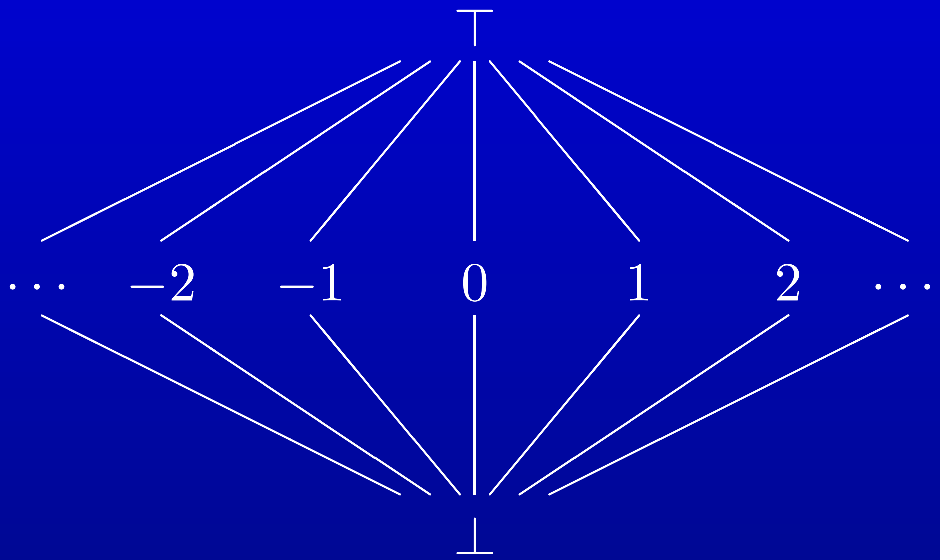

$$\boxed{\texttt{i} = \bot \sqcap 1}$$

Intraprocedural Analysis

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        i=1;
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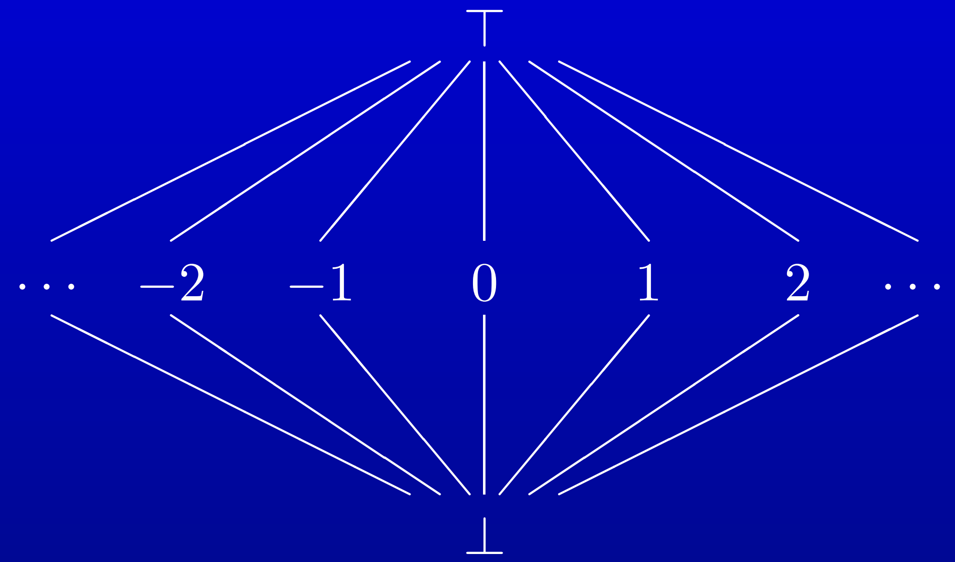

$\boxed{\mathtt{i} = 1}$

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

Intraprocedural Analysis

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int foo() {
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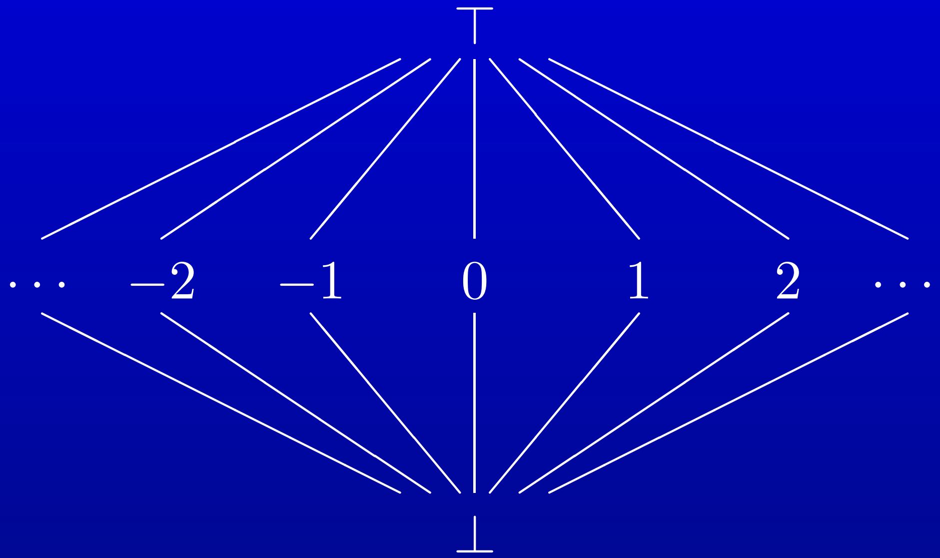

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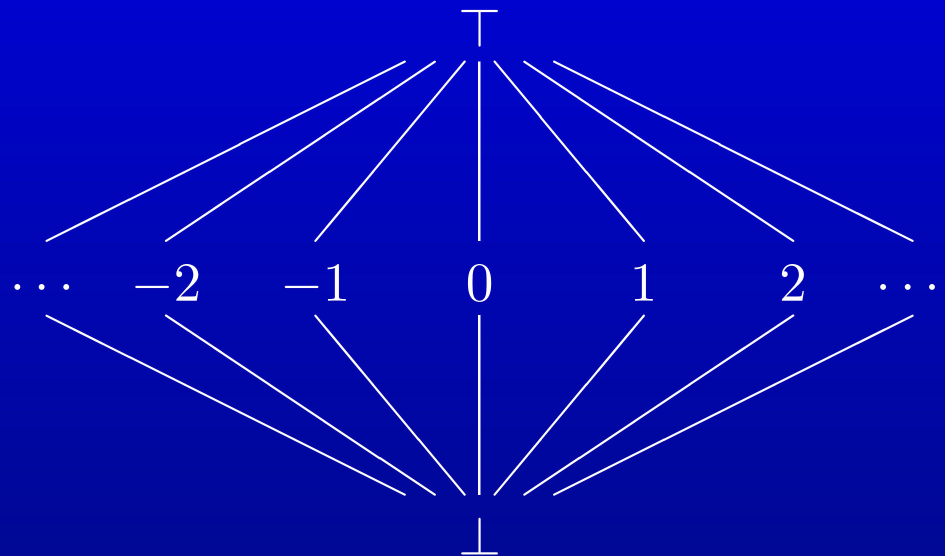

$$\boxed{\texttt{i} = 1 \sqcap 2}$$

Intraprocedural Analysis

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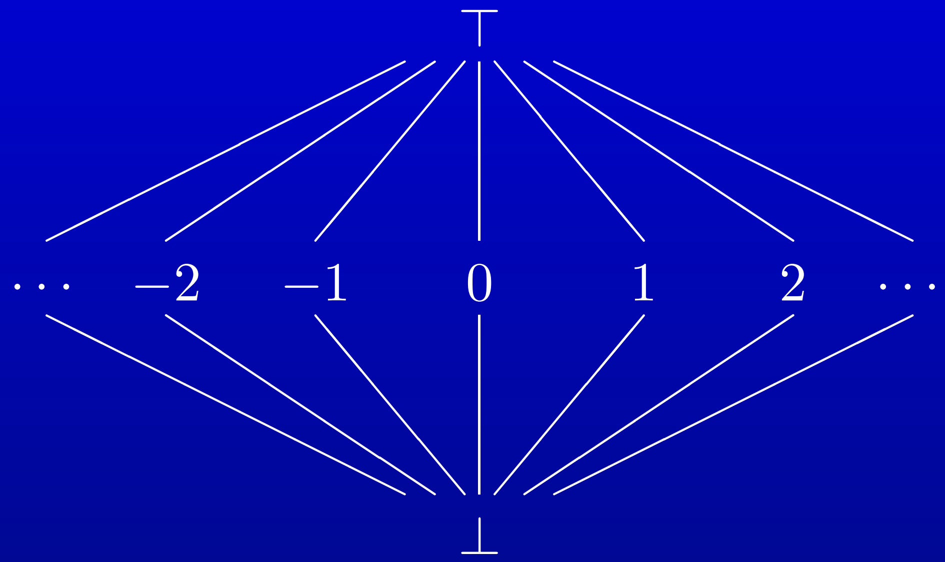

$$\boxed{\mathtt{i} = 1 \sqcap 2 = \top}$$

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

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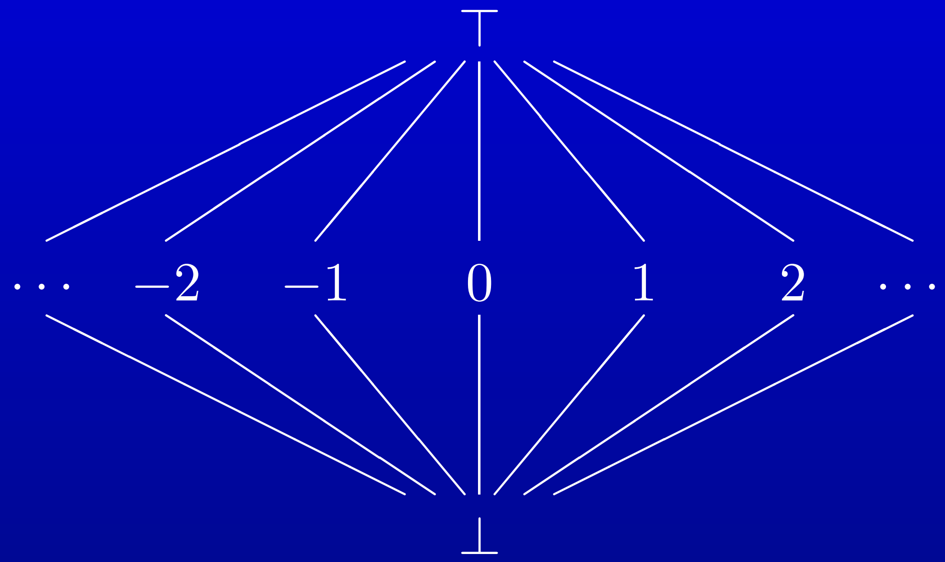

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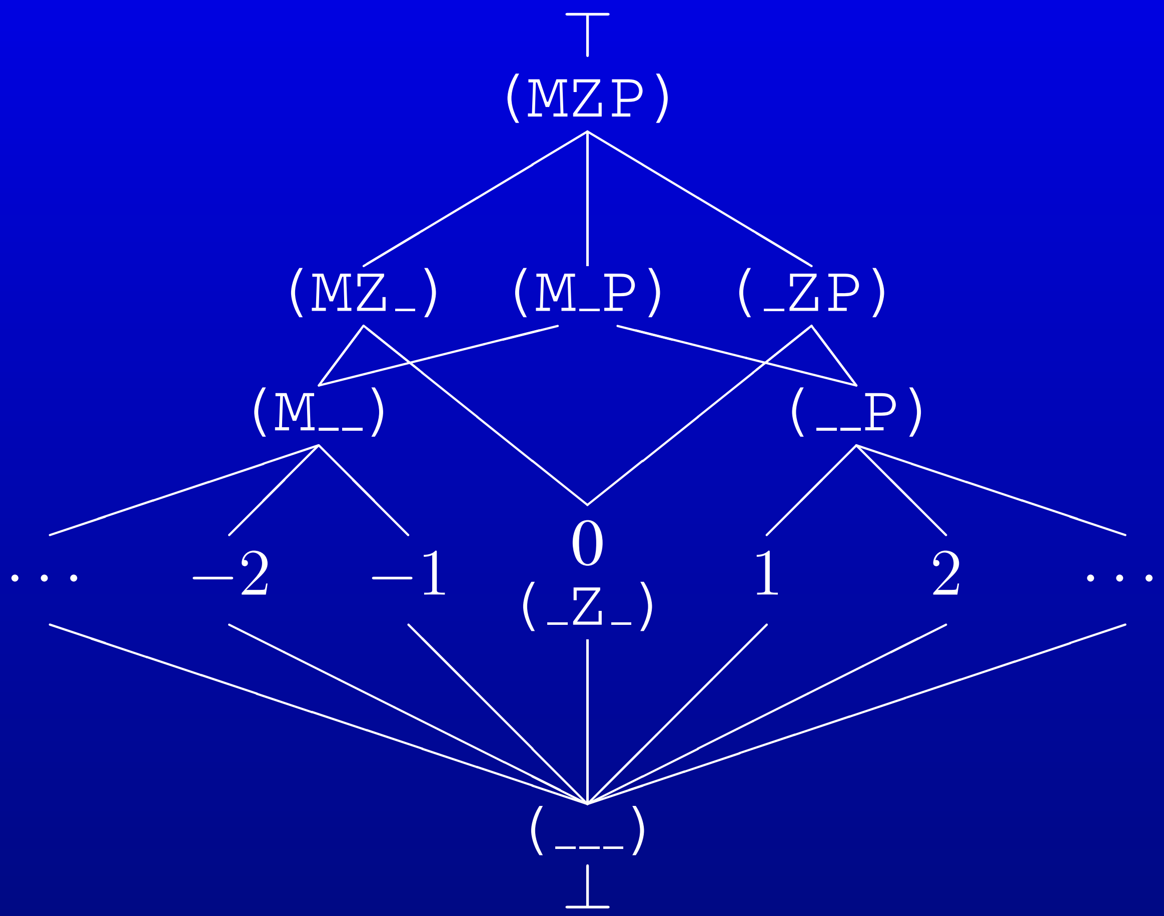
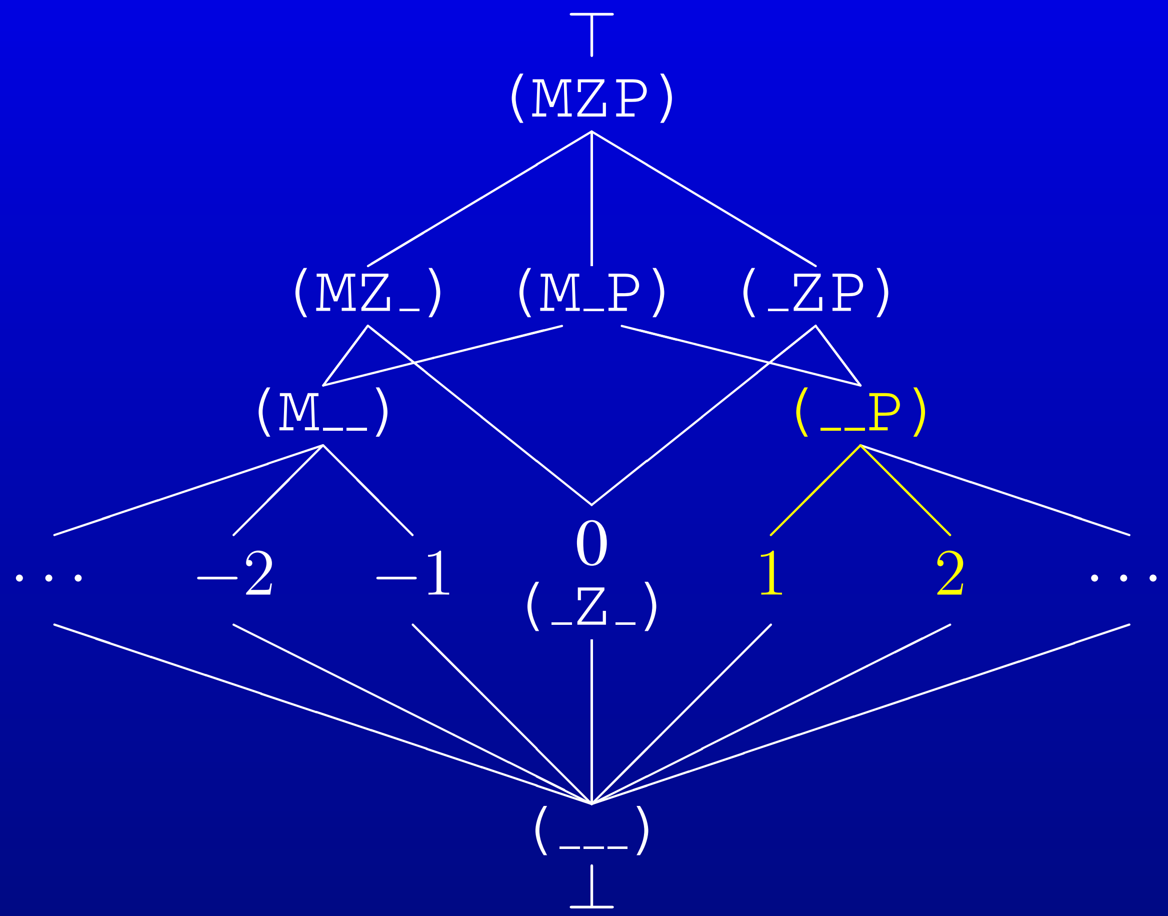
[Because $1 \sqsubseteq \top$ and $2 \sqsubseteq \top$]

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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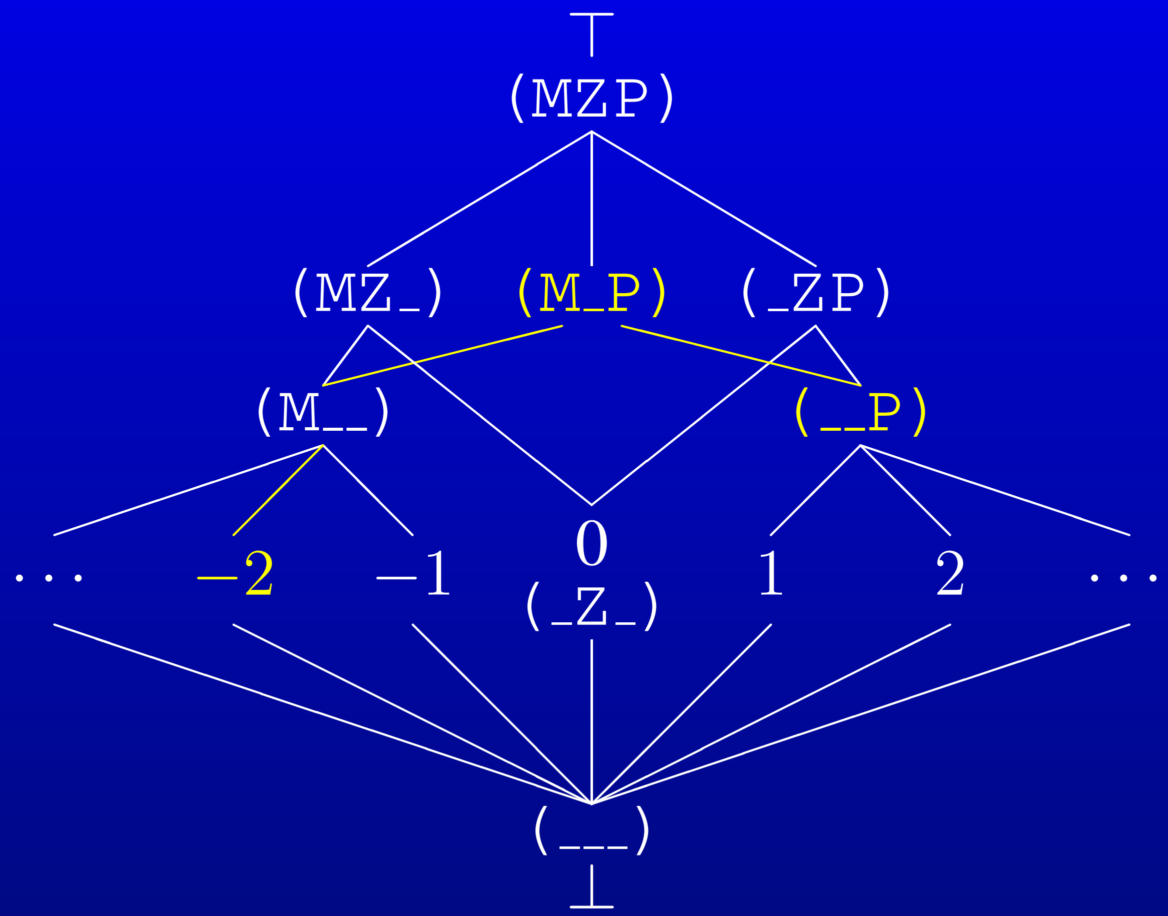

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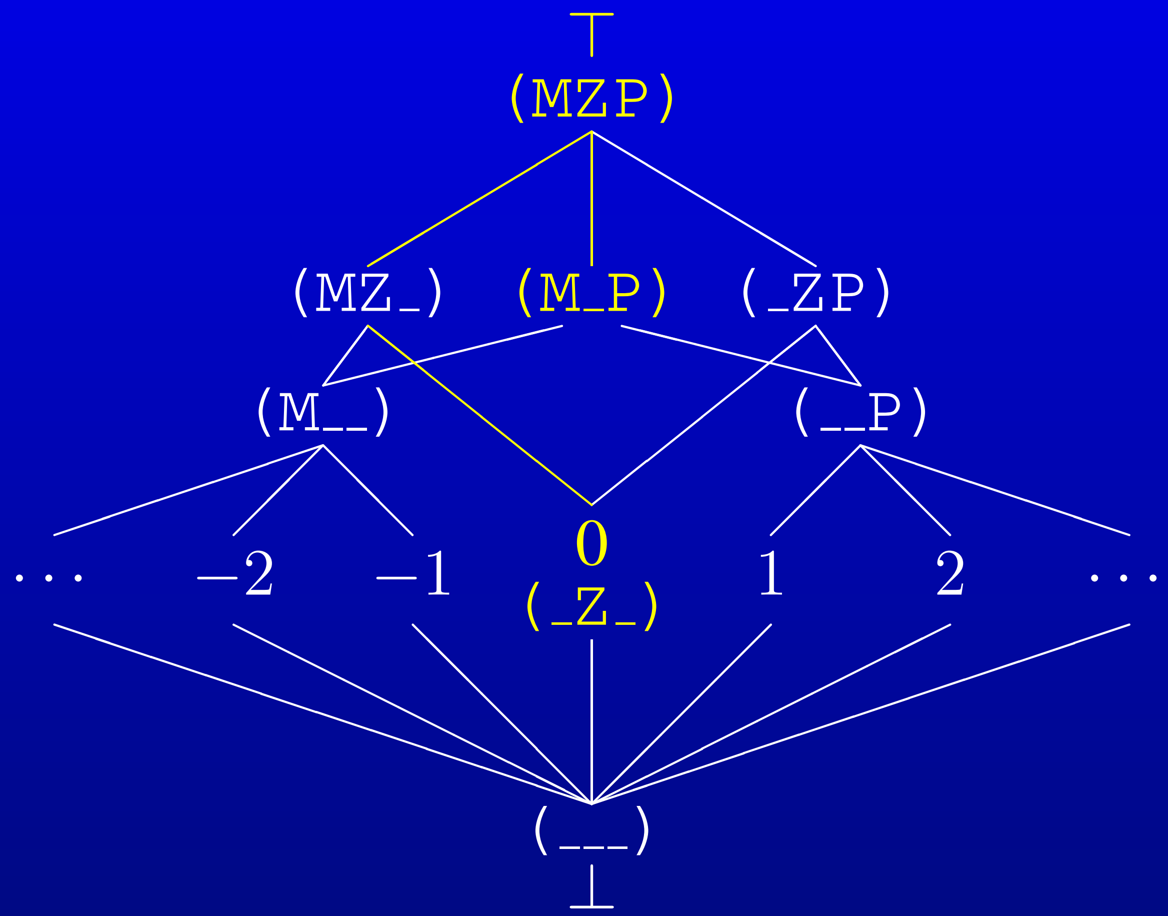

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Example, redux

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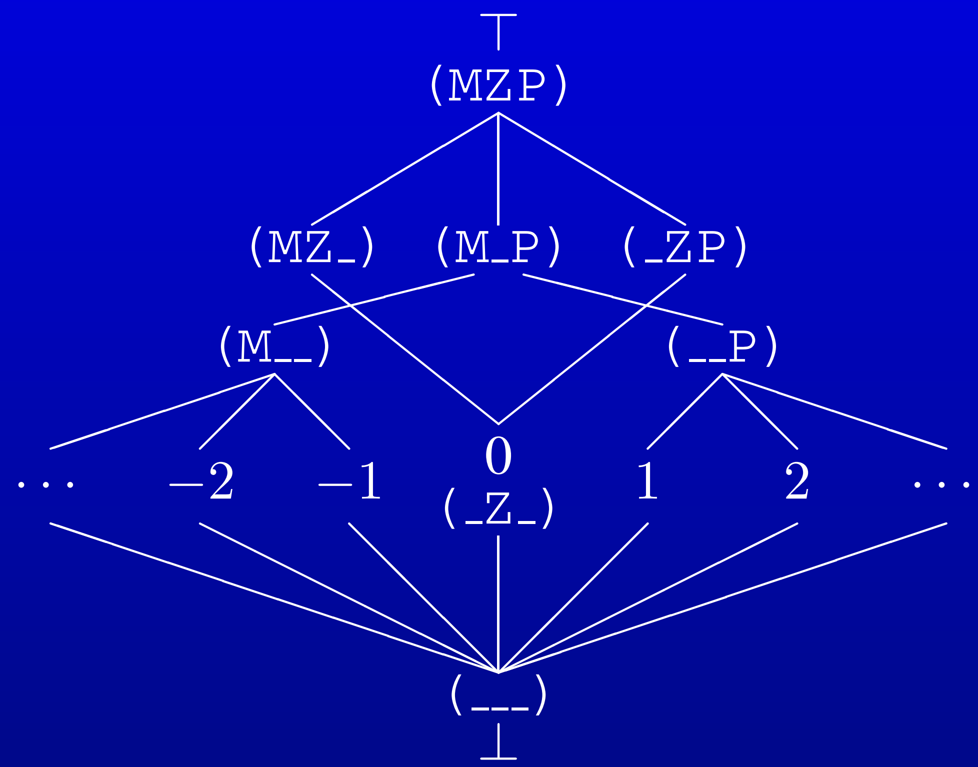

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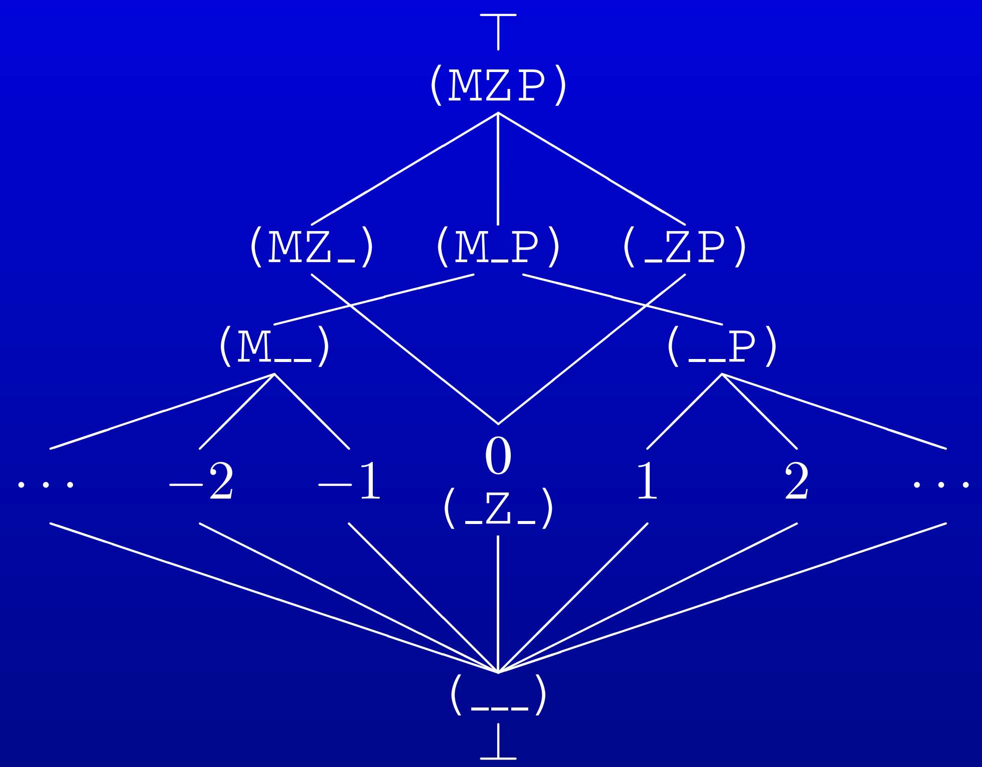

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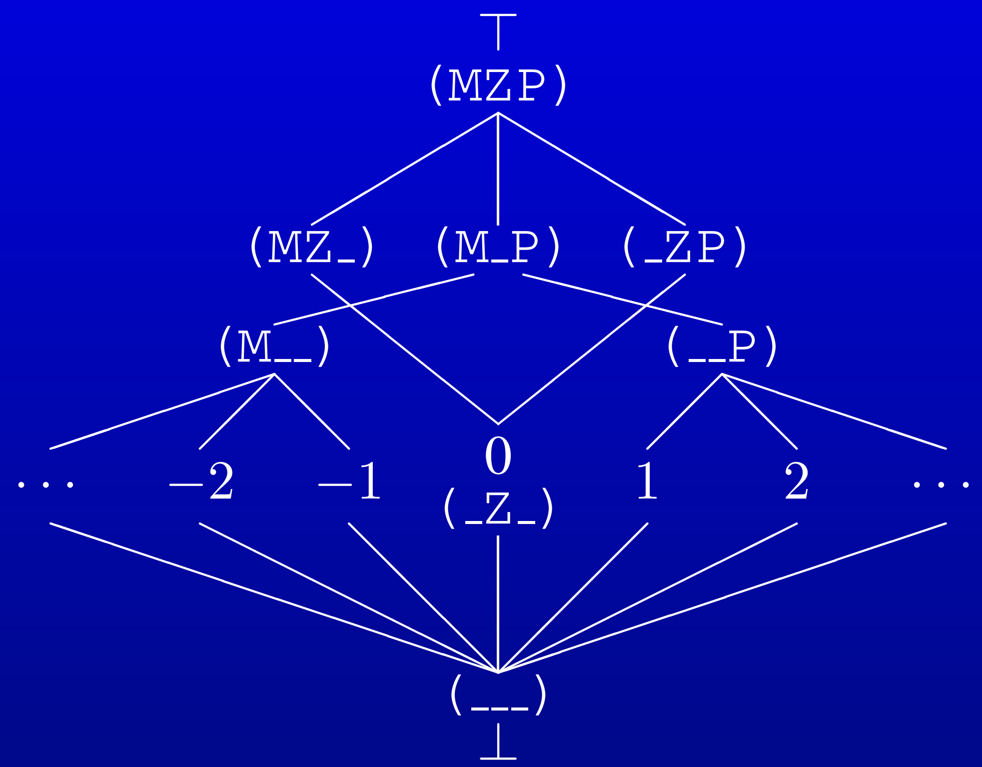

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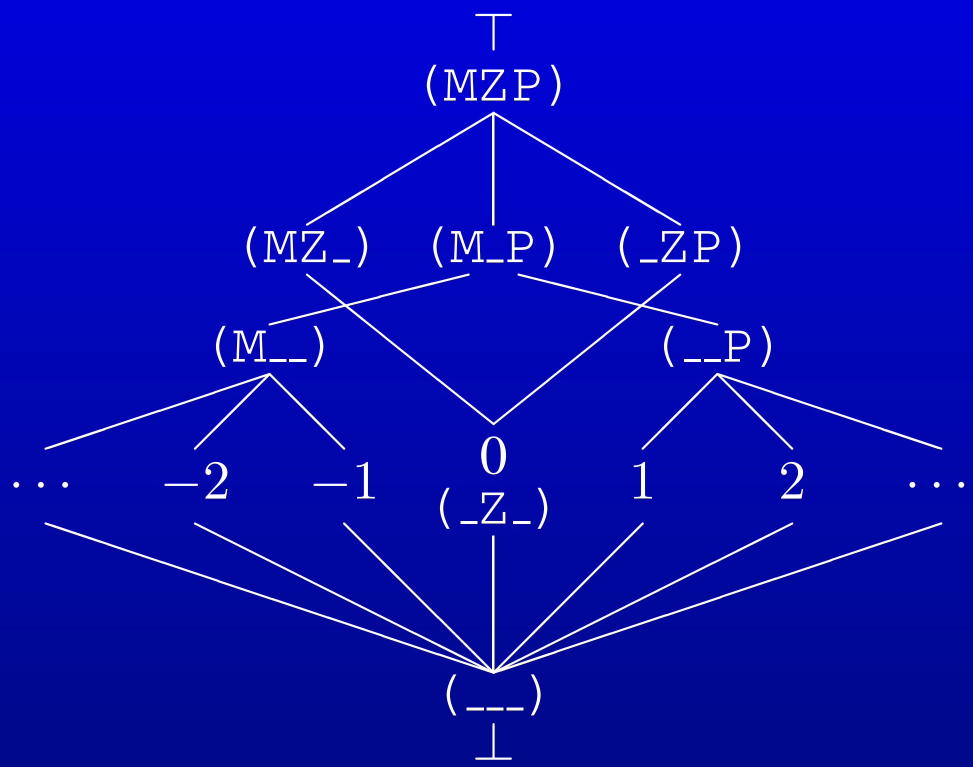

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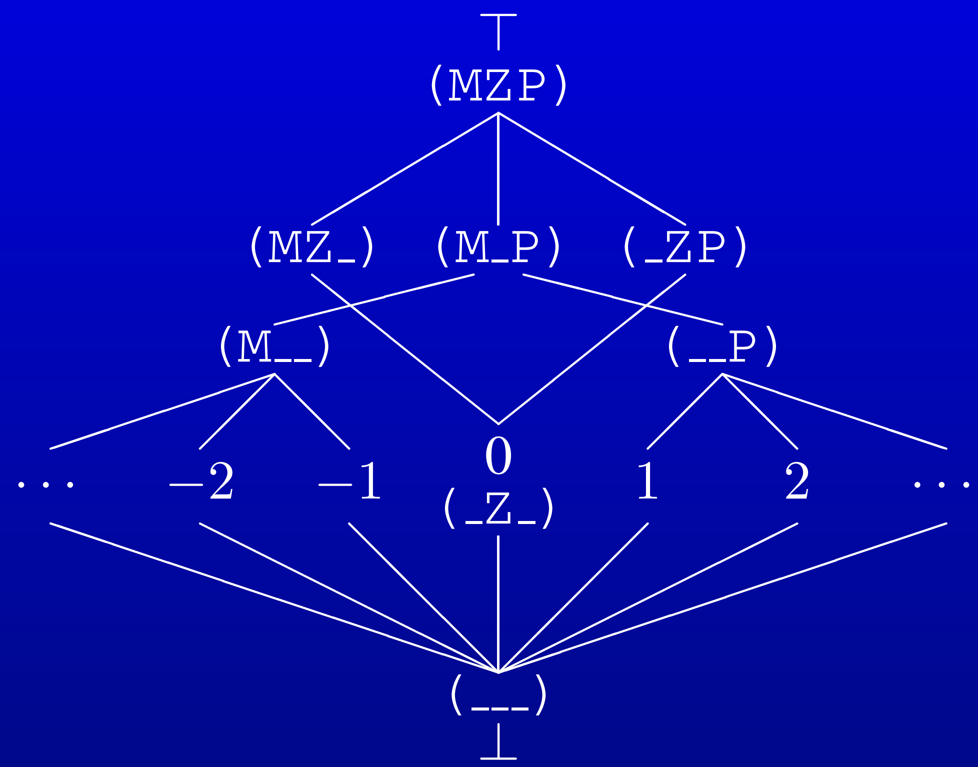

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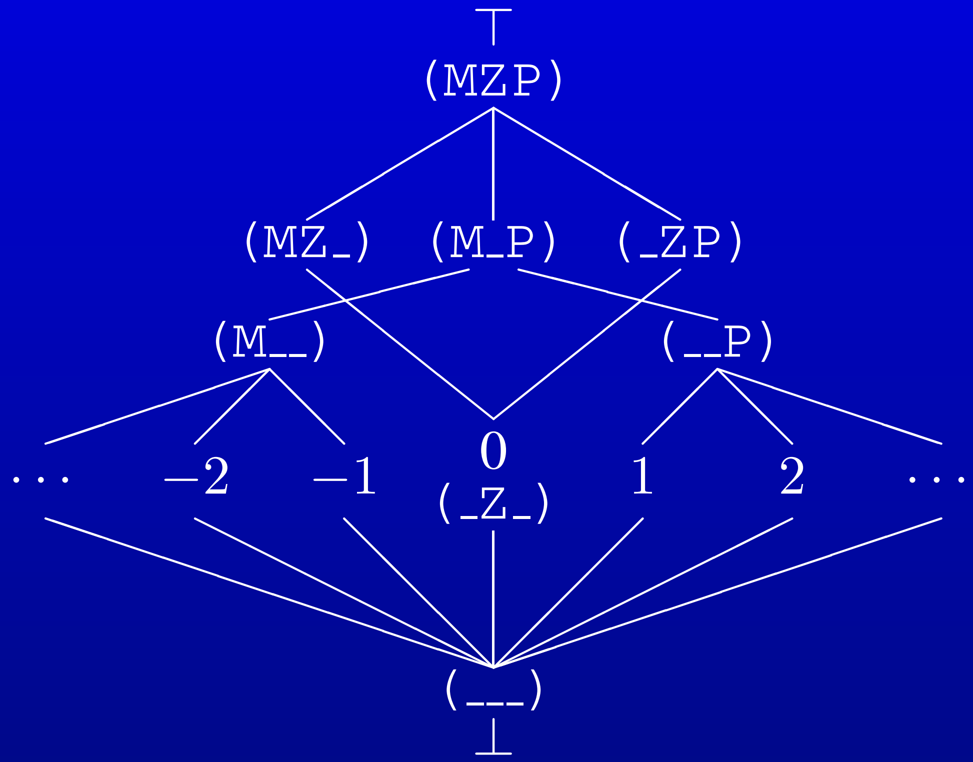

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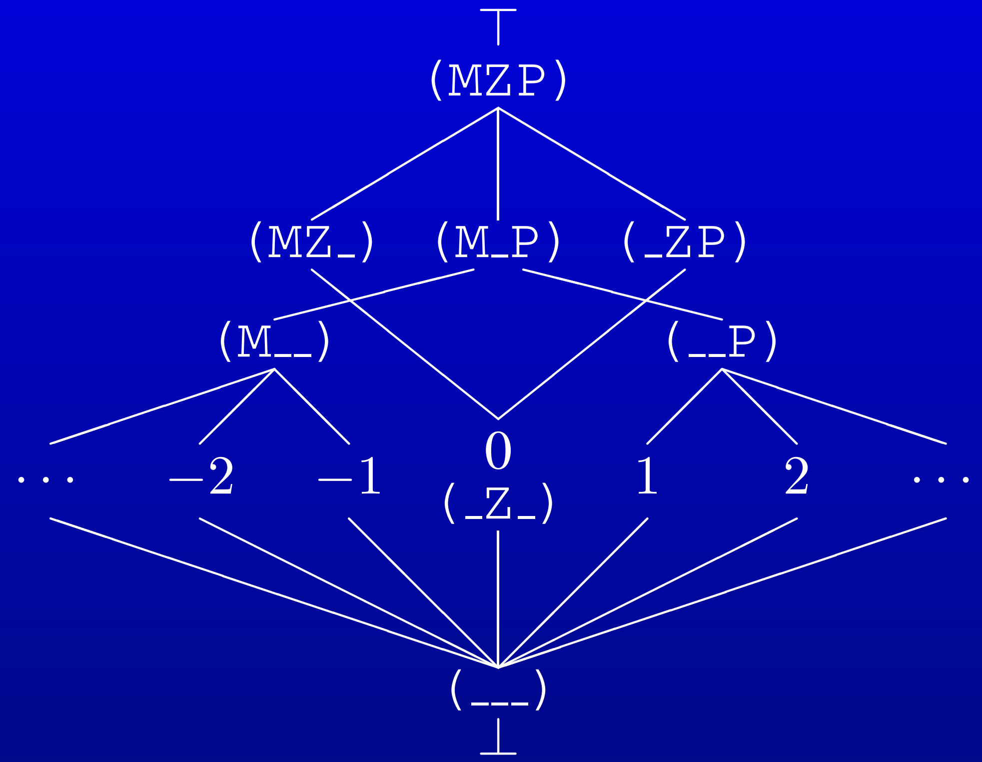

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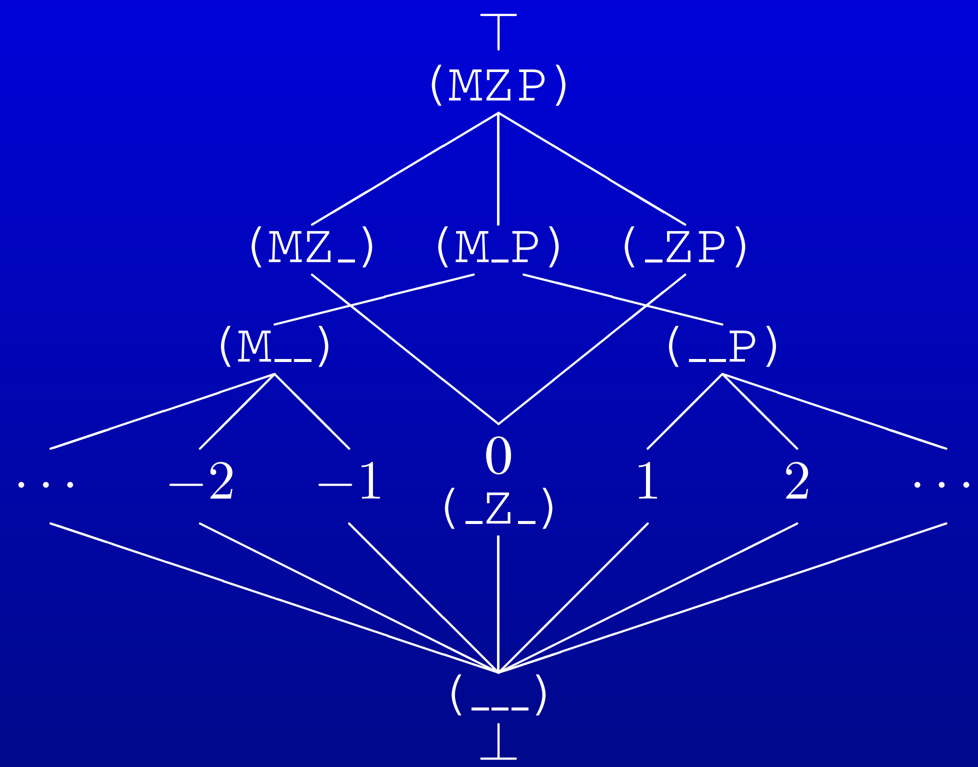

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Extending the lattice

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

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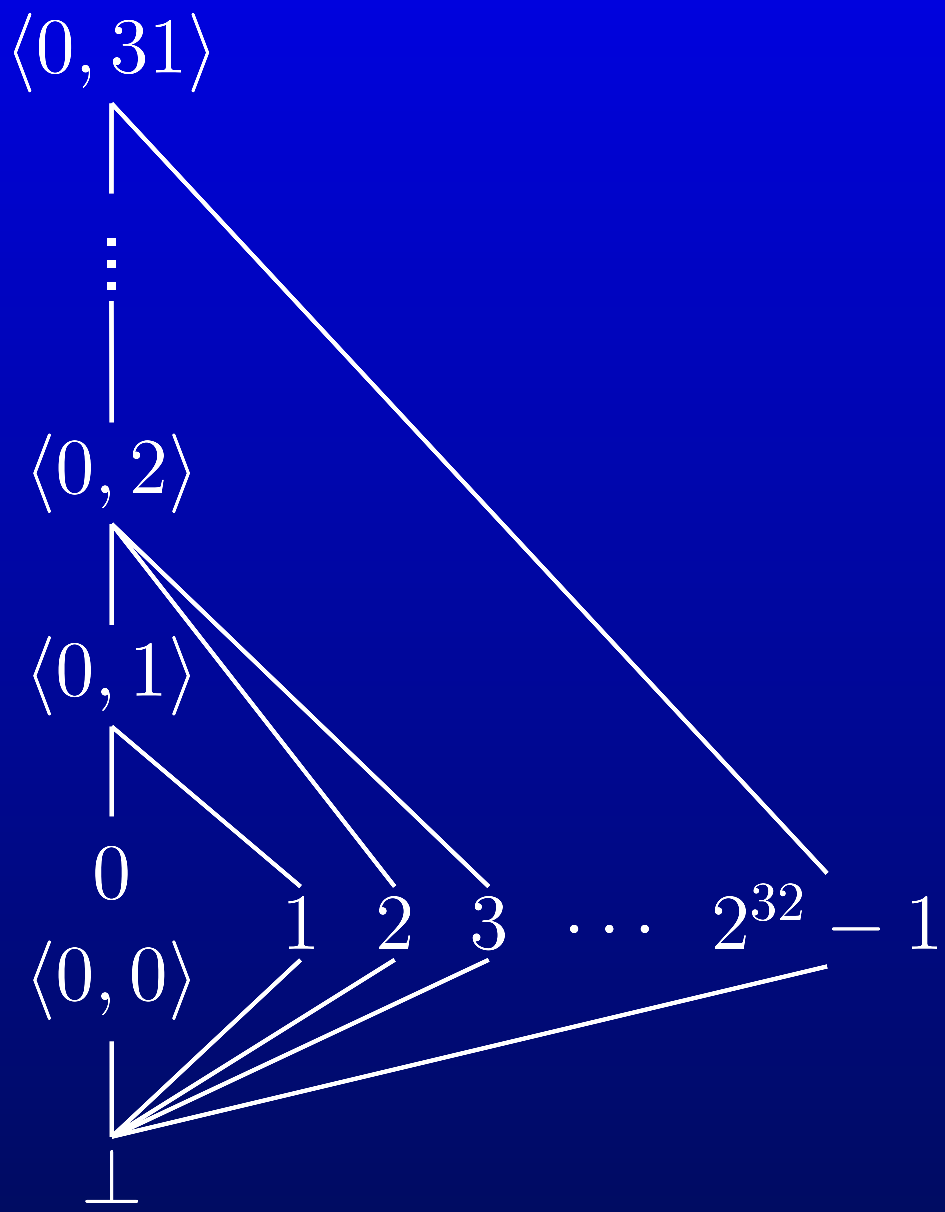
In lattice context:

$$\begin{array}{c} | \\ \texttt{(\_\_P)} \\ | \end{array} \quad \Rightarrow \quad \begin{array}{c} \langle 0, 31 \rangle \\ | \\ \vdots \\ | \\ \langle 0, 3 \rangle \\ | \\ \langle 0, 2 \rangle \\ | \\ \langle 0, 1 \rangle \end{array}$$

Bitwidth lattice detail



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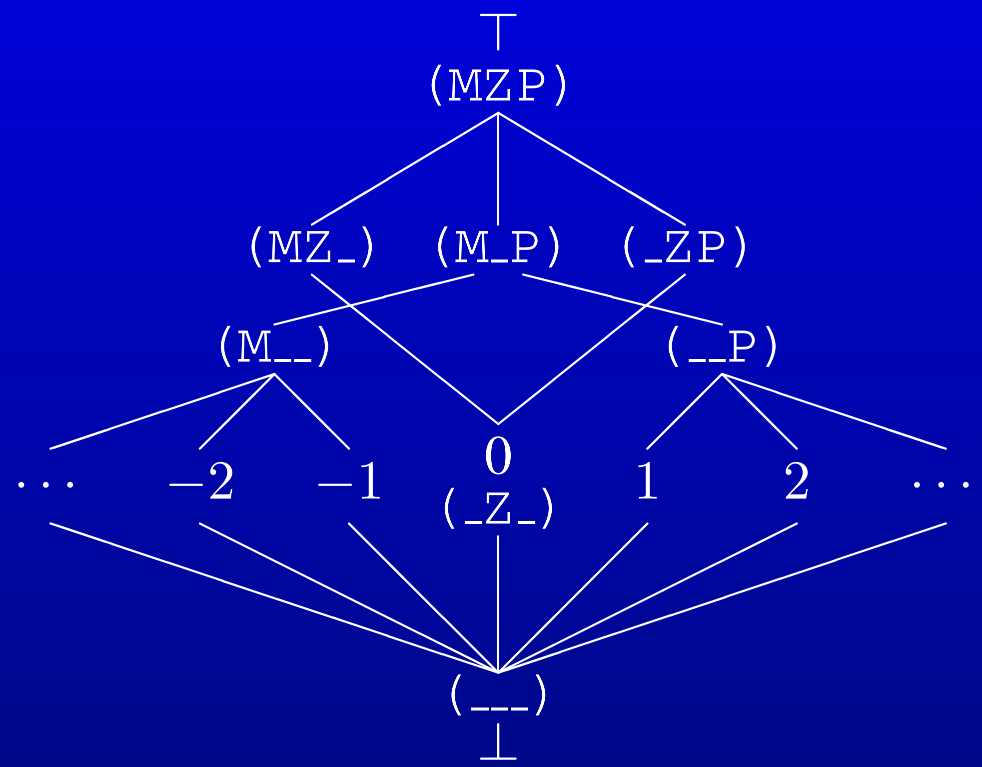

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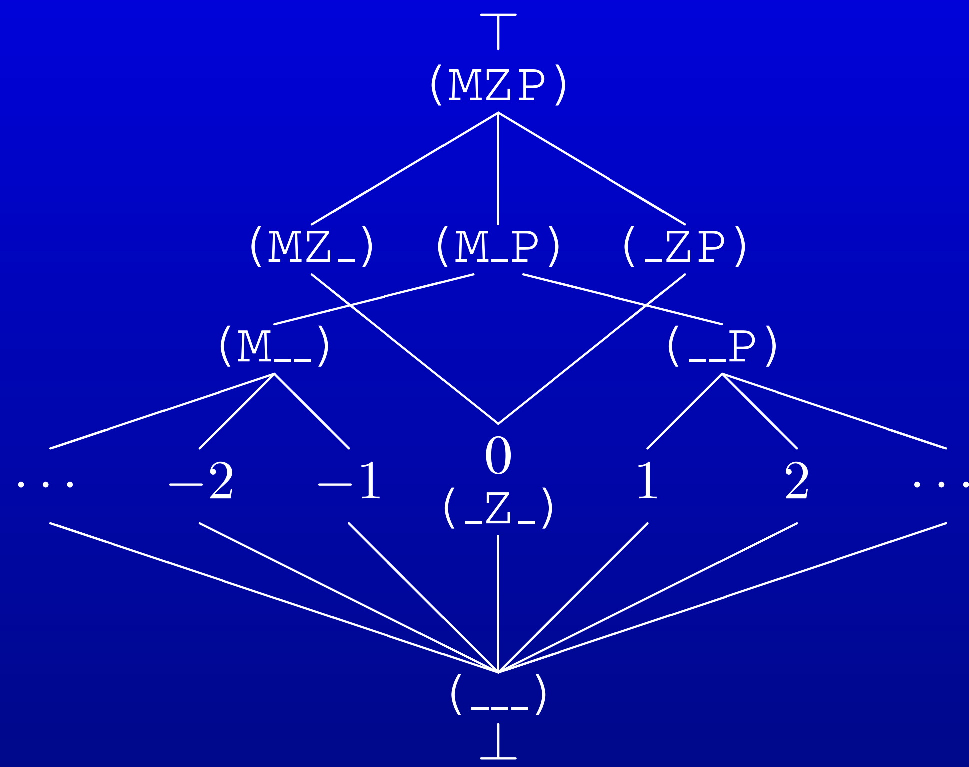

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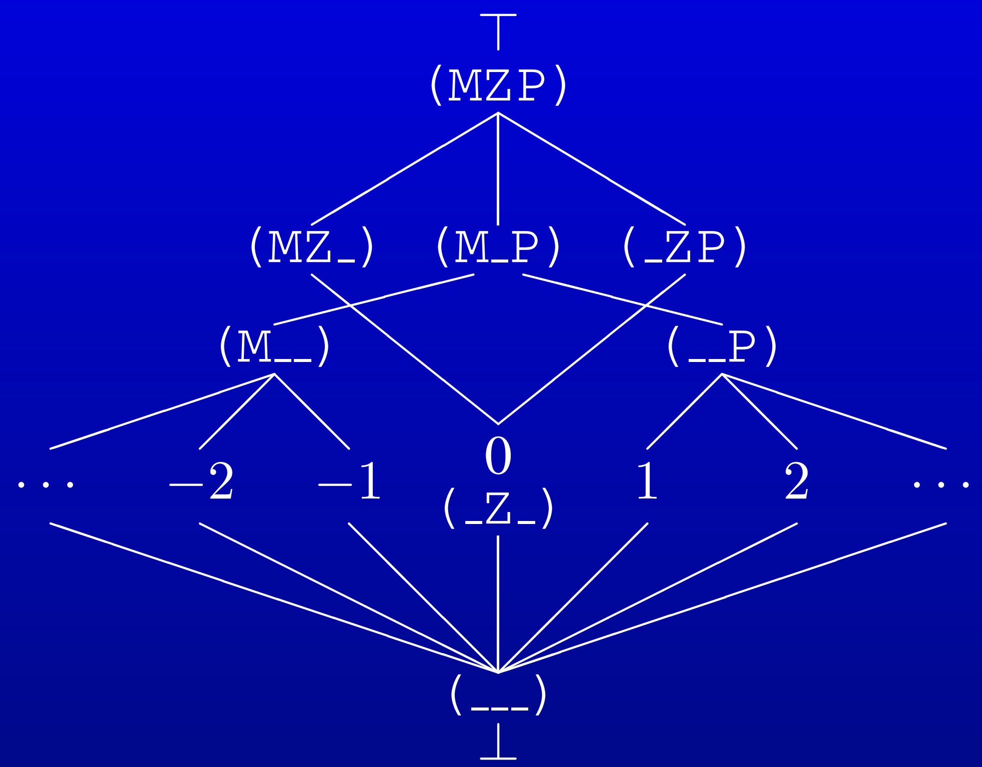

$$\boxed{\mathtt{i} = \bot \sqcap 1}$$

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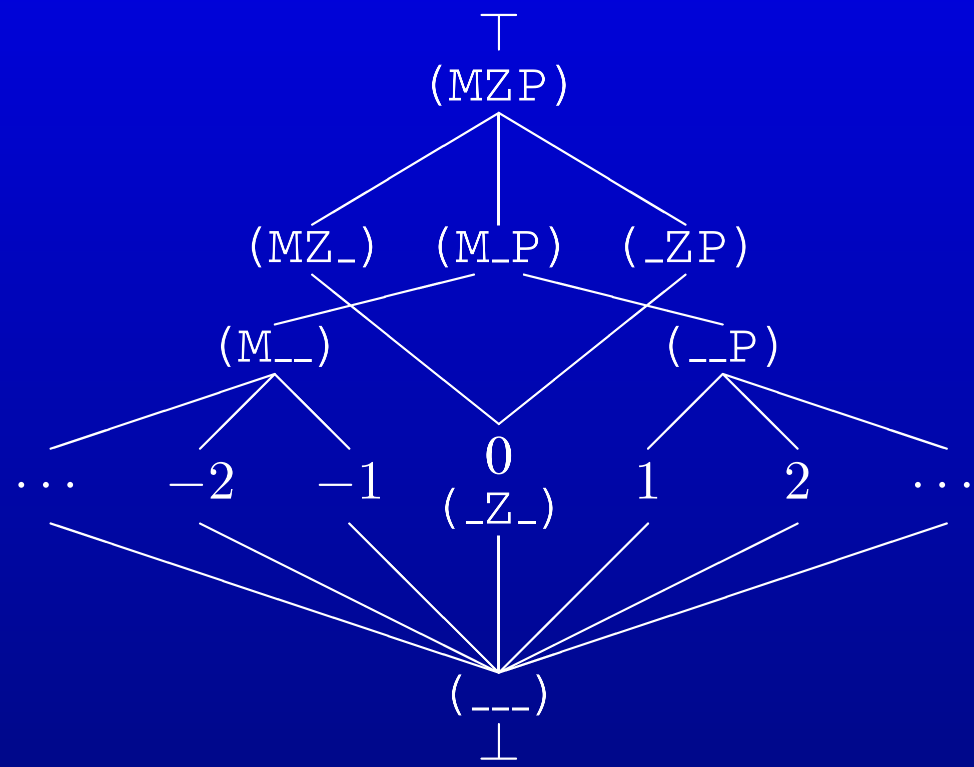

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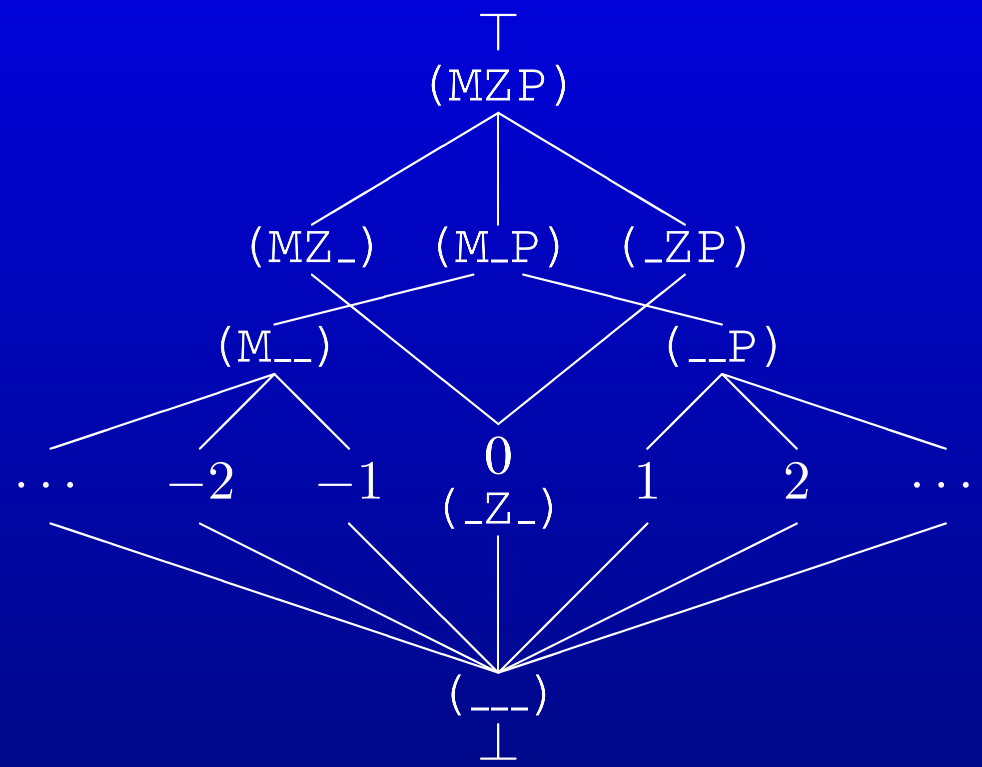

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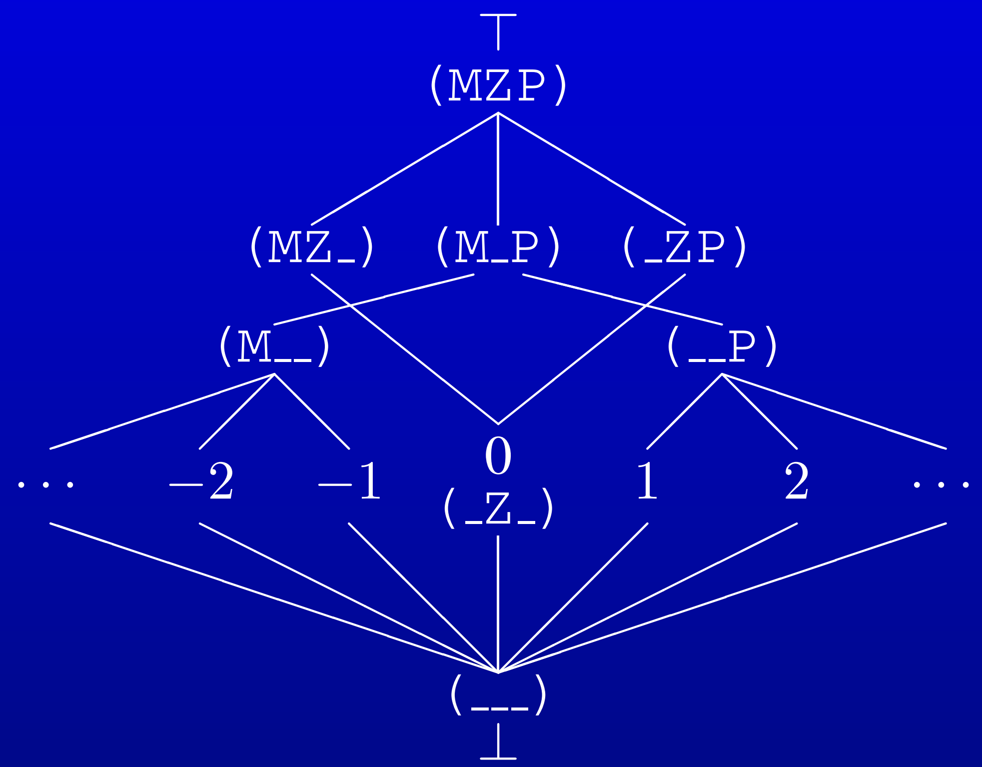

$$\boxed{\mathtt{i} = 1 \sqcap 2}$$

Example redux, redux

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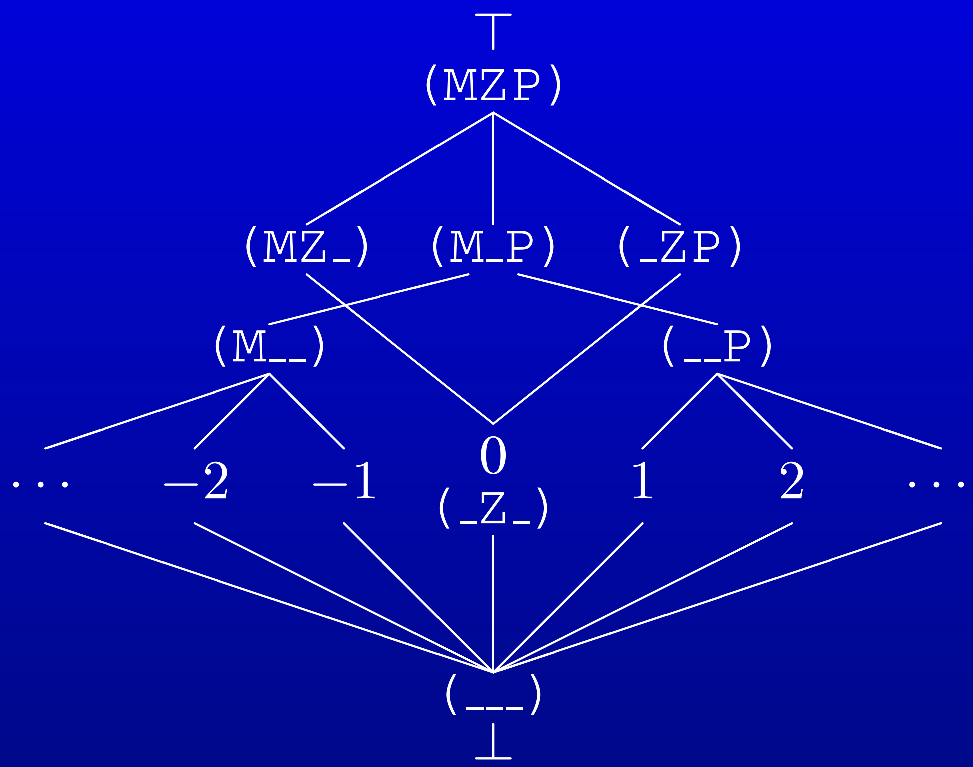
        i=2;
    if (i>0)
        ⋮
}
```



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

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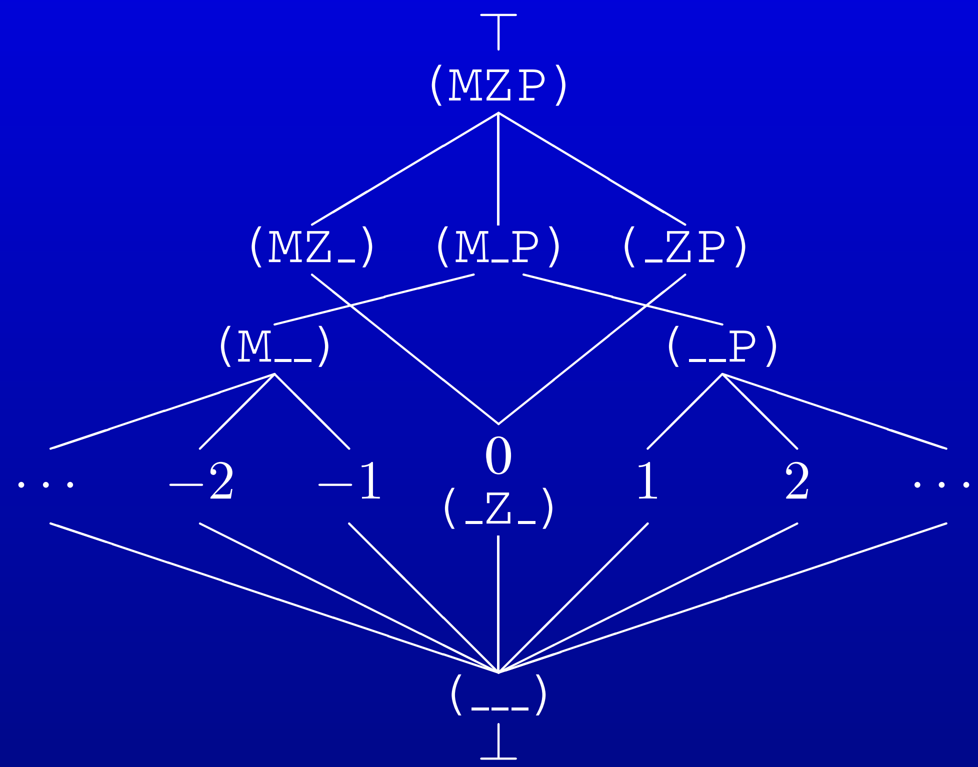


$$\boxed{\mathtt{i} = 1 \sqcap 2 = \langle 0, 2 \rangle}$$

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 (...)
        a.f=1;
    else
        b.f=2;
    if (c.f>0)
        ⋮
}
```

Interprocedural analysis

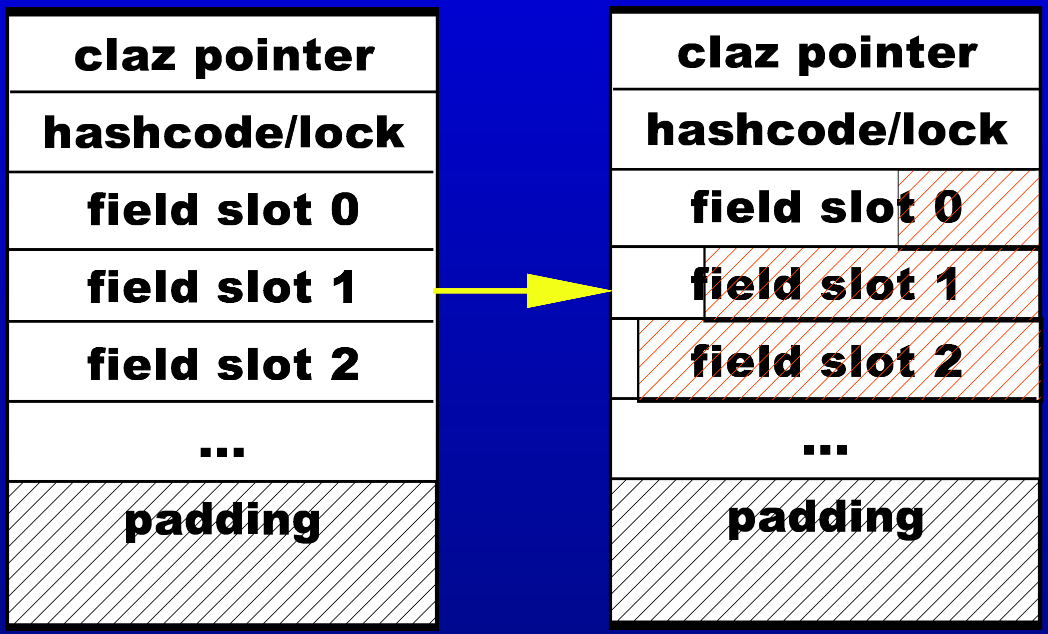
```
int foo() {
    if (...)
        a.f=1;
    else
        b.f=2;
    if (c.f>0)
        ⋮
}
```

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

All cars are black

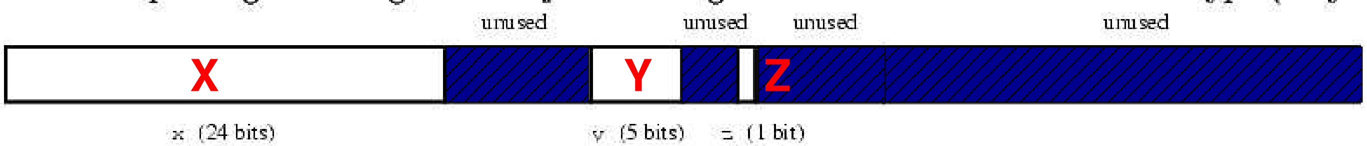
```
void paint(int color) {
    if (this.model == FORD)
        color = BLACK;
    this.color = color;
}
```

Field compression using bitwidths

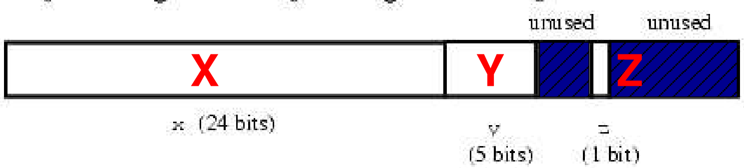


Field packing

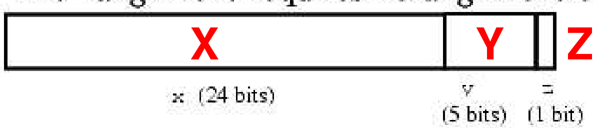
Standard packing word-aligns the object and aligns each field to the width of its type (4-byte data is 4-byte aligned):



“Byte” alignment byte-aligns the object and all fields:



“Bit” alignment requires no alignment of objects or fields:



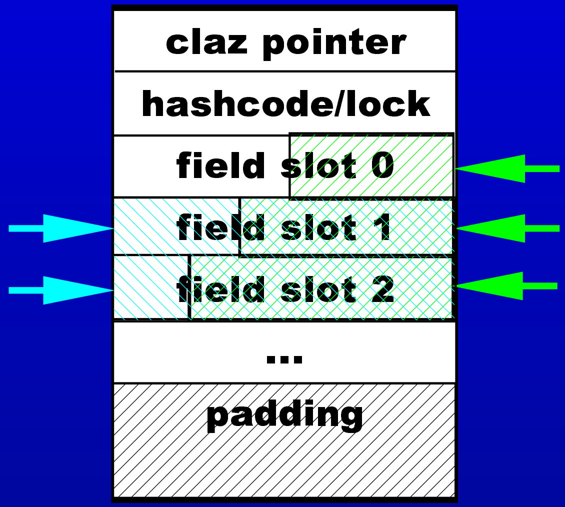

```
class A {
    int x; /* actual width 24 bits */
    byte y; /* actual width 5 bits */
    boolean z; /* actual width 1 bit */
}
```

Object header omitted.

How to compress objects

Three broad techniques:

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



Mostly-constant field elimination

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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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public final class String {
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    ...
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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);
    }
}
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Specialization example:

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    ...
    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;
}
```

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    this.count = val.length;
}
```

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, 1);

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.
- Can be done recursively on multiple fields.
  - Profiling guides splitting order if there are multiple candidates.
- 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.

Key properties (revisited)

To use static specialization we need:

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Key properties (revisited)

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Creating external fields

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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$\rightarrow$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 {
    private final char value[];
    private final int offset;
    private final int count;
    public char charAt(int i) {
        return value[offset+1];
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```
public final class String {
    private final char value[];
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    private final int count;
    public char charAt(int i) {
        return value[getOffset()+1];
    }
    public String substring(int start) {
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        int ncnt = count - start;
        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
Object	Field	Value
Object	Field	Value
Object	Field	Value
Object	Field	Value
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...	...	...

Key **Value**

- “open addressed” for low overhead.

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- load-factor of 2/3
- 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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- 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%.

Other details

- Use value profiling to identify classes where field externalization will be worthwhile.

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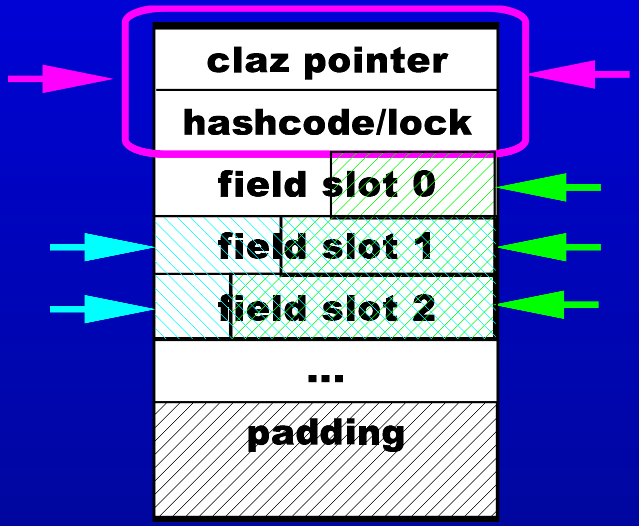
- Use value profiling to identify classes where field externalization will be worthwhile.
- In our experiments, looked for integer "mostly-constant" values in the range $[-5, 5]$ for numeric types. Only looked at `null` as a candidate for pointer types.
- 0 and 1 by far the most common.

How to compress objects

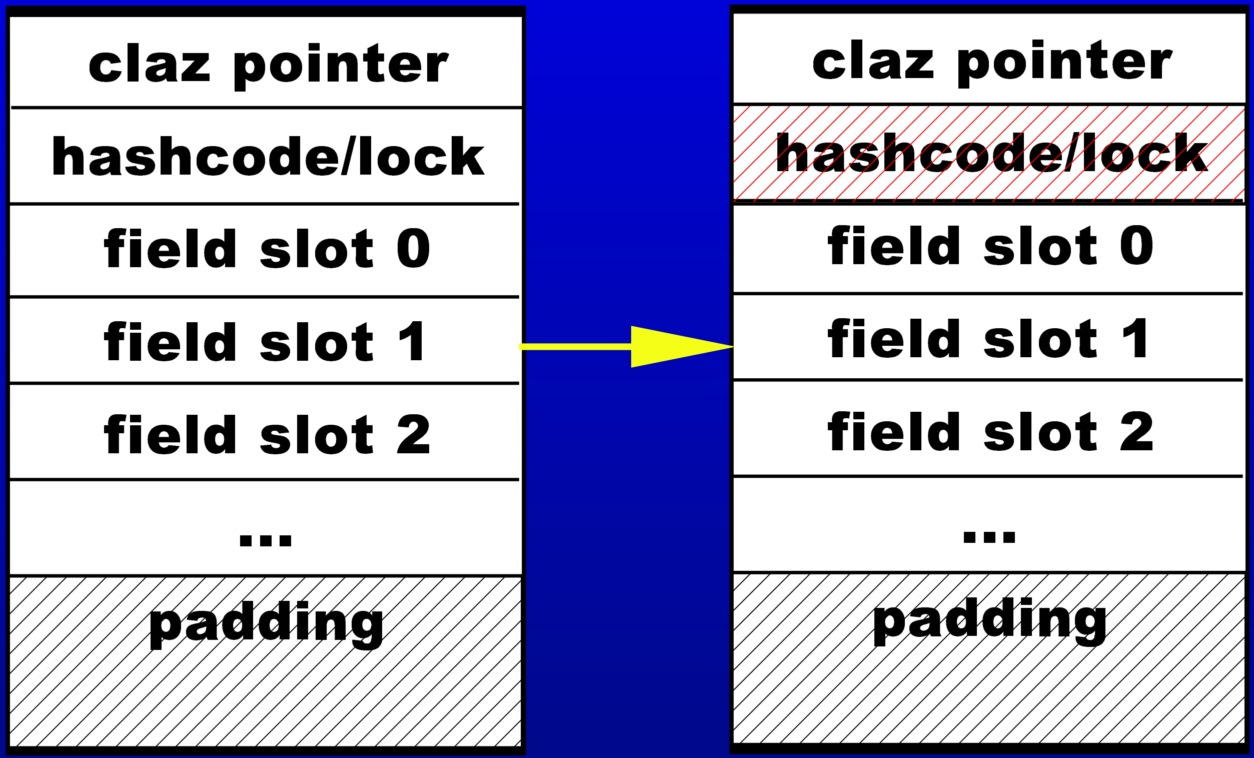
Three broad techniques:

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



Header optimizations:

Hashcode/Lock compression



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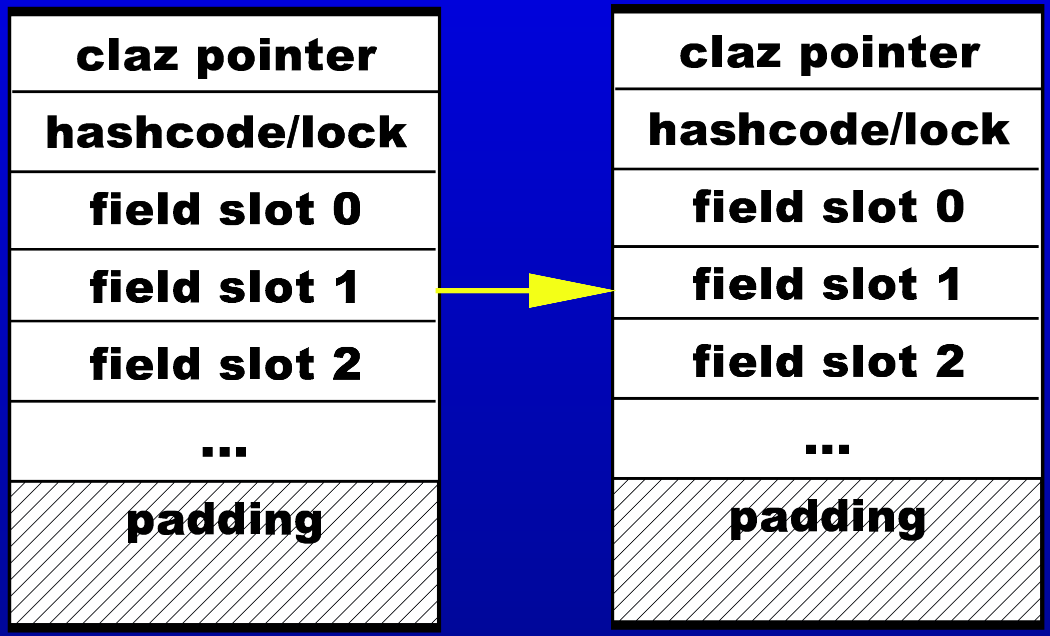
- Implemented as a special case of field externalization.
- The hashcode/lock field often unused because:
  - Most objects do not use their built-in hashcode.
  - Most objects are not synchronization targets.
- Could also use a static pointer analysis.

Header optimizations:

claz compression



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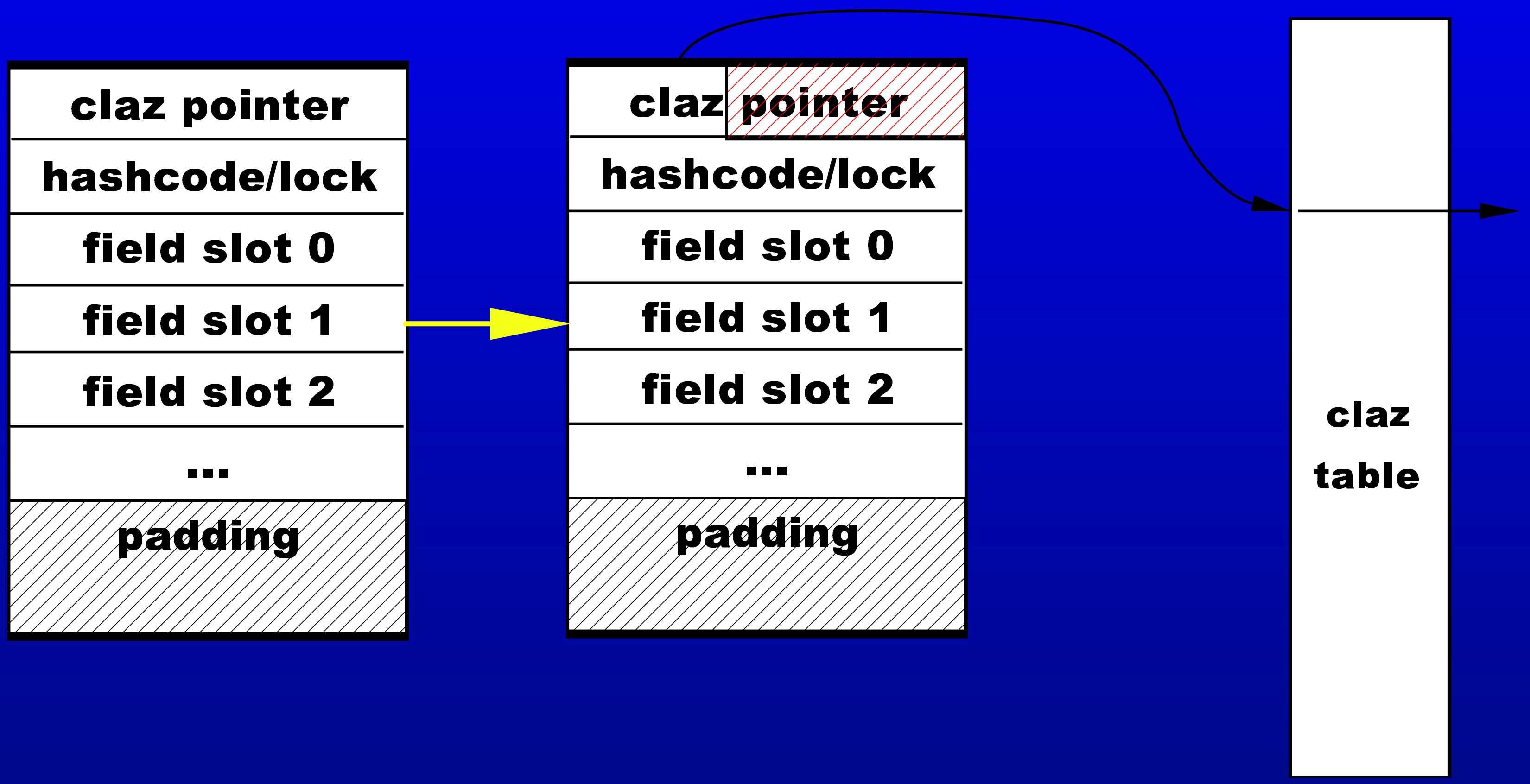

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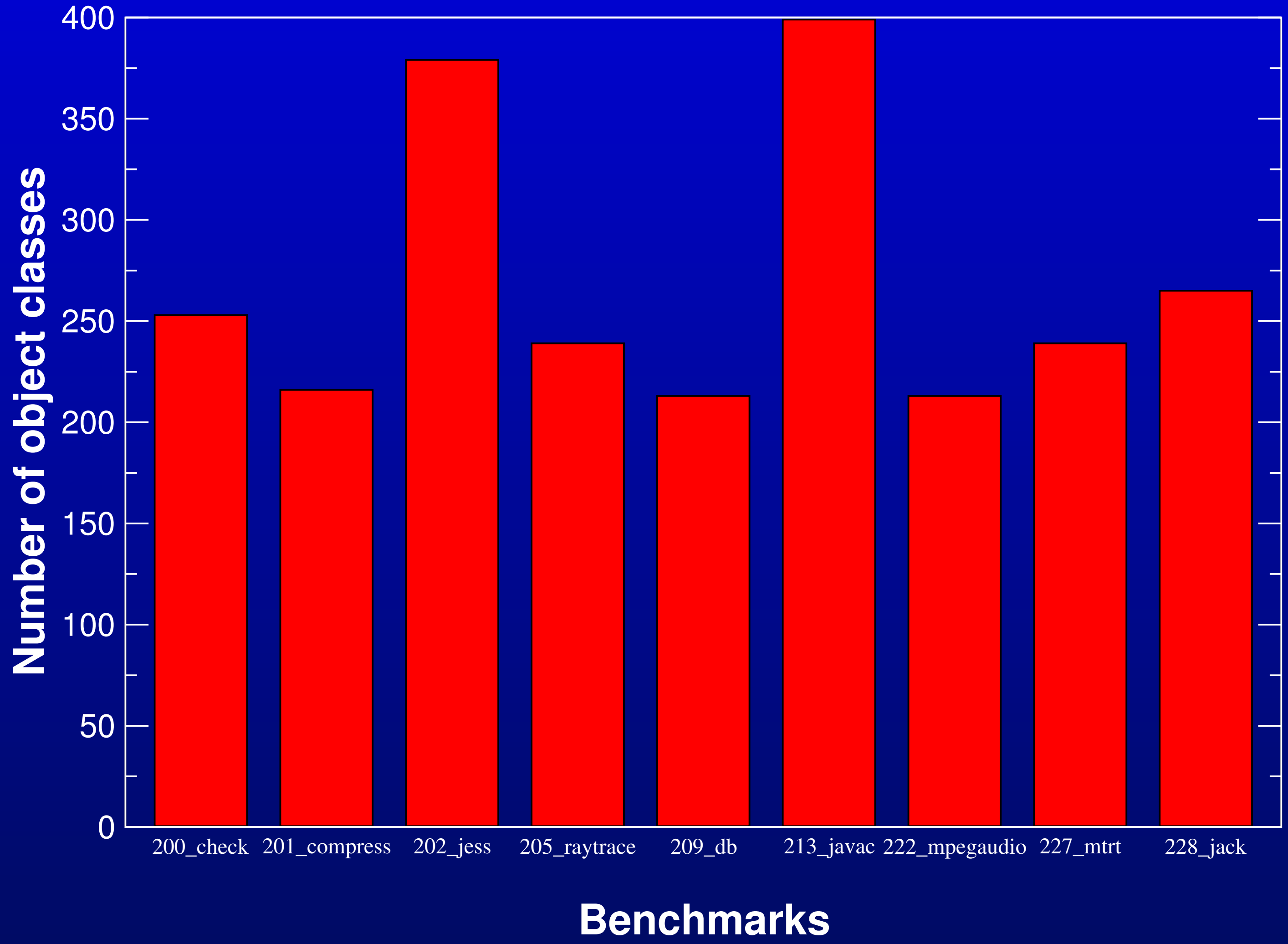
- With co-operation of GC, works in dynamic environments.
- Many applications use less than 256 object types.

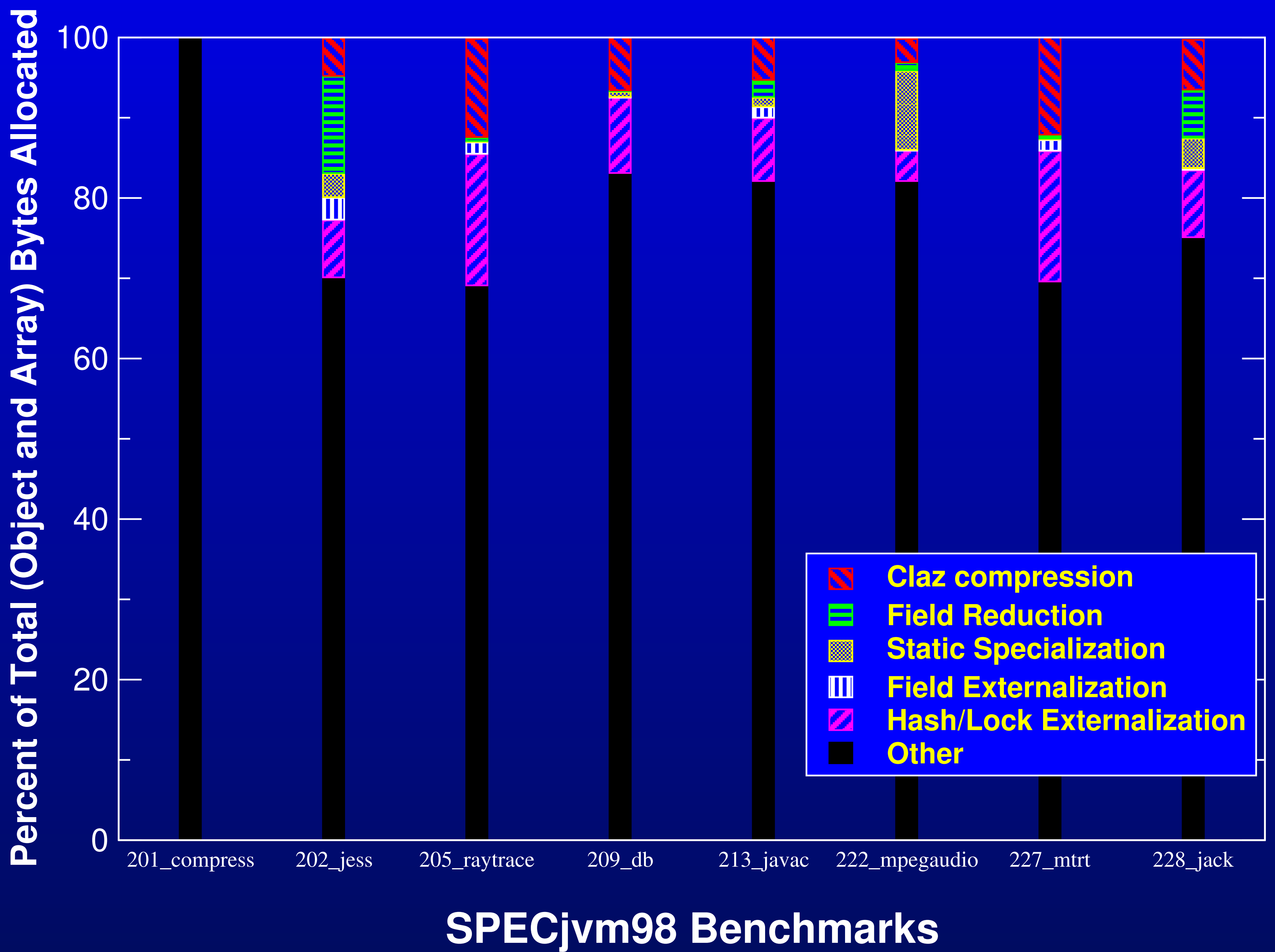
Class statistics

Class statistics for applications in SPECjvm98 benchmark suite:

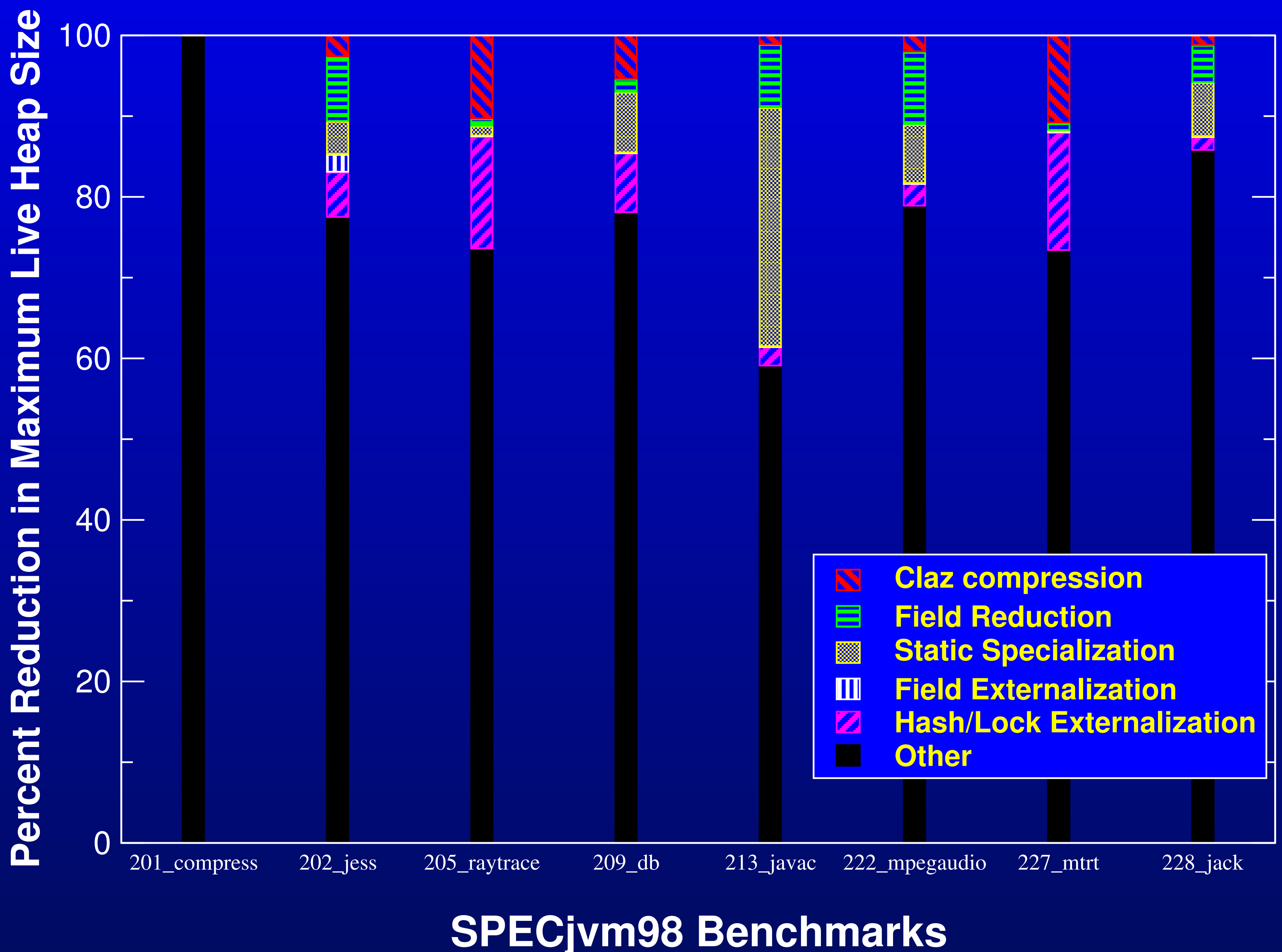


How well does it work?

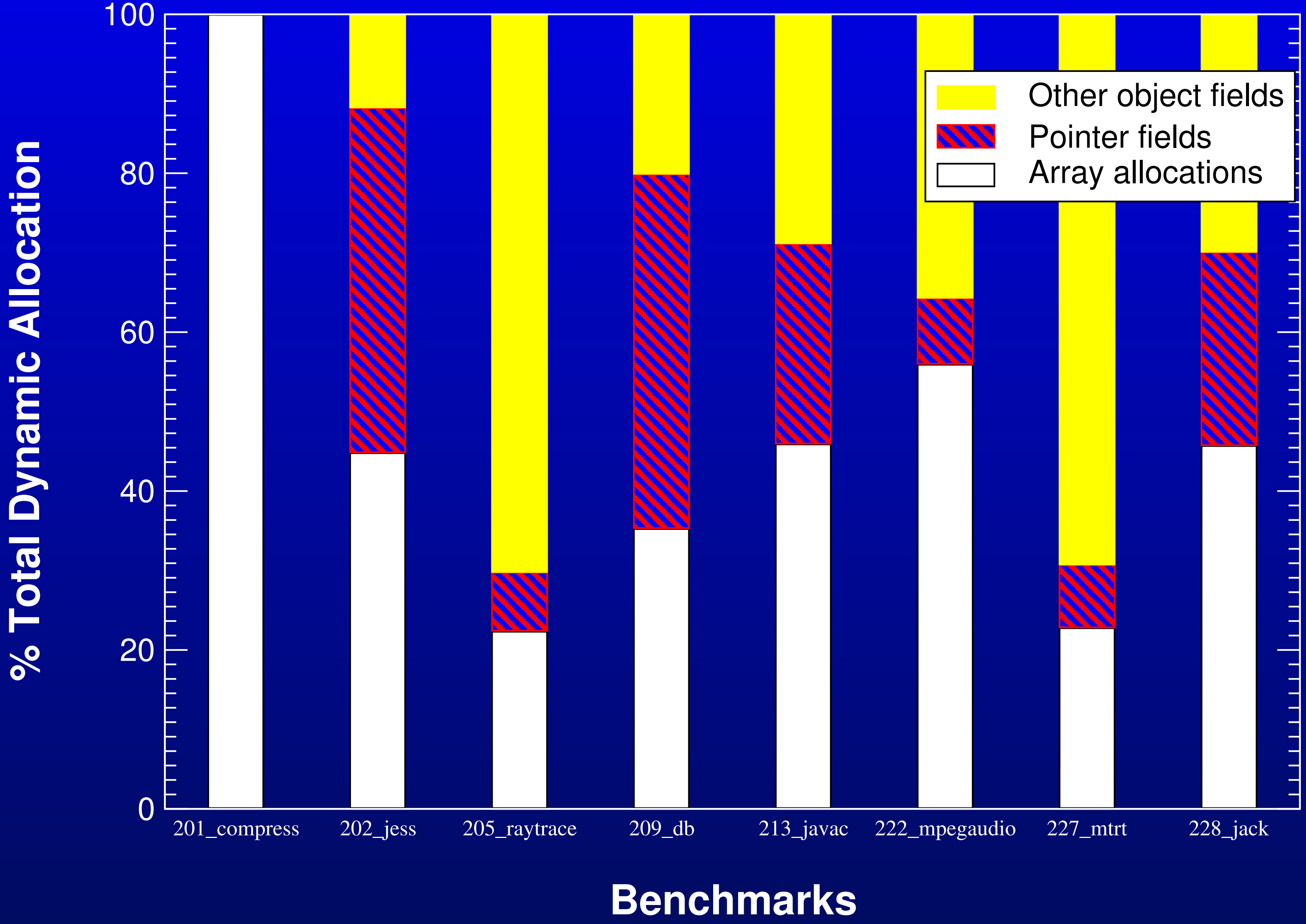
Reduction in total allocations



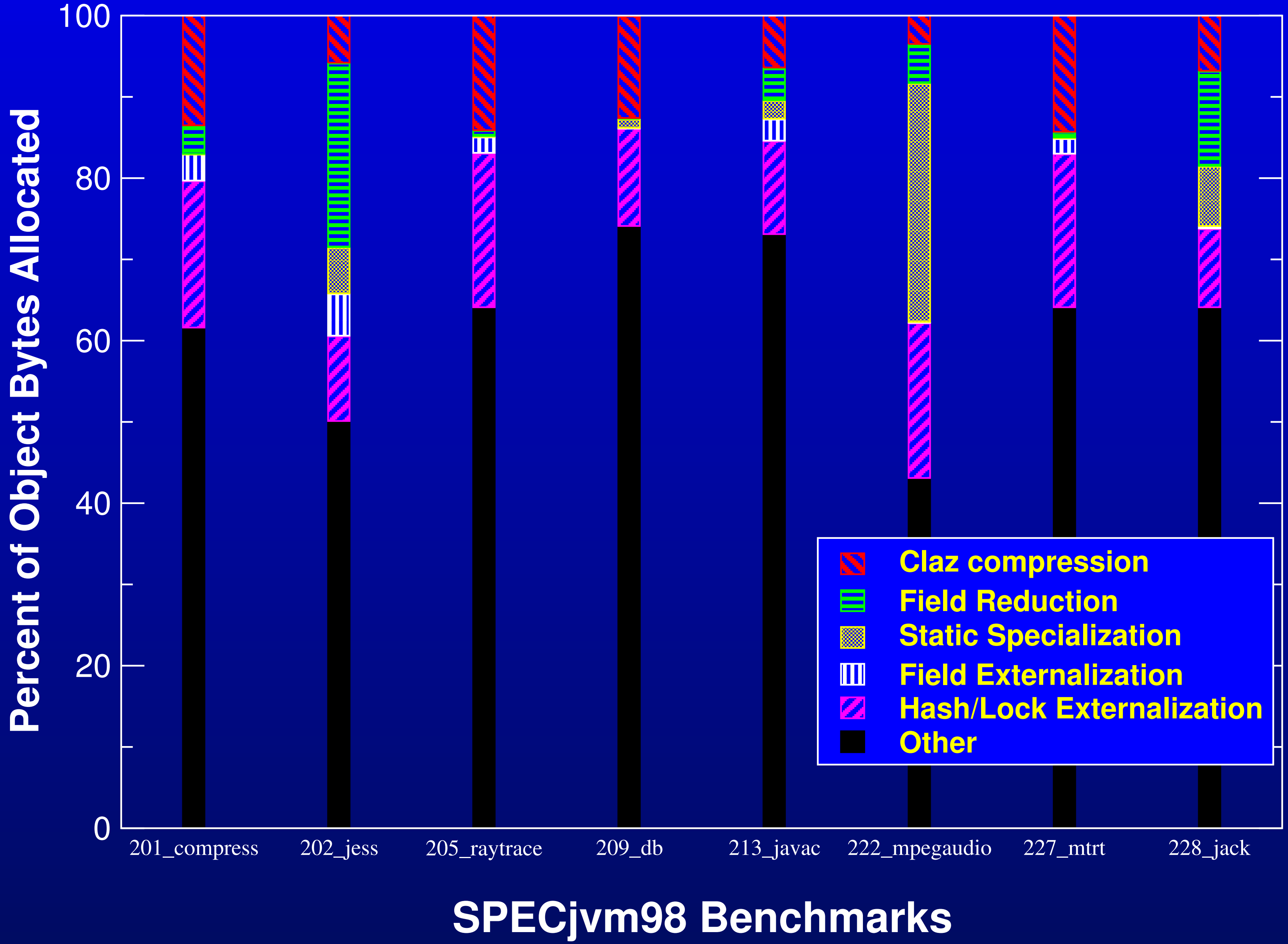
Reduction in total live data



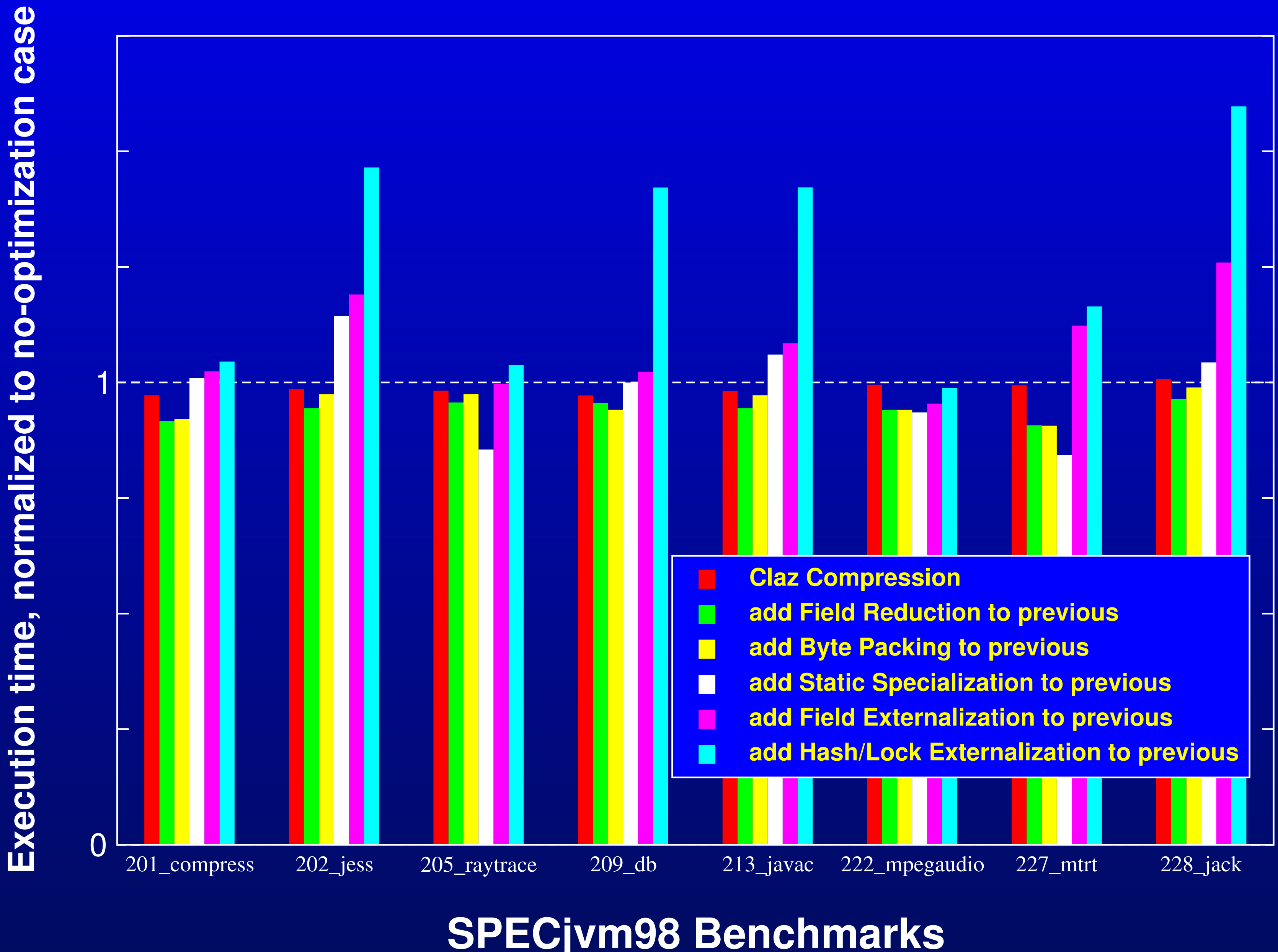
Available reduction opportunities



Reduction in object allocations



Moderate performance impact



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  - Enable *internalization*.

Related Work

- Reducing lock overhead.
  - Bacon, Sweeney (OOPSLA ’96)
  - Onodera, Kawachiya (OOPSLA ’99)
  - Agesen, Detlefs, Garthwaite, Knippel, Ramakrishna, White (OOPSLA ’99)
- Escape analysis.
  - Aldrich, Chambers, Sirer, Eggers (SAS ’99)
  - Bogda, Hözle (OOPSLA ’99)
  - Whaley, Rinard (OOPSLA ’99)
  - Choi, Gupta, Serrano, Sreedhar, Midkiff (OOPSLA ’99)
  - Ruf (PLDI ’00)
  - Sălcianu, Rinard (PPoPP ’01)

Related Work II

- Space and time usage of Java programs.
  - Dieckmann, Hölzle (ECOOP ’99)
  - Bacon, Fink, Grove (ECOOP ’02)
- Bitwidth Analyses
  - Ananian (MIT ’99)
  - Rugină, Rinard (PLDI ’00)
  - Stephenson, Babb, Amarasinghe (PLDI ’00)
  - Budiu, Sakr, Walker, Goldstein (Europar ’00)
- Dead members in C++
  - Sweeney, Tip (PLDI ’98)

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  - In one case, over 40% reduction in total live data.
- Even more space reduction is possible!
- Performance impact was acceptable and tunable.

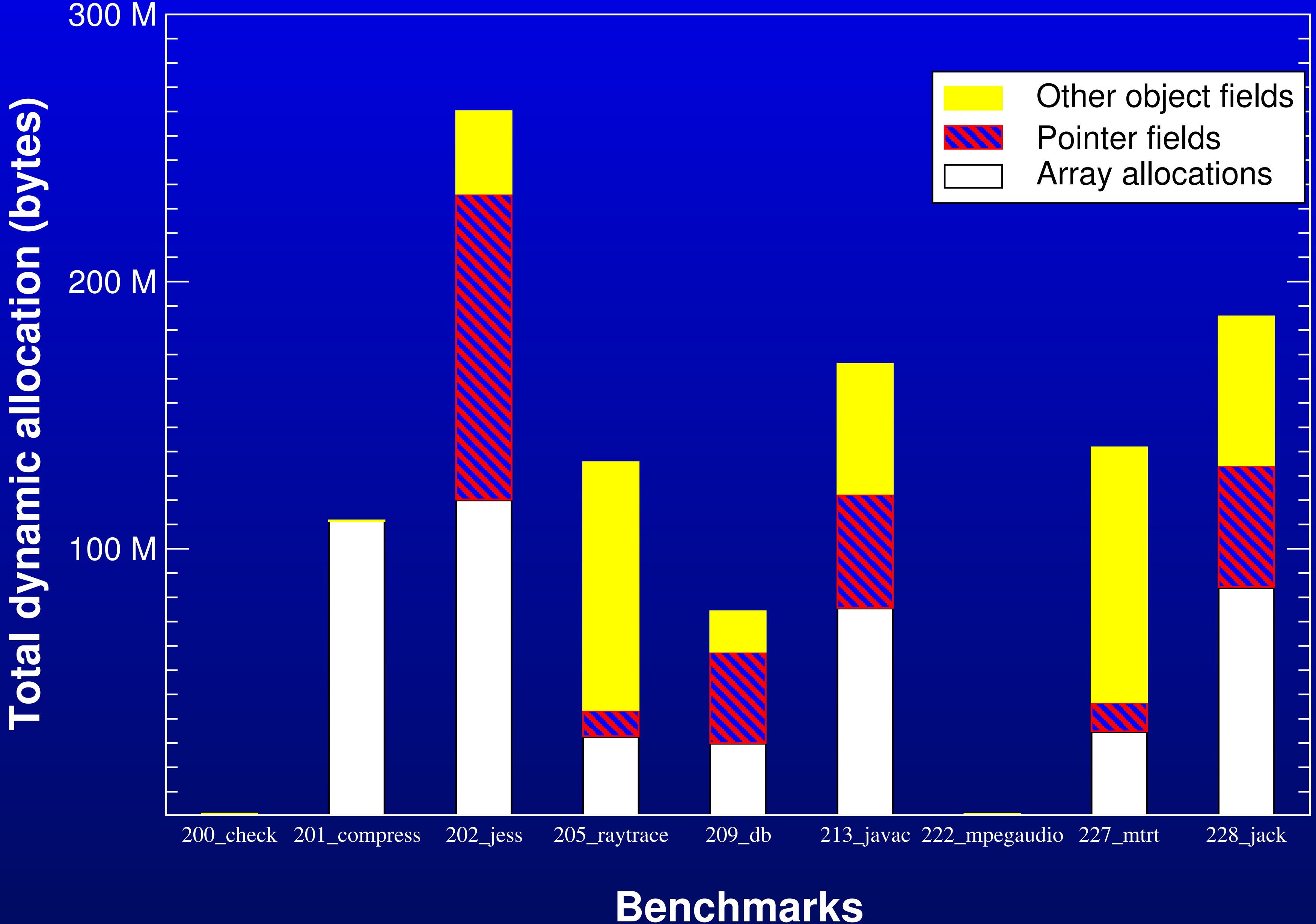
Size Optimizations for Java Programs

FLEX homepage
http://flex-compiler.lcs.mit.edu

This talk:
http://flex-compiler.lcs.mit.edu/Harpoon/papers.html

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

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

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

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

- The compiler can do it for us!