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.
Why space optimizations?

Embedded applications:
- Better use of existing fixed memory resources
- Reduce memory costs of new devices.

Performance:
- "Memory wall" getting higher.
- Space optimizations increase the effective cache size, improving performance.
- Added ALU ops getting comparatively cheaper.
Why space optimizations?

• Embedded applications:
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Structure of a Java Object

- Typical of many O-O languages.
How to compress objects

Three broad techniques:

<table>
<thead>
<tr>
<th>claz pointer</th>
</tr>
</thead>
<tbody>
<tr>
<td>hashcode/lock</td>
</tr>
<tr>
<td>field slot 0</td>
</tr>
<tr>
<td>field slot 1</td>
</tr>
<tr>
<td>field slot 2</td>
</tr>
<tr>
<td>...</td>
</tr>
<tr>
<td>padding</td>
</tr>
</tbody>
</table>
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Three broad techniques:

- Field compression
How to compress objects

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- Mostly-constant field elimination
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How to compress objects

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![Diagram of object structure with fields and padding markers]
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.

```java
class Car {
    int color;
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```
Field Compression

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

BLACK=0
```
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.

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

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.

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

BLACK=0  RED=1  BLUE=2
```
How are these analyses performed?
Intraprocedural overview

- Combined Sparse Predicated Typed Constant (SPTC)
- Forward (sparse) dataflow algorithm discovers:
  - Executability of each control-flow edge
  - Program constants (SPTC)
  - Bitwidth specifications for all abstract values
  - Number of bits in smallest negative number
  - Number of bits in largest positive number
Intraprocedural overview

- Combined Sparse Predicated Typed Constant and Bitwidth analysis
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  - Program constants (SPTC)
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    - Number of bits in *smallest negative* number
    - Number of bits in *largest positive* number
Bitwidth analysis domains

Domains:

- $\mathcal{C} : \mathbb{Z}$, integer constants
  - $c \in \mathcal{C}$

- $\mathcal{T} : \mathbb{N}_0 \times \mathbb{N}_0$, bitwidth specifications ($\mathbb{N}_0 = \{0, 1, 2, \ldots\}$)
  - $\langle m, p \rangle \in \mathcal{T}$

- $\mathcal{L} : (\mathcal{C} \cup \mathcal{T}) \perp$, abstract value lattice
Bitwidth analysis domains

Domains:

- $C : \mathbb{Z}$, integer constants
  - $c \in C$
- $T : \mathbb{N}_0 \times \mathbb{N}_0$, bitwidth specifications ($\mathbb{N}_0 = \{0, 1, 2, \ldots\}$)
  - $\langle m, p \rangle \in T$
- $L : (C \cup T)_\perp$, abstract value lattice

Concretization: $L \rightarrow 2^\mathbb{Z}$

- $C[\bot] = \emptyset$
- $C[c] = \{c\}$
- $C[\langle m, p \rangle] = \{n \mid -2^m < n < 2^p\}$
Ordering relationships in $\mathcal{L}$

For all $c \in \mathcal{C}$, $\langle m, p \rangle \in \mathcal{T}$:

$\perp \sqsubseteq c$ and $\perp \sqsubseteq \langle m, p \rangle$

$\langle m_1, p_1 \rangle \sqsubseteq \langle m_2, p_2 \rangle \iff m_1 \leq m_2 \land p_1 \leq p_2$

$c \sqsubseteq \langle m, p \rangle \iff \text{bw}(c) \sqsubseteq \langle m, p \rangle$
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\downarrow \sqsubseteq c \quad \text{and} \quad \downarrow \sqsubseteq \langle m, p \rangle
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\]

\[
c \sqsubseteq \langle m, p \rangle \quad \text{iff} \quad \text{bw}(c) \sqsubseteq \langle m, p \rangle
\]

where:

\[
\text{bw}(c) : \mathcal{C} \to \mathcal{T} = \begin{cases} 
\langle 0, 0 \rangle & c = 0 \\
\langle 0, 1 + \lceil \ln|c| \rceil \rangle & c > 0 \\
\langle 1 + \lceil \ln|c| \rceil, 0 \rangle & c < 0 
\end{cases}
\]
Ordering relationships in $\mathcal{L}$

For all $c \in \mathcal{C}$, $\langle m, p \rangle \in \mathcal{T}$:

\[ \perp \sqsubseteq c \quad \text{and} \quad \perp \sqsubseteq \langle m, p \rangle \]

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\[ c \sqsubseteq \langle m, p \rangle \quad \text{iff} \quad \text{bw}(c) \sqsubseteq \langle m, p \rangle \]

where:

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- Positive: $0 \ldots 0 \overbrace{1x \ldots XXX}^{1+\lfloor \ln |c| \rfloor}$
- Negative: $1 \ldots 1 \overbrace{0x \ldots XXXX}^{1+\lfloor \ln (|c| - 1) \rfloor}$
Ordering relationships in $\mathcal{L}$

For all $c \in \mathcal{C}$, $\langle m, p \rangle \in \mathcal{T}$:

- $\bot \sqsubseteq c$ and $\bot \sqsubseteq \langle m, p \rangle$
- $\langle m_1, p_1 \rangle \sqsubseteq \langle m_2, p_2 \rangle$ iff $m_1 \leq m_2 \land p_1 \leq p_2$
- $c \sqsubseteq \langle m, p \rangle$ iff $\text{bw}(c) \sqsubseteq \langle m, p \rangle$

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\end{cases}$$

0...0 1X...XXX Positive

1+ln(|c|)=-1

1...1 0X...XXXX Negative
Ordering relationships in $\mathcal{L}$

For all $c \in \mathcal{C}$, $\langle m, p \rangle \in \mathcal{T}$:

$$\bot \sqsubseteq c \quad \text{and} \quad \bot \sqsubseteq \langle m, p \rangle$$

$$\langle m_1, p_1 \rangle \sqsubseteq \langle m_2, p_2 \rangle \quad \text{iff} \quad m_1 \leq m_2 \wedge p_1 \leq p_2$$

$$c \sqsubseteq \langle m, p \rangle \quad \text{iff} \quad \text{bw}(c) \sqsubseteq \langle m, p \rangle$$

where:

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\end{cases}$$

$1 + \lfloor \ln |c| \rfloor = p$  $1 + \lfloor \ln(|c| - 1) \rfloor \leq m$

Positive  Negative
Some abstract evaluation rules

Negation:

\[- \langle m, p \rangle = \langle p, m \rangle\]

Addition:

\[\langle m_l, p_l \rangle + \langle m_r, p_r \rangle = \langle 1 + \max(m_l, m_r), 1 + \max(p_l, p_r) \rangle\]

Multiplication:

\[\langle m_l, p_l \rangle \times \langle m_r, p_r \rangle = \langle \max(m_l + p_r, p_l + m_r), \max(m_l + m_r, p_l + p_r) \rangle\]

Bitwise-AND:

\[\langle 0, p_l \rangle \& \langle 0, p_r \rangle = \langle 0, \min(p_l, p_r) \rangle\]
\[\langle m_l, p_l \rangle \& \langle m_r, p_r \rangle = \langle \max(m_l, m_r), \max(p_l, p_r) \rangle\]
Intraprocedural bitwidth analysis

• Given domains:
  • $\mathcal{E}$, CFG edges
  • $\mathcal{V}$, (SSI form) variables
• The intraprocedural analysis discovers:
  • a set $e : 2^\mathcal{E}$ of executable edges
  • a map $\text{val} : \mathcal{V} \rightarrow \mathcal{L}$ giving abstract values valid for all possible executions
SSI form

Allows us to discover facts about \( i \) at points \( A \) and \( B \):

\[
i = \ldots;
\]
\[
\ldots
\]
\[
i = \ldots;
\]
\[
\text{while (0}<i \quad \&\& \quad i <50) \{ \\
\quad \ldots=i \quad ; \quad // A \\
\}
\]
\[
\ldots=i \quad ; \quad // B
\]
SSI form

Allows us to discover facts about $i$ at points $A$ and $B$:

$i_0 = \ldots$;

$\ldots$

$i_1 = \ldots$;

while ($0 < i_1$ && $i_1 < 50$) {

$\ldots = i_2$; // $A$

}$

$\ldots = i_3$; // $B$

\[
\text{val}(i_2) \subseteq \langle 0, 6 \rangle \\
1 + [\ln 50]
\]
Interprocedural overview

• Field-based extension from intra- to interprocedural analysis.
Interprocedural overview

- **Field-based** extension from intra- to interprocedural analysis.
  - Ignore the left component of expression $o.f$
  - Single analysis value for each declared field
Interprocedural overview

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  - Ignore the left component of expression \( o \cdot f \)
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- **Context-sensitive** implementation.
  - Discriminate between variables (but not fields) in distinct calling contexts.
Interprocedural overview

- **Field-based** extension from intra- to interprocedural analysis.
  - Ignore the left component of expression $o \cdot f$.
  - Single analysis value for each declared field.
- **Context-sensitive** implementation.
  - Discriminate between variables (but not fields) in distinct calling contexts.
- All results in this talk use zero-length context (context-insensitive).
We use a field-based interprocedural analysis.

- Given domains:
  - $\mathcal{E}$, CFG edges
  - $\mathcal{V}$, (SSI form) variables
  - $\mathcal{M}$, call sites in the program
  - $\mathcal{F}$, declared fields in the program
- The interprocedural analysis discovers:
  - A set $e : 2^{\mathcal{E} \times \mathcal{M}^*}$ of executable edges
  - A map $\text{val} : ((\mathcal{V} \times \mathcal{M}^*) + \mathcal{F}) \rightarrow \mathcal{L}$ giving abstract values valid for all possible executions
  - A set $\text{Read} : 2^\mathcal{F}$ of readable fields
All cars are black

```java
void paint(int color) {
    if (this.model == FORD)
        color = BLACK;
    this.color = color;
}
```
Using the analysis:

Field compression using bitwidths

<table>
<thead>
<tr>
<th>claz pointer</th>
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</tr>
</thead>
<tbody>
<tr>
<td>hashcode/lock</td>
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</tr>
<tr>
<td>field slot 0</td>
<td>field slot 0</td>
</tr>
<tr>
<td>field slot 1</td>
<td>field slot 1</td>
</tr>
<tr>
<td>field slot 2</td>
<td>field slot 2</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>padding</td>
<td>padding</td>
</tr>
</tbody>
</table>

Ananian/Rinard, LCTES’03 – p. 18
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):

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>unused</td>
<td>unused</td>
<td>unused</td>
</tr>
</tbody>
</table>

- \(X\) (24 bits)
- \(Y\) (5 bits)
- \(Z\) (1 bit)

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

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>unused</td>
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</table>

- \(X\) (24 bits)
- \(Y\) (5 bits)
- \(Z\) (1 bit)

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

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Z</th>
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<tbody>
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</tr>
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- \(X\) (24 bits)
- \(Y\) (5 bits)
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Object header omitted.

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

Ananian/Rinard, LCTES’03 – p. 19
How to compress objects

Three broad techniques:

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

- It’s easy to remove constant fields.
Mostly-constant field elimination

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- Key idea: remove mostly constant fields.
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  - Static analysis/profiling.
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  - Transform objects to remove fields w/ the common value.
Mostly-constant field elimination

- It’s easy to remove constant fields.
- Key idea: remove mostly constant fields.
  - **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.
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-occurring 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).
Transforming the class

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- **SmallString** without the field.
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Problems:
Transforming the class

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Problems:

- The code could directly access the to-be-removed field.
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- 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).

Problems:

- The code could directly access the to-be-removed field.
- Allocation sites directly instantiate the old class.
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);
}
}
Specialization example:
java.lang.String

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

    public char charAt(int i) {
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    }

    public String substring(int start) {
        int noff = offset + start;
        int ncnt = count - start;
        return new String(value, noff, ncnt);
    }
}
```
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; }
}

Ananian/Rinard, LCTES’03 – p. 26
Transforming allocation sites

Case 1: field is constant in constructor.

```java
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

Case 1: field is constant in constructor.

```java
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;
}

Ananian/Rinard, LCTES’03 – p. 28
Transforming allocation sites

Case 2: field is simple function of constructor parameter.

```java
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.

```java
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.

```java
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.
- 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 cannot be mutated after the constructor completes except by subclasses.
Key properties (revisited)

To use static specialization we need:

- A field with a frequently-occurring 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:

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Creating external fields

- Sometimes fields are *run-time* constants (or nearly so) but not *compile-time* constants.
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- Examples: sparse matrices, “two-input nodes” in Jess expert system, the “next” field in short linked lists.
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.

To achieve our storage savings, we interpret a nonexistent entry as the frequent "mostly-constant" value.

If a field is set to the "mostly-constant" value, remove its entry from the map.
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- To achieve our storage savings, we interpret a nonexistent entry as the frequent “mostly-constant” value.

- If a field is set to the “mostly-constant” value, remove its entry from the map.
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);
    }
}


Externalization example:

```java
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);
    }
}
```
public final class String {
    private final char value[];
    private final int offset;
    private final int count;
    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);
    }
    protected int getOffset() {
        Integer i = External.map.get(this, "offset");
        if (i == null) return 0;
        else return i.intValue();
    }
}
External map implementation

- “open addressed” for low overhead.
External map implementation

- “open addressed” for low overhead.
- load-factor of 2/3
**External map implementation**

<table>
<thead>
<tr>
<th>Object</th>
<th>Field</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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</tbody>
</table>

- “open addressed” for low overhead.
- load-factor of 2/3
- two-word key and one-word values means break-even point is 82%
External map implementation

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<tbody>
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</tr>
</tbody>
</table>

Open–addressed Hashtable

- “open addressed” for low overhead.
- 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!

- Use small integers to enumerate fields.

---

Ananian/Rinard, LCTES’03 – p. 36
We can do better!

- Use small integers to enumerate fields.
- Offset the object pointer by the field index to get a 1-word key.

<table>
<thead>
<tr>
<th>Open-addressed Hashtable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Object + Field</td>
</tr>
<tr>
<td>Object + Field</td>
</tr>
<tr>
<td>Object + Field</td>
</tr>
<tr>
<td>Object + Field</td>
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<tr>
<td>Object + Field</td>
</tr>
<tr>
<td>Object + Field</td>
</tr>
<tr>
<td>Object + Field</td>
</tr>
<tr>
<td>...</td>
</tr>
</tbody>
</table>

Key | Value
--- | ---
We can do better!

- 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.
We can do better!

- 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%.

<table>
<thead>
<tr>
<th>Object + Field</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Object + Field</td>
<td>Value</td>
</tr>
<tr>
<td>Object + Field</td>
<td>Value</td>
</tr>
<tr>
<td>Object + Field</td>
<td>Value</td>
</tr>
<tr>
<td>Object + Field</td>
<td>Value</td>
</tr>
<tr>
<td>Object + Field</td>
<td>Value</td>
</tr>
</tbody>
</table>

Key | Value
--- | ---
Other details

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

- 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

<table>
<thead>
<tr>
<th>claz pointer</th>
<th>claz pointer</th>
</tr>
</thead>
<tbody>
<tr>
<td>hashcode/lock</td>
<td>hashcode/lock</td>
</tr>
<tr>
<td>field slot 0</td>
<td>field slot 0</td>
</tr>
<tr>
<td>field slot 1</td>
<td>field slot 1</td>
</tr>
<tr>
<td>field slot 2</td>
<td>field slot 2</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>padding</td>
<td>padding</td>
</tr>
</tbody>
</table>
Header optimizations:
Hashcode/Lock compression

- Implemented as a special case of field externalization.
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.
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

- claz pointer
- hashcode/lock
- field slot 0
- field slot 1
- field slot 2
- ...
- padding

- claz pointer
- hashcode/lock
- field slot 0
- field slot 1
- field slot 2
- ...
- padding
Header optimizations:
claz compression

claz pointer
hashcode/lock
field slot 0
field slot 1
field slot 2
...
padding

claz pointer
hashcode/lock
field slot 0
field slot 1
field slot 2
...
padding

claz table

Ananian/Rinard, LCTES’03 – p. 41
Header optimizations:
claz compression

- Replace claz pointer with a (smaller) table index. Only instantiated types need be indexed.
Header optimizations: claz compression

- Replace claz pointer with a (smaller) table index. Only instantiated types need be indexed.
- With co-operation of GC, works in dynamic environments.
Header optimizations: claz compression

- Replace claz pointer with a (smaller) table index. Only instantiated types need be indexed.
- With co-operation of GC, works in dynamic environments.
- Many applications instantiate less than 256 object types.
Class statistics

Class statistics for applications in SPECjvm98 benchmark suite:

Ananian/Rinard, LCTES’03 – p. 43
How well does it work?
Experimental setup

- Implemented all analyses and transformations with MIT FLEX Java compiler infrastructure.
  - Whole-program static compiler.
  - Generates C or native code for ARM/MIPS/Sparc.
- SPECjvm98 benchmark suite with full input size.
  - JDK 1.1.8 class libraries.
- Benchmarks run on dual-processor 900 MHz Pentium III running Debian Linux.
  - C backend, GCC 2.95, -O9
Reduction in total allocations

SPECjvm98 Benchmarks

Percent of Total (Object and Array) Bytes Allocated

- Claz compression
- Field Reduction
- Static Specialization
- Field Externalization
- Hash/Lock Externalization
- Other

201_compress 202_jess 205_raytrace 209_db 213_javac 222_mpegaudio 227_mtrt 228_jack

Ananian/Rinard, LCTES’03 – p. 46
Reduction in total live data

SPECjvm98 Benchmarks

Percent Reduction in Maximum Live Heap Size

Claz compression
Field Reduction
Static Specialization
Field Externalization
Hash/Lock Externalization
Other

0  20  40  60  80  100

201_compress  202_jess  205_raytrace  209_db  213_javac  222_mpegaudio  227_mtrt  228_jack

Ananian/Rinard, LCTES’03 – p. 47
Available reduction opportunities

Benchmarks

% Total Dynamic Allocation

- Other object fields
- Pointer fields
- Array allocations

201_compress 202_jess 205_raytrace 209_db 213_javac 222_mpegaudio 227_mtrt 228_jack

Ananian/Rinard, LCTES’03 – p. 48
Reduction in object allocations

Ananian/Rinard, LCTES’03 – p. 49
Moderate performance impact

![Graph showing execution time normalized to no-optimization case for SPECjvm98 Benchmarks. The graph compares different optimizations including Claz Compression, add Field Reduction to previous, add Byte Packing to previous, add Static Specialization to previous, add Field Externalization to previous, and add Hash/Lock Externalization to previous.]
How can we make this even better?

Currently no array analysis/can't distinguish between different uses of a class.

Use pointer analysis to discriminate among objects by allocation site; optimize each alloc site.

We hardly compress pointers at all.

Investigate region-based/enumerated approaches.

Zhang, Gupta (ICCC '02)

The mostly-constant analysis requires profiling.

Investigate heuristic methods.

Leverage dynamic profiling; identify cold fields.

We know nothing about "eld-like" maps.

Enable internalization.

Ananian/Rinard, LCTES'03 – p. 51
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Ananian/Rinard, LCTES’03 – p. 51
Related Work

- Reducing lock overhead.
  - Bacon, Konuru, Murthy, Serrano (PLDI ’98)
  - 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)
  - Rugina, Rinard (PLDI ’00)
  - Stephenson, Babb, Amarasinghe (PLDI ’00)
  - Budiu, Sakr, Walker, Goldstein (Europar ’00)

- Dead members in C++
  - Sweeney, Tip (PLDI ’98)
Conclusions

- We identified a variety of opportunities for space reductions in object-oriented programs.
- We described analyses and transformations to exploit these opportunities.
- 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 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.
Bitwidth analysis

Motivation:

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

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

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

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

Ananian/Rinard, LCTES’03 – p. 58
Bitwidth analysis

Motivation:

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

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

- The compiler can do it for us!
Intraprocedural Analysis

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

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

Ananian/Rinard, LCTES’03 – p. 59
Intraprocedural Analysis

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

![Intraprocedural Analysis Diagram](image)
Intraprocedural Analysis

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

\[ i = \bot \sqcap 1 \sqcap 2 \]
Intraprocedural Analysis

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

\[ i = \bot \land 1 \land 2 = \top \]

[Because \(1 \subseteq \top\) and \(2 \subseteq \top\)]
Intraprocedural Analysis

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

\[ i = \bot \land 1 \land 2 = \top \]

[Because \( 1 \subseteq \top \) and \( 2 \subseteq \top \)]
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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Example, redux

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

![Diagram of tree structure](image)
Example, redux

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

Ananian/Rinard, LCTES’03 – p. 61
Example, redux

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

\[
i = \bot \sqcap 1 \sqcap 2
\]
Example, redux

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

```
i = ⊥ □ 1 □ 2 = (□P)
```
Example, redux

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

```
\[ i = \bot \cap 1 \cap 2 = (\_\_\_P) \]
```
Extending the lattice

Replace \( M \) and \( P \) in previous lattice entries with positive integers \( m \) and \( p \). Encode zero as \( m = p = 0 \).
Extending the lattice

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

\[
\begin{align*}
(\_\_\mathbf{P}\_\_\_) & \Rightarrow \langle 0, p \rangle \\
(\mathbf{M}\_\_\_\_) & \Rightarrow \langle m, 0 \rangle \\
(\_\_\mathbf{Z}\_\_\_) & \Rightarrow \langle 0, 0 \rangle
\end{align*}
\]
Extending the lattice

Replace \( M \) and \( P \) in previous lattice entries with positive integers \( m \) and \( p \). Encode zero as \( m = p = 0 \).

\[
\begin{align*}
(_P\,P) & \Rightarrow \langle 0, p \rangle \\
(M_\,\_\,\_) & \Rightarrow \langle m, 0 \rangle \\
(Z_\,\_\,\_) & \Rightarrow \langle 0, 0 \rangle
\end{align*}
\]

In lattice context:

\[
\begin{align*}
\langle 0, 31 \rangle \\
\vdots \\
\langle 0, 3 \rangle \\
\langle 0, 2 \rangle \\
\langle 0, 1 \rangle
\end{align*}
\]
Bitwidth lattice detail

\[ \langle 0, 31 \rangle \]
\[ \vdots \]
\[ \langle 0, 2 \rangle \]
\[ \vdots \]
\[ \langle 0, 1 \rangle \]
\[ \vdots \]
\[ \langle 0, 0 \rangle \]

\[ \begin{array}{ccccccc}
0 & 1 & 2 & 3 & \cdots & 2^{32} - 1 \\
\end{array} \]
Example redux, redux

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

Diagram: Tree structure with labeled nodes and values.
Example redux, redux

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

\[ i = \bot \]
int foo() {
    if (...) {
        i=1;
    } else {
        i=2;
    }
    if (i>0) {
        ...
    }
}
Example redux, redux

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

i = ⊥ ∩ 1 ∩ 2 = \langle 0, 2 \rangle
```
```c
int foo() {
    if (...
        i=1;
    else
        i=2;
    if (i>0)
        ;
}

\[
i = \bot \sqcap 1 \sqcap 2 = \langle 0, 2 \rangle
\]
Bitwidth combination rules
Bitwidth combination rules

\[ \langle m, p \rangle = \langle p, m \rangle \]
Bitwidth combination rules

- \( \langle m, p \rangle = \langle p, m \rangle \)

\( \langle m_l, p_l \rangle + \langle m_r, p_r \rangle = \langle 1 + \max(m_l, m_r), 1 + \max(p_l, p_r) \rangle \)
Bitwidth combination rules

\[
- \langle m, p \rangle = \langle p, m \rangle \\
\langle m_l, p_l \rangle + \langle m_r, p_r \rangle = \langle 1 + \max(m_l, m_r), 1 + \max(p_l, p_r) \rangle \\
\langle m_l, p_l \rangle * \langle m_r, p_r \rangle = \left\langle \begin{array}{c}
\max(m_l + p_r, p_l + m_r), \\
\max(m_l + m_r, p_l + p_r)
\end{array} \right\rangle
\]
Bitwidth combination rules

- \( \langle m, p \rangle \) = \( \langle p, m \rangle \)

\( \langle m_l, p_l \rangle + \langle m_r, p_r \rangle \) = \( \langle 1 + \max(m_l, m_r), 1 + \max(p_l, p_r) \rangle \)

\( \langle m_l, p_l \rangle \times \langle m_r, p_r \rangle \) = \( \langle \max(m_l + p_r, p_l + m_r), \max(m_l + m_r, p_l + p_r) \rangle \)

\( \langle 0, p_l \rangle \& \langle 0, p_r \rangle \) = \( \langle 0, \min(p_l, p_r) \rangle \)

\( \langle m_l, p_l \rangle \& \langle m_r, p_r \rangle \) = \( \langle \max(m_l, m_r), \max(p_l, p_r) \rangle \)
Bitwise-AND, continued

\[
\text{bw}(n) = \begin{cases} 
\langle 0, 0 \rangle & n = 0 \\
\langle 0, 1 + \lfloor \ln|n| \rfloor \rangle & n > 0 \\
\langle 1 + \lfloor \ln|n| \rfloor, 0 \rangle & n < 0 
\end{cases}
\]
Bitwise-AND, continued

\[
\text{bw}(n) = \begin{cases} 
\langle 0, 0 \rangle & n = 0 \\
\langle 0, 1 + \lfloor \ln |n| \rfloor \rangle & n > 0 \\
\langle 1 + \lfloor \ln |n| \rfloor, 0 \rangle & n < 0
\end{cases}
\]

\[
\begin{array}{c}
0 \ldots 0 \underbrace{1x \ldots XXX} \\
\text{Positive}
\end{array}\quad \begin{array}{c}
1 \ldots 1 \underbrace{0x \ldots XXXX} \\
\text{Negative}
\end{array}
\]
Bitwise-AND, continued

\[ \text{bw}(n) = \begin{cases} 
  \langle 0, 0 \rangle & n = 0 \\
  \langle 0, 1 + \lfloor \ln|n| \rfloor \rangle & n > 0 \\
  \langle 1 + \lfloor \ln|n| \rfloor, 0 \rangle & n < 0
\end{cases} \]

\[ 1 + \lfloor \ln|n| \rfloor = p \]

0...0 1X...XXX Positive

1...1 0X...XXXX Negative

Ananian/Rinard, LCTES'03 – p. 66
Bitwise-AND, continued

\[ \text{bw}(n) = \begin{cases} 
\langle 0, 0 \rangle & n = 0 \\
\langle 0, 1 + \left\lfloor \ln |n| \right\rfloor \rangle & n > 0 \\
\langle 1 + \left\lfloor \ln |n| \right\rfloor, 0 \rangle & n < 0 
\end{cases} \]

1 + \lfloor \ln |n| \rfloor = p

Positive

0...0 1X...XXX

1 + \lfloor \ln(|n| - 1) \rfloor \leq m

Negative

1...1 0X...XXXX
Bitwise-AND, continued

\[ \text{bw}(n) = \begin{cases} 
\langle 0, 0 \rangle & n = 0 \\
\langle 0, 1 + \lfloor \ln |n| \rfloor \rangle & n > 0 \\
\langle 1 + \lfloor \ln |n| \rfloor, 0 \rangle & n < 0 
\end{cases} \]

\[ 1 + \lfloor \ln |n| \rfloor = p \]

0...0 1X...XXX Positive

1...1 0X...XXXX Negative

\[ \langle 0, p_l \rangle \& \langle 0, p_r \rangle = \langle 0, \min(p_l, p_r) \rangle \]
\[ \langle m_l, p_l \rangle \& \langle m_r, p_r \rangle = \langle \max(m_l, m_r), \max(p_l, p_r) \rangle \]
int foo() {
    if (...) {
        i=1;
    } else {
        i=2;
        if (i>0) {
            ...
        }
    }
}
int foo() {
    if (...) {
        a.f=1;
    } else {
        b.f=2;
        if (c.f>0)
            ...
    }
}
Interprocedural analysis

```c
int foo() {
    int foo() {
        if (...) {
            a.f=1;
        } else {
            b.f=2;
        }
    }
    if (c.f>0) {
        ...
    }
}
int bar() {
    int bar() {
        this.f=1;
    }
    this.f=2;
}
int bar() {
    if (this.f>0) {
        ...
    }
}
Ananian/Rinard, LCTES’03 – p. 67
```