Size Optimizations for Java Programs

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LCTES'03, June 2003

Notes

Nothing should be said on the title slide.

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.

Notes

This talk is about size optimizations for Java programs. Our goal is to reduce the amount of memory used by object-oriented programs (in this case, Java) by using static whole-program analyses to identify opportunities and applying transformations to effect the reduction.

Why space optimizations?

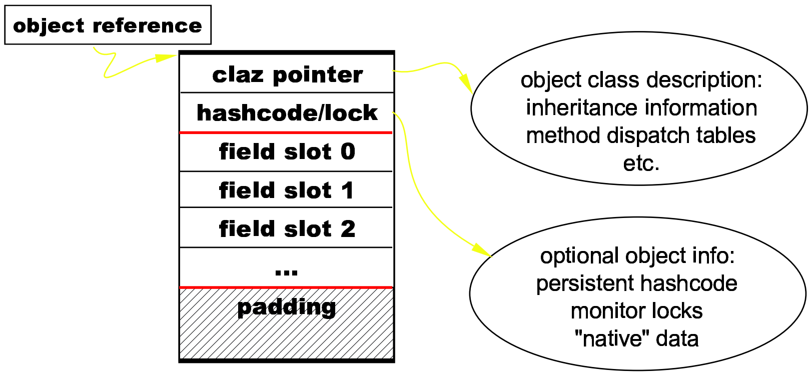
- Embedded applications:
  - Better use of existing fixed memory resources.
  - Reduce memory costs of new devices.
- Performance:
  - “Memory wall” getting higher.
  - Space optimizations increase the effective cache size, improving performance.
  - Added ALU ops getting comparatively cheaper.

Notes

Why are we trying to optimize the space consumption of programs? @ Let’s consider embedded systems first. Existing devices have a fixed amount of memory. We’d like to push more aggressive applications into these devices. We’d also like to reduce the memory sizes, thus costs, for devices embodying new applications.
@ But, perhaps surprisingly, space optimizations are also likely to be crucial for performance as well. The disparity between processor speed and memory speed is getting larger, and space optimizations increase the effective cache size of a system, by packing more of the data you are interested in into the cache. Furthermore, the extra ALU operations for packing and unpacking data into space-efficient forms are getting cheaper and cheaper.
So let’s look at how space usage can be optimized.

Structure of a Java Object

- Typical of many O-O languages.



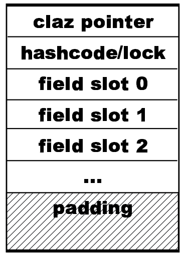
Notes

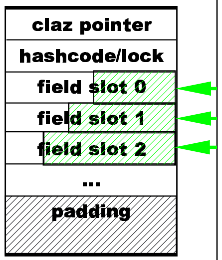
Here’s our starting point. This is how most Java implementations lay out objects. I want you to notice that there are three kinds of space in this layout, helpfully delineated with red lines. The first section of the object usually consists of information required by the runtime implementation but not directly specified by the programmer. This includes a claz pointer, which points to an external structure of information about the object’s type, and some information to support the hashcode and locking semantics of Java. The second section of the object contains the fields declared by the programmer. If this were a car object, these fields might indicate the color and model of the car. The last section consists of padding which the runtime implementation will add to bring the various parts of the object to certain alignment boundaries.

How to compress objects

Three broad techniques:

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





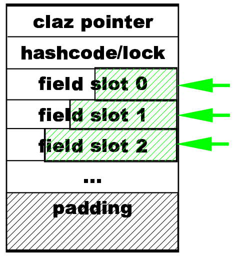
Notes

There are three broad techniques we are going to use to effect our size reductions: @ field compression, which reduces the size of the programmer-declared fields and the padding between fields, @ mostly-constant field elimination, to completely eliminate memory used to store common values, and @ header optimizations, which leverage more-efficient representations for the data needed by the runtime. We will look at each of these in order, starting with…

How to compress objects

Three broad techniques:

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



Notes

…field compression.

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

Notes

Field compression targets the space directly allocated by the programmer. In the sample class at the bottom of the slide, we define an object representing cars. Its first field is a color, and it is declared an integer which allows the enumeration of up to 2^{32} different colors of cars.
@ The first analysis we do is a standard sparse conditional constant propagation pass over the whole program to identify unused, unread, or constant fields. @ Suppose we're building Ford Model-T's. Since they only come in black, this field will be constant and can be removed.
@ A novel contribution is the next step, bitwidth analysis, which discovers tighter upper bounds on field sizes. @ Actually, Model-T's were produced in several different colors before Ford started mass-production. Our bitwidth analysis could determine that we really only need two bits to store colors, since our program only ever stores three different colors in a Car object.
@ After we perform the analysis, we use the results to reduce the space used by the fields. We'll talk about this later.

How are these analyses performed?

Notes

So how do we actually obtain the information we need to do field compression?

Intraprocedural overview

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

Notes

We'll start by describing the intraprocedural analysis. @ We are going to show the combined SPTC and Bitwidth analysis used for field compression. The SPTC analysis will be a little bit simplified in this presentation. @ This is a forward dataflow algorithm which will primarily discover @ a bitwidth specification for every value used by an executable statement in the program — and in the process discover and trim constants and dead code, corresponding to unused functionality in the program or libraries.
@ Our bitwidth specification will tell us the number of bits required to store all the possible values at a program point. Because Java has signed integer types, we will separate our specifications, so that the bitwidth of negative and positive ranges are tracked separately.
And here is how we formalize this: @

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

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

$$\begin{aligned} \mathbb{C}\,[\perp] &= \emptyset \\ \mathbb{C}\,[\,c\,] &= \{c\} \\ \mathbb{C}\,[\langle m, p\rangle] &= \{n \,|\, {-2^m} < n < 2^p\} \end{aligned}$$

Notes

These are the domains we need for the analysis. Our abstract lattice domain $\mathcal{L}$ will include integer constants, represented by the domain $\mathcal{C}$ as well a domain $\mathcal{T}$ of tuples of non-negative integers. The $\mathcal{T}$ domain represents bitwidth constraints, split into negative and positive parts. The first member of the tuple, m, will represent the bitwidth of any possible negative values, and the second member, p will represent the bitwidth of positive values.
Our lattice of abstract values for the bitwidth analysis will range over the raised sum of $\mathcal{C}$ and $\mathcal{T}$.
@ The concretization function gives the full set of concrete values which can be represented by a lattice value. Constants represent a singleton set containing themselves, of course. Notice that a tuple $\langle m, p\rangle$ represents all integer values greater than -2^m and less than 2^p, always including zero.

Ordering relationships in $\mathcal{L}$

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

$$\begin{array}{rcl} \bot \sqsubseteq c & \text{and} & \bot \sqsubseteq \langle m, p\rangle \\ \langle m_1, p_1\rangle \sqsubseteq \langle m_2, p_2\rangle & \text{iff} & m_1 \le m_2 \wedge p_1 \le p_2 \\ c \sqsubseteq \langle m, p\rangle & \text{iff} & \textbf{bw}(c) \sqsubseteq \langle m, p\rangle \end{array}$$

where:

$$\textbf{bw}(c) : \mathcal{C} \to \mathcal{T} = \begin{cases} \langle 0, 0\rangle & c = 0 \\ \langle 0, 1 + \lfloor \ln|c| \rfloor\rangle & c > 0 \\ \langle 1 + \lfloor \ln|c| \rfloor, 0\rangle & c < 0 \end{cases}$$

$$\texttt{0...0}\overbrace{\texttt{1X...XXX}}^{1+\lfloor \ln|c| \rfloor = p} \qquad \texttt{1...1}\overbrace{\texttt{0X...XXXX}}^{1+\lfloor \ln(|c|-1) \rfloor \le m}$$

Positive Negative

Notes

The lattice ordering is implicitly given by the concretization function, but we'll define it explicitly. The ordering in turn defines the meet operation over the lattice. The $\bot$ value will represent "no information" and is less than all members of $\mathcal{C}$ and $\mathcal{T}$ in the lattice. Members of $\mathcal{T}$ are compared component-wise; a bitwidth is lesser only if both its components are lesser. Finally, a constant c is less-than-or-equal-to a bitwidth specification only if the function **bw** of c is less-than-or-equal-to the bitwidth specification, @ where **bw**(c) computes the number of bits needed to represent the signed constant c. Constants are incomparable in the lattice. @ To give more intuition, for values in twos complement binary notation @ the p component of the result represents the location of the first one in the number, and the @ m component constrains the location of the first zero.

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:

$$\langle m_l, p_l\rangle * \langle m_r, p_r\rangle = \left\langle \begin{array}{l} \max(m_l + p_r, p_l + m_r), \\ \max(m_l + m_r, p_l + p_r) \end{array} \right\rangle$$

Bitwise-AND:

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

$$\langle m_l, p_l\rangle \,\&\, \langle m_r, p_r\rangle = \langle \max(m_l, m_r), \max(p_l, p_r)\rangle$$

Notes

Here are some of the abstract evaluation rules we use for unary and binary operations over our bitwidth value domain.
@ The first entry simply says that negation exchanges the positive and negative bitwidths. The symmetric definition for our negative and positive bitwidths which you saw in the previous slide, where we tracking the bitwidth of the *absolute value* of the number, we chosen so that we don't lose information in this rule.
@ The second entry gives the rules for addition: we have to add one to the width to allow for carry out.
@ The rule for multiplication should remind you that we're operating in the log-domain.
@ The underlying numeric representation shows through in our rules for logical-AND; this first rule is a special-case for ANDing two positive values. The result will always be positive, and leading zeros in the smaller number will always force leading zeros in the result.
@ If either value can be negative, the result must be more pessimistic, because every negative range includes the "all-ones" value -1.

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 **val** $: \mathcal{V} \to \mathcal{L}$ giving abstract values valid for all possible executions

Notes

Formally, the result of our intraprocedural bitwidth analysis is a set e of executable edges and a mapping from all variables to a lattice element constraining their values in all possible program executions.
It's worth noting here that our analysis is performed on the program in Static Single Information form…

SSI form

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

```
i₀= ...;
...
i₁= ...;
while (0<i₁ && i₁<50) {
    ...=i₂; // A
}
...=i₃; // B
```

$$\textbf{val}(\mathtt{i}_2) \sqsubseteq \langle 0, \underbrace{6}_{1+\lfloor \ln 50 \rfloor} \rangle$$

Notes

…SSI is a variant of Static Single Assignment form which @ allows us to split the definitions and uses of `i` in order to distinguish the values produced in the two different assignments to `i` at the start of this example, as well as distinguish the possible values of `i` at point A ($\langle 0, 6\rangle$) and at point B.

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
- Context-sensitive implementation.
  - Discriminate between variables (but not fields) in distinct calling contexts.
- All results in this talk use zero-length context (context-insensitive).

Notes

We extend our intraprocedural analysis to a field-based interprocedural analysis. @ This means we ignore the left-hand size of an expression `o.f` and determine a single analysis value for each declared field in the program. @ Our implementation of the analysis is context-sensitive, but we found that using context didn't improve the accuracy of the analysis commensurate with the large increase in analysis time. @ Thus all results presented in this talk will use a zero-length context. And, formally. . . @

Interprocedural analysis

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 **val** $: ((\mathcal{V}\times\mathcal{M}^*)+\mathcal{F})\rightarrow\mathcal{L}$ giving abstract values valid for all possible executions
  - a set **Read** $: 2^{\mathcal{F}}$ of readable fields

Notes

. . . this describes the interprocedural analysis. The domain $\mathcal{F}$ represents the declared fields of the program, and the domain $\mathcal{M}$ represents call sites. Both the executability of an edge and the value of a variable depend on an execution context, $\mathcal{M}^*$. In the field-based analysis our value map **val** maps not only variables but also fields to lattice values. We also collect a set **Read** of fields read by executable statements in the program to allow us to eliminate unread fields.

All cars are black

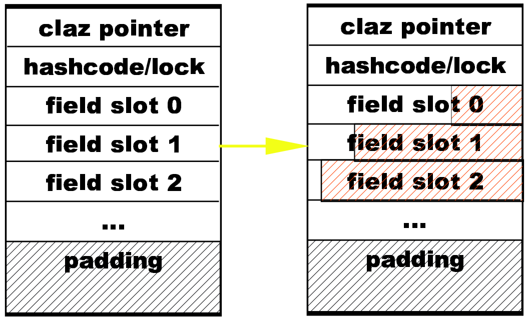
```
void paint(int color) {
    if (this.model == FORD)
        color = BLACK;
    this.color = color;
}
```


Notes

Returning to our car example, we can see how our initial Sparse Predicated Typed Constant analysis could determine that, if all cars' model is FORD, then all car's color will be BLACK. Having determined this, we can simply substitute BLACK for the color wherever it appears and remove the field. However, if there are non-FORD cars, we can still use our bitwidth analysis to determine a bound on how many bits we need to represent the various car colors that we see assigned to the color field.

Using the analysis:

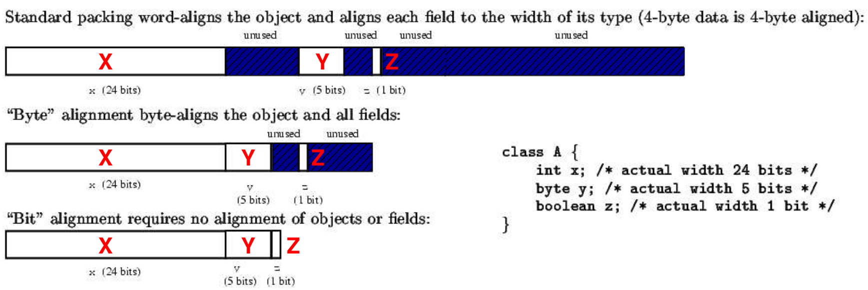
Field compression using bitwidths



Notes

Now we're going to show how the analysis results are used to transform the program.
Once we've used our analysis to determine accurate widths for fields, we would like to shrink the objects' allocations to use only the space actually needed for each field. So if we have less than 256 colors, we can use a single byte in the object structure to represent color.

Field packing



Object header omitted.

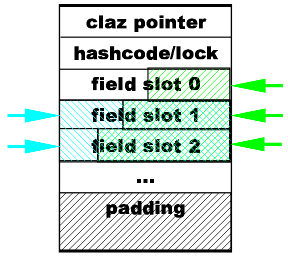
Notes

The actual situtation is a little more complicated. There is padding within and at the end of the object, required for various reasons. The heap allocator may prefer to have the chunks it returns aligned on certain boundaries, and the machine architecture may prefer to access, for example, word data aligned at word boundaries. At some runtime cost, we can overcome these limitations. At the top, is the standard "Java" object packing. All fields are aligned to their natural size, so that, word-sized fields will always begin at word boundaries. In this work we implemented a "byte" alignment strategy, where all fields are placed at the nearest *byte* boundaries, irrespective of their preferred alignment. One can also imagine a "bit" alignment strategy where each field uses *exactly* the number of bits it requires. At runtime we must then perform bit-masking and -extraction operations to access the fields. We found very little additional space-savings potential from going to bit alignment, which is why the numbers we will present use "byte" alignment.

How to compress objects

Three broad techniques:

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



Notes

Let's return to our outline. So far we have talked about field compression; using bitwidth analysis to reduce the static size of fields allocated in objects, and using field packing to reduce the amount of object padding. Now we will talk about "Mostly-constant field elimination," our second space-reduction technique.

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.

Notes

It's easy to remove constant fields; we just replace the field reference with the appropriate constant. @ But our key idea here is that it is also possible to replace *mostly*-constant fields. @ We identify fields which have a certain value "most of the time" using @ static analysis and profiling. @ We can then transform the objects to remove fields with the common value, so that we only spend space on fields with unusual values. @ Our techniques for doing this are called static specialization and externalization. The types of "mostly-constant" fields that can be removed are slightly different with the two techniques; we will look at static specialization first.

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);
    }
}
```


Notes

We're going to jump right in with an example. This is `java.lang.String` from the Java standard class library. It has three fields: a character array and an integer length and offset. This representation was chosen to allow you to perform the substring operation in constant time; you don't have to copy the character array, you just create a new string with a different offset and length and share the same array.

The interesting thing about `java.lang.String` is that the `offset` field is almost *always* zero. Only strings created with the `substring()` method have non-zero offset fields. And the offset field is never changed after the object is created. These are the key properties needed to enable static specialization.

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.

Notes

In order to apply our technique, we need to find a "mostly-constant" field, which in our example is `String.offset`, with the value "mostly zero", and, importantly, the value of that field cannot 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).

Problems:

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

Notes

So, how are we going to save memory in `java.lang.String`? We're going to split the class in two: there will be a `SmallString` class without the offset field, and a `BigString` class that does have it.
@ A couple of problems that come up:

- @ What happens to places in `SmallString` where the removed offset field is referenced?
- @ And when we see an allocation of `String`, do we change it to `SmallString` or `BigString`?

Specialization example:

java.lang.String

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


Notes

Let's go back and see how this works. We take the `String` class, rename it @ `SmallString` and remove the `offset` field. But what do we do with the references to the now-deleted field? @ We solve this problem by *virtualizing* the field: adding a `getOffset()` accessor method (which always returns zero) and replacing references to `offset` with calls to `getOffset()`. *Now, `BigString`...*

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; }
}
```


Notes

Now we create `BigString` as an almost-trivial subclass of `SmallString`. It shared all of the same functionality, except `BigString` *has* an offset field, and implements `getOffset()` in the way you'd expect. So any object which needs a non-zero offset can instatiate `BigString` and things will work as expected.

From our key properties, remember that there are no assignments *to* the `offset` field except in the constructor. But what do we do there? And how do we tell if we're supposed to replace a call to the `String` constructor with a `SmallString` or a `BigString`?

It turns out there are three cases to worry about.

Transforming allocation sites

Case 1: field is constant in constructor.

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

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


Notes

In the first case, the field is constant in the constructor. Every instantiation which uses this constructor will set `offset` to zero. (And as we mentioned before, it is never reset after construction.) So we just @ remove the assignment to `offset` and replace the instantiation of `String` with that of `SmallString`.

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;
}
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);
```


Notes

But what if we have code like this, where we don't know what value `x` will have when the `String` is created? This is essentially the case for the `substring` method of `String`. In this case, the value of the offset field is a simple function of some parameter given to the constructor. Here's our solution: @ we add a test around the allocation site, so that we can construct a Small or Big string depending on the value `x` actually has at runtime.

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;
}
```


Notes

But what about code such as this? Here we know *nothing* about the value of offset, as it is derived programmatically *within the constructor*. There's no easy test we can do outside the constructor. @ Here we must simply give up and always allocate an instance of `BigString`. Code such as this is not actually found in `java.lang.String`, but this solution allows us to take advantage of frequently-constant fields in many cases with a fairly neutral (no cost, no gain) fallback in the worst case.

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.

Notes

Let's review the static specialization transformation: we split the target class into two parts, one of which has the field and one which doesn't, and use virtual accessor functions to hide this split from users of the class. We can do this recursively on multiple fields; we use profiling to determine the best splitting order in that case. We have two constraints: @ the fields must be "mostly-constant", and then cannot be modified after the completion of the constructor. Our implementation actually allows subclasses to modify the fields; because they extend the "big" version of the class, such mutation is safe. We don't rely on fields being explicitly marked `final` by the programmer.

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~~

Notes

But what if the first of these conditions hold, @ but the second doesn't?

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.

Notes

Sometimes fields are *run-time* constants but not *compile-time* constants. @ Some examples are sparse matrices, an example from the SPEC benchmark suite, and short linked lists. In graphics applications, the background color will typically be another example. What are we going to do in this case?
@ Our solution is to exploit the relationship between fields and maps to reduce memory overhead when we're storing the common value.

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.

Notes

Read this slide.

. . . This means we don't actually have to store this value in the map; we can just remove the entry instead.

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[offsetoffsetgetOffset()+1];
    }
    public String substring(int start) {
        int noff = offsetoffsetgetOffset() + 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();
    }
}
```


Notes

Let's see how it would work if we took our static specialization example and externalized the field, instead. @ Again, the field is deleted from the class. But now, the @ `getOffset()` method references an external map.

External map implementation

Object	Field	Value
Object	Field	Value
Object	Field	Value
Object	Field	Value
Object	Field	Value
Object	Field	Value
Object	Field	Value
Object	Field	Value
Object	Field	Value
...	...	...

- “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.)

Notes

The efficiency of this external map crucially dictates how much space savings we are able to achieve with this scheme. So let’s look at implementation for a moment. We choose an “open-addressed” hash table, to keep our overhead low. The alternative is some sort of linked-bucket structure, and the links between buckets add crucially to our overhead. @ Every hash table needs to have some entries empty in order to have good performance; we assume a load-factor of 2/3, which means that 1/3 of the hashtable slots will be empty. @ We can do the math, and find that a two-word key and one-word values mean our break-even point is 82%; @ that means that no more than 18% of the fields can *differ* from the “mostly-constant” value in order to attain any space savings at all.

We can do better!

Object + Field	Value
Object + Field	Value
Object + Field	Value
Object + Field	Value
Object + Field	Value
Object + Field	Value
Object + Field	Value
Object + Field	Value
Object + Field	Value
... ...	...

- 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%.

Notes

We can do better than this, though: since all we really need is a unique identifier for the object/field pair, we can simply @ offset the object pointer to obtain a one-word key. @ Note that this is like using a pointer to the *field* instead of a field ID and a pointer to the *object*; the field we would like to point to is not actually present in the object, though. This means that @ the scheme imposes a limit of the number of fields which may be externalized, based on the number of non-externalized fields, including header fields, remaining in the object. @ This limitation is not overly burdensome, however, and we lower our break-even point to 66%.

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.

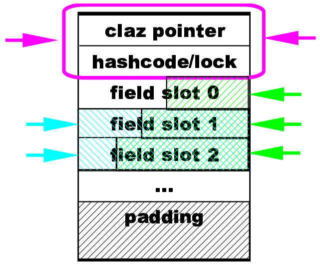
Notes

A few more implementation details: First, we use value profiling to identify where externalization will be worthwhile. Remember, we need at least 2/3 of the values to be some constant. @ When we did the profiling, we looked at integer constants from -5 to 5 and at `null` for pointer types. @ We found that 0 and 1 were by far the most common "mostly-constant" values; in a production implementation you could look only at these two and get most of our savings.

How to compress objects

Three broad techniques:

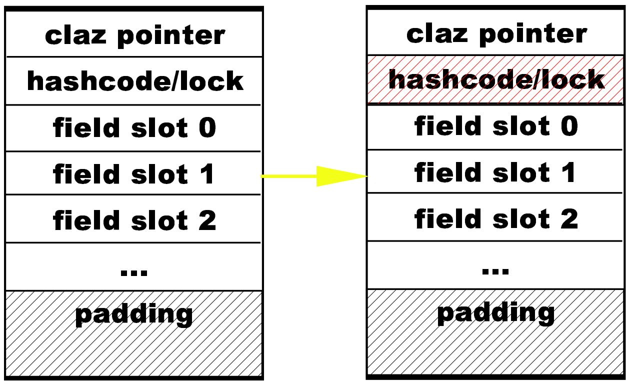
- Field compression
- Mostly-constant field elimination
- Header optimizations



Notes

Returning to our outline. We talked about using bitwidth and constant analysis to compress fields, and at two different techniques for eliminating the space required to store "mostly-constant" values. Now we'll quickly look at header optimizations, which reduce the amount of overhead needed by the runtime implementation.

Header optimizations:
Hashcode/Lock compression



Notes

Of the two words in a typical object header, let's look at the hashcode/lock field first. We were able to completely eliminate this field in a large proportion of our objects.

Header optimizations:
Hashcode/Lock compression

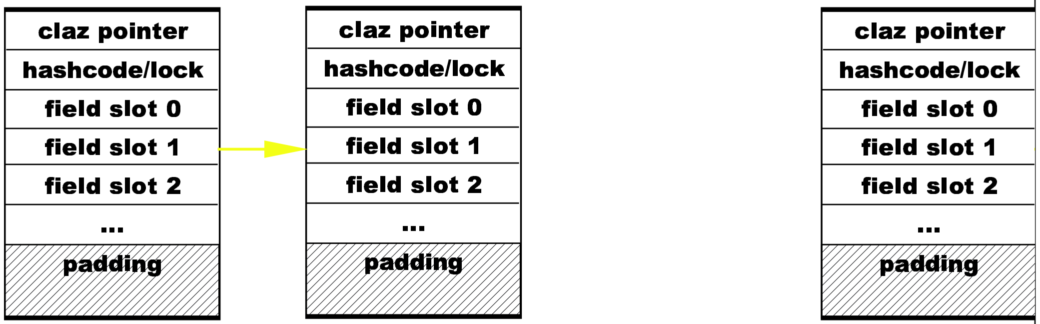
- Implemented as a special case of field externalization.
- The hashcode/lock field often unused because:
  - Most objects do not use their built-in hashcode.
  - Most objects are not synchronization targets.
- Could also use a static pointer analysis.

Notes

We implemented this as a special case of field externalization. @ Although we can't always tell at compile-time, in fact this field is very infrequently used. Most object types either are never used as keys in a hashtable, or implement their own hashing method not based on the identity-based hash specified by the Java semantics. Similarly, most programs are either not multi-threaded, or when they are, perform synchronization on only a small handful of their object types. Using externalization means that we allocate space as-needed in an external map; @ we could also use a static pointer analysis and techniques similar to static specialization to remove these fields from types where they are statically unused.

Header optimizations:

claz compression



Notes

And now looking at the second word: the claz pointer typically points directly to some structure with information about the object type. @ We can save space by imposing a level of indirection and using a small *table index* instead.

Header optimizations:

claz compression

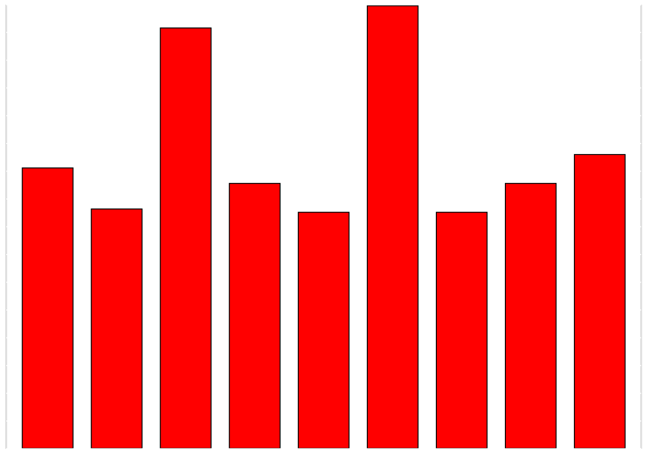
- Replace `claz` pointer with a (smaller) table index. Only instantiated types need be indexed.
- With co-operation of GC, works in dynamic environments.
- Many applications instantiate less than 256 object types.

Notes

Our static analysis can tell how many *instantiated* types are in the program, and thus bound the index size. @ But this can even work in a dynamic environment, with a little co-operation from the GC. @ We'd like to reduce the claz pointer to a single byte. Is this possible in practice? How many classes are in typical applications?

Class statistics

Class statistics for applications in SPECjvm98 benchmark suite:



Notes

Here are the class statistics, etc. Note that all but three are below 256 classes, or *1 byte* of claz index. I have never seen an application that required more than 2 bytes of claz index.

How well does it work?

Notes

So how well does all this work?

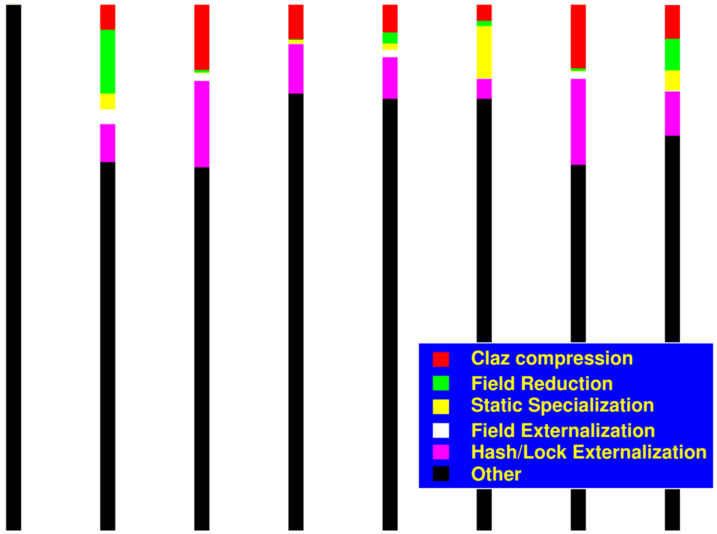
Experimental setup

- 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

Notes

Read this slide.

Reduction in total allocations



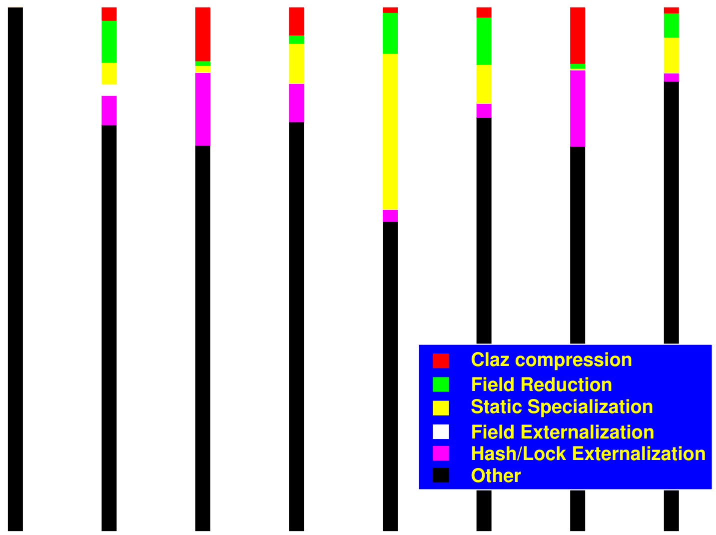
Notes

This is the reduction in *total number of bytes allocated* during the run of the programs. The black bar represents the amount of allocation remaining after all our transformations. Smaller bars are better. The programs at the bottom are from the SPECjvm98 benchmark suite, and represent real, complete, Java applications. Let me quickly step through them: here on the left is `compress`, a gzip-compression program. `jess` in an expert system, `raytrace` is a graphics rendering program — `mtrt` is actually the same program, but run in multi-threaded mode; the numbers are slightly different because (in theory) we can't do as much hash/lock externalization, because the locking capability of Java is being used. In practice, you can see it doesn't have much effect. `db` is a simple database, `javac` is the Sun java compiler, `mpegaudio` is an MP3 decoder, and `jack` is a parser generator.

The `mpegaudio` benchmark gets the most benefit here from static specialization, and `jess` and `jack` from field compression.

A reduction in total allocated bytes is great, it reduces the amount of allocation and collection work the garbage collector has to do, but what you'd really like to see is a reduction in the maximum *live data* in the program. This would mean that the program would run in a smaller memory environment.

Reduction in total live data

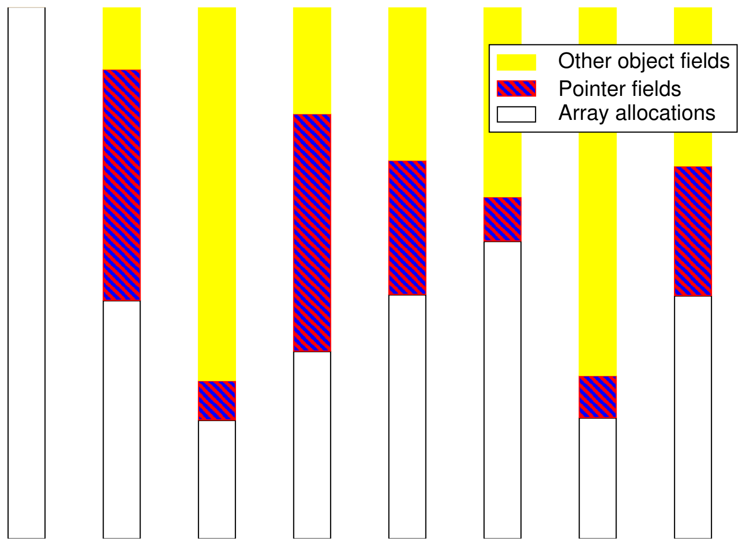


Notes

And that is what we see here. Again, black is live data after all our transformations, smaller is better. You'll notice the numbers look roughly the same, but they improve a lot for javac; what this shows you is that the objects we target in javac are precisely the ones which are live the longest and stress the system the most.

OK. You no doubt have noticed by now that compress is getting no help at all by anything we are doing. Why is that?

Available reduction opportunities

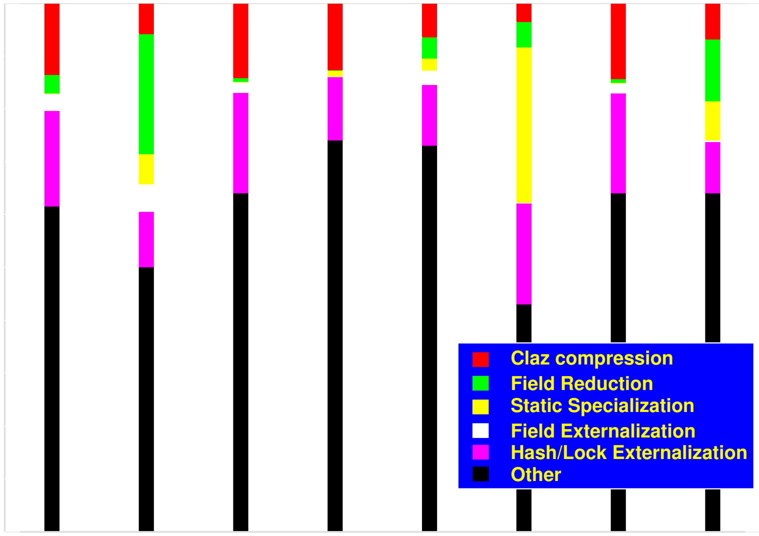


Notes

This graph shows the percent of total allocated bytes which consist of arrays (as opposed to objects), and pointer fields in objects. Our transformations are all object-oriented, and none of them currently target arrays. In addition, the field compression techniques I've been describing are fundamentally integer-based; apart from sometimes being able to remove mostly-null fields, they are not terribly effective on fields of pointer type. So the yellow bars show you how much of the program is *left* for our techniques to optimize, after you take away the pointers and the arrays. Compress is *all* array allocations; hence our poor performance should make sense now. The thing to notice here is that we do a fantastic job with the portion of the program allocation that we're targetting.

You might want to consider how we do solely on the *object* allocations in the program; discounting all array allocations.

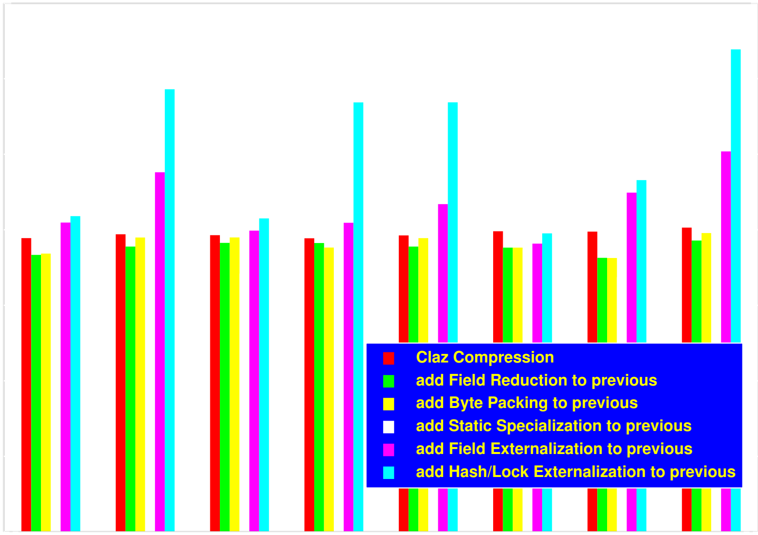
Reduction in object allocations



Notes

And that's what we show here. Smaller black is better. There are very sizable reductions now. But they have to be taken with a grain of salt: we know already that compress has almost no object allocations, so even though we do well on those that are present, it doesn't "really" matter.

Moderate performance impact



Notes

We've talked about some transformations that impact performance; this graph shows you what that performance impact really is. One represents the speed of the program before we touch it. Each bar, as we go left to right, represents the addition of one transformation to the previous program. You'll notice that the first three transformations, which are claz/field compression and byte-packing, offer a moderate speed *improvement* over the original code. This is due to better performance in the garbage collector and cache as we shrink the objects. The potential performance penalty for the claz indirection and the unaligned memory accesses are overwhelmed by the GC and caching improvements.

Static specialization, the white bar, gives back some of that performance gain. This is due to the fact that we've virtualized field accesses, so where you previously had a simple memory access, you now have a method call and the overhead that goes with that. There are various techniques we could use to mitigate this.

Field externalization costs a little more, because it's a more expensive form of field virtualization. In mtrt and jack it seems we are probably externalizing too many fields, and we're getting significant performance penalties. In jack, if you look at our live data numbers, you'll see that the space gain this is giving us is minimal; so our heuristics for choosing fields definitely need further tweaking.

In four cases, the final step, hash/lock externalization, costs about 30% of our performance. These are programs which lock extensively, although none of them strictly need to do *any* locking. Static techniques for lock-removal will mitigate this cost greatly.

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 "field-like" maps.
  - Enable *internalization*.

Notes

So how can we go even further with this? @ First off, we currently do nothing with allocated arrays. Further, we make decisions for all instances of a class, so if a class is used in multiple very different ways, we are forced to pick one strategy for all uses. @ The solution is to use pointer analysis to help discriminate among objects and arrays, which will allow us to apply the techniques we've been describing. @ On a related note, we don't attempt to compress fields with pointer values at all. @ We have a region-based approach to limiting pointer sizes which we feel is worth exploring in this regard, and @ Zhang and Gupta have described an orthogonal technique which it may be useful to incorporate. @ Our "mostly-constant" transformations are dependent on profiling. @ We could either find good heuristics to remove the profiling requirement, @ or embrace run-time profiling, which would allow us to avoid transforming "hot" fields. @ Finally, we've used maps to implement fields via externalization; @ it's worth exploring whether fields can more space-efficiently implement some *maps* in the program.

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)

Notes

The has been related work on reducing lock overhead, and in escape analyses to statically remove locking operations.

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)

Notes

We’ve also seen some surveys to attempt to quantify the space and time usage of Java programs, and devise efficient runtime representations.
Bitwidth analyses have been investigated, starting with my Master’s thesis in 99. An early focus was reducing the size of generated circuits in hardware compilers; the Europar paper also investigates applying the technique to MMX-like SIMD instruction sets.
Sweeney and Tip investigated a dead member analysis in C++ which is a subset of the constant field elimination technique I discussed at the beginning of this talk.

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.

Notes

Read this slide.
It’s worth mentioning the “memory wall” in this regard. We’ve already seen a decent improvement in performance in many cases for some of these transformations, caused simply by reducing memory costs (including GC) and improving caching. This is despite adding extra instructions in the form of indirections, unaligned accesses, and virtualization. One can expect that the memory wall will continue to get higher and the benefits of increasing the effective cache size will get greater, even as the ALU cost of unpacking operations becomes releatively cheaper.
We believe this work has shown that space optimizations can be remarkably effective.

Size Optimizations for Java Programs

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

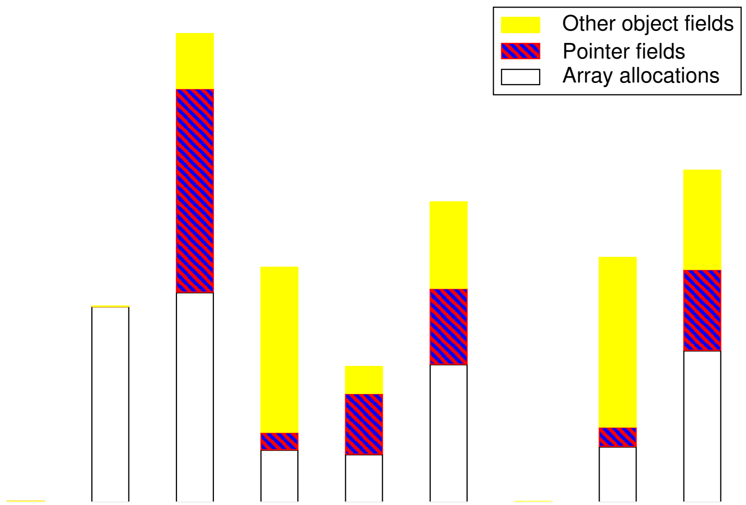
This talk:
http://flex-compiler.lcs.mit.edu/Harpoon/papers.html

Notes

The Graveyard Of Unused Slides follows this point.

Notes

Available reduction opportunities



Notes

This is the “total bytes” version of the slide.

Bitwidth analysis

Motivation:

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

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

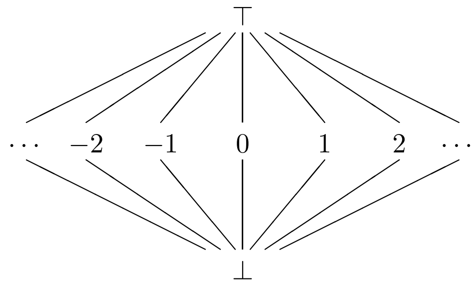
- The compiler can do it for us!

Notes

Why specify widths manually when the compiler can do it?

Intraprocedural Analysis

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



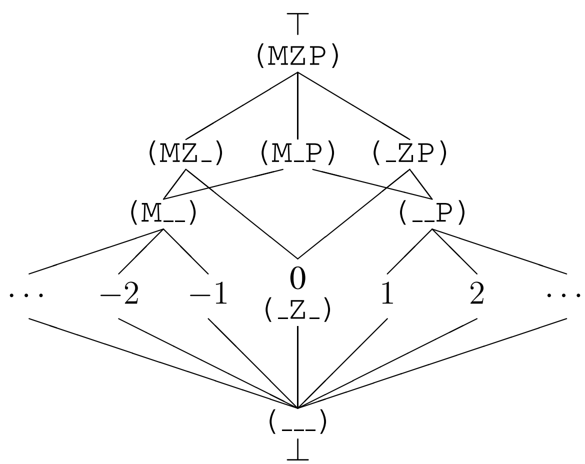
$$\boxed{\mathtt{i} = \perp \sqcap 1 \sqcap 2 = \top}$$

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

Notes

Let's look at a quick example of how the Sparse Predicated Typed Constant analysis is done. @ We have this simple program, which assigns values to an integer variable `i` and then tests the result. @ When we perform the dataflow analysis, we will abstract the value domain of the program using this lattice of integer constants. The $\perp$ value indicates that nothing is known about the value of a variable. We start `i` at $\perp$ and find @ that the two assignments to `i` are executable, @ so we compute $1 \sqcap 2$, @ which yields the $\top$ element in the lattice. The $\top$ element usually means, "I give up, I can't constrain this value any more, it could be anything." This example illustrates the limitations of the simplified SPTC lattice shown here, because @ when we now look at the final if statement, the analysis can't tell that, one way or another, `i` will always be positive and thus this comparison will always be true. The $\top$ element means that *any* value is possible for `i`, which is a very conservative approximation.

A signed integer lattice



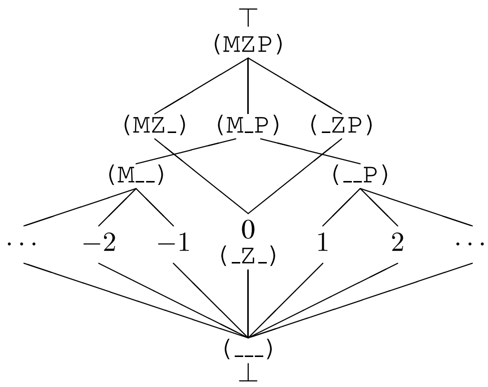
An integer lattice for signed integers. A classification into negative (M), positive (P), or zero (Z) is grafted onto the standard flat integer constant domain.

Notes

So let's see how we'd extend the lattice to make the analysis stronger. Here we have a lattice that allows us to classify values as positive or negative, even if we don't know what the actual value will be. @ Here if we perform meet on 1 and 2 we get the element `(__P)`, which indicates "any positive number". If we then do a meet with a negative number, say, -2, @ we'll get `(M_P)`, or "a non-zero number". If we later discover an assignment of zero, @ we finally get the $\top$ element.

Example, redux

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



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

Notes

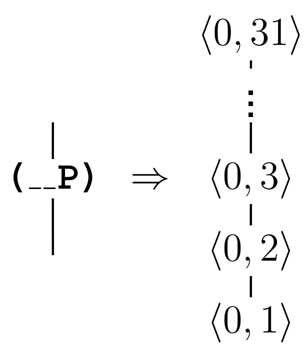
With the new lattice, we start at $\bot$ as before. @ Looking at `i=1` and `i=2`, we @ do the meet and now we get @ `(__P)`, or "a positive integer." @ This time, when we get to the comparison, we can tell that `i>0` will always be true.

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_) $\Rightarrow \langle 0, 0\rangle$

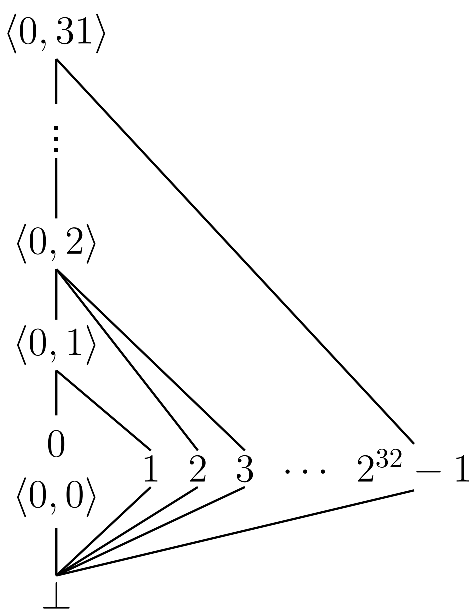
In lattice context:



Notes

To perform bitwidth analysis, we need only extend this signed integer value lattice a little further. We replace all the letters M and P in the previous lattice entries with positive integers m and p indicating the *bitwidths* of the negative and positive portions of the possible values. @ We now represent these lattice entries as tuples $\langle m, p\rangle$, and use the $\langle 0, 0\rangle$ tuple to represent zero — what our previous lattice would have called `(_Z_)`. @ We can imagine expanding each node in our previous lattice with distinct tuples, with the ordering relations shown.

Bitwidth lattice detail

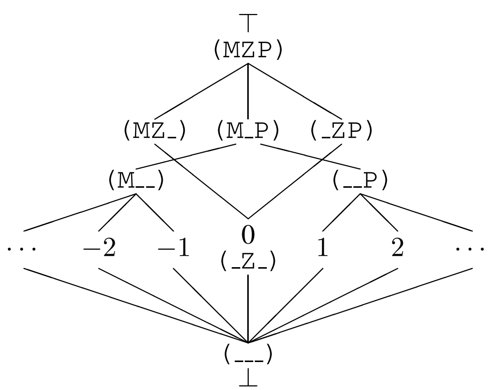


Notes

The picture is actually a little more complicated. Here we see a small piece of the new expanded lattice. We see that performing a meet of any two positive integers will result in a tuple which accurately reflects the minimum bitwidth needed to represent both numbers.

Example redux, redux

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



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

Notes

Revisiting our example: we still start with $\mathtt{i} = \bot$. @ Looking at `i=1` and `i=2`, we @ perform the meet, and @ now we get the tuple $\langle 0, 2 \rangle$, indicating that `i` can not be negative and that we only need two bits to store the positive portion. @ We can still tell at the comparison point that `i>0` will always be true, but the real value of this analysis will be the space reductions we obtain when we apply it to fields.

Bitwidth combination rules

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

Notes

Here are some of the combination rules we use to perform abstract evaluation of unary and binary operations using our bitwidth value domain.
@ The first entry simply says that negation exchanges the positive and negative bitwidths. Note that we're tracking the bitwidth of the *absolute value* of the number, so the rule for negation is simply interchanging the positive and negative portions of the tuple.
@ The second entry gives the rules for addition: we have to add one to the width to allow for carry out.
@ The rule for multiplication should remind you that we're operating in the log-domain.
@ The underlying numeric representation shows through in our rules for logical-AND; let's look at this more closely.

Bitwise-AND, continued

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

$$
\texttt{0...0}\,\overbrace{\texttt{1X...XXX}}^{1+\lfloor \ln|n| \rfloor = p} \qquad \texttt{1...1}\,\overbrace{\texttt{0X...XXXX}}^{1+\lfloor \ln(|n|-1) \rfloor \le m}
$$

Positive — Negative

$$
\begin{aligned}
\langle 0, p_l\rangle \ \&\ \langle 0, p_r\rangle &= \langle 0, \min(p_l, p_r)\rangle \\
\langle m_l, p_l\rangle \ \&\ \langle m_r, p_r\rangle &= \langle \max(m_l, m_r), \max(p_l, p_r)\rangle
\end{aligned}
$$

Notes

Let's review the precise definition of our bitwidth tuples. Both the negative and positive portions of the tuple are equal to this expression. @ The structure of two's complement numbers is as shown. Note that the location of the first one in a positive number is @ given by the p portion of the tuple, and similarly, the location of the first zero in a negative number is @ given by m.
@ Now let's look again at our bitwise-AND rules. When ANDing two positive integers, the resulting bitwidth will match the smaller of the two inputs, since leading zeros will force zeros on the output. But if negative numbers are possible, we must use a far more conservative rule to account for the leading ones in the twos-complement representation of negative numbers. The m-component of the tuple identifies the leftmost *zero*, so clearly the largest m will dictate where the leftmost zero can be in the result. The p component identifies the leftmost *one*, and since the all-ones value -1 is included in all negative ranges, the largest positive value input could emerge unchanged. We cannot create a larger positive value because the AND operation cannot create ones anywhere there is a zero in the input.

Interprocedural analysis

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

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


Notes

Our examples have all been intraprocedural. We use a *field-based* technique to perform the analysis interprocedurally, maintaining a single analysis value for each distinct object field. @ Instead of maintaining a value for `i`, we maintain a value for field `f`. Note that even though the object on the left changes, we're still going to treat these as the same abstract location. @ This works even when the various accesses take place in different methods.