Reusable, Generic Compiler Analyses and Transformations

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Motivation and overview

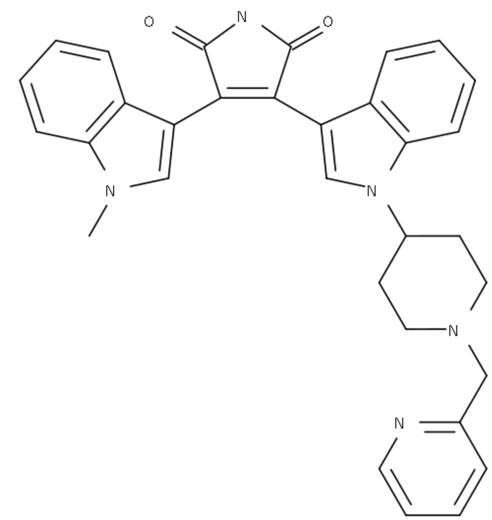
- Compiler optimizations are limited to the optimizations and types built in by the compiler writer
- Cannot be extended to user-defined types
- Cannot be extended with user-defined (high-level) optimizations
- Leverage ideas from generic programming to enable
  - Applying optimizations to classes of types
  - Extending compiler with new optimizations

Optimizations are like pharmaceuticals

- Vendors work on “blockbusters”
  - Optimizations that apply to many programs
  - Tend to be low-level
- Many other optimizations are left out
  - Not enough impact to justify implementing
- See Robison, “Impact of Economics on Compiler Optimization” (Java Grande/ISCOPE 2001)

“Orphan” optimizations

- We all have application-specific optimizations that we want
- None of them by itself is worthwhile to put into a production-grade compiler
- Therefore, vendors will not add them
  - And users cannot add the optimizations themselves
- But users would still benefit from them
  - Both for performance and readability



Compilers lack high-level optimizations

- Consider ATLAS (auto tuning)
  - Well-studied problem (matrix-matrix multiplication)
  - Needs hand-applied, library-specific optimizations
- User-defined data types have no custom optimization support at all
  - But would benefit from having such support
  - Example: $\mathrm{std::list}$ (can cancel iterator $++$ and $--$, etc.)
- Functional language compilers do some because of guarantees on the algebraic structure of data types
  - But there is more that cannot be done that way

Optimization reuse

- Good optimizations are hard to write
  - Many corner cases (pointers, casts, exceptions, etc.)
  - Use results of pointer analysis, path-sensitivity, etc.
- Users are not able to write them
- Compiler writers do not want to write too many
- Reuse of a few optimizations for different tasks would mitigate these problems

Benefits of optimization reuse

- Better performance of user code
- Compilers more effective and easier to write
- Allows user-written, sophisticated optimizations by even unsophisticated users by building from expert-written generic optimizations
- Increased adoption of abstract data types due to simpler interfaces
  - cf. Mateev et al's matrix library

Identities

- Many types and operations have similar identities:

$$\textbf{int } \mathrm{x};$$
$$\textbf{int } \mathrm{y} = \mathrm{x} + 0;$$
$$\quad \rightarrow \mathrm{y} = \mathrm{x}$$

$$\textbf{double } \mathrm{w};$$
$$\textbf{double } \mathrm{v} = \mathrm{w} * 1.;$$
$$\quad \rightarrow \mathrm{v} = \mathrm{w}$$

$$\mathrm{matrix\ m};$$
$$\mathrm{matrix\ m2} = \mathrm{mul(m, identity(nrows(m)))};$$
$$\quad \rightarrow \mathrm{m2} = \mathrm{m}$$

Monoids

- In all of these cases, operation with an identity is a null operation (and can be removed)
- Mathematicians have a name for all operations with the identities $0 + x \to x$ and $x + 0 \to x$: a *monoid*
  - Binary associative operator with identity
- ***Write the optimization in terms of monoid***
- **One** optimization can optimize all monoids
  - Including all previous cases
  - Even though they seem very different

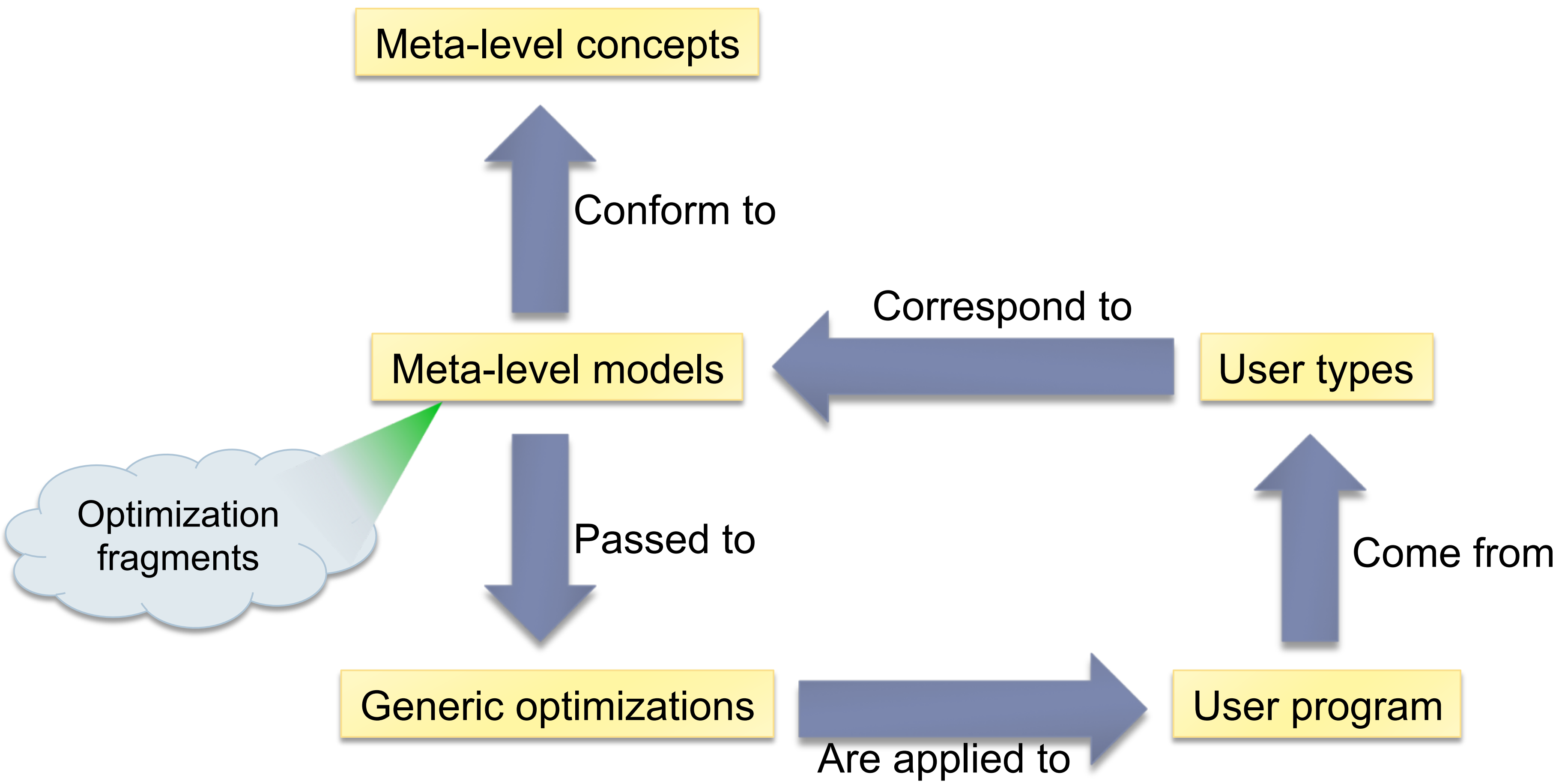
Generic programming

- An organizational principle for software libraries
  - Based on properties of types
- Three major components:
  - Concepts: constraints on types
  - Models: satisfaction of those constraints
  - Generic algorithms/data structures: apply to all types that model certain concepts
- Similar constructs are in several languages

Concept-based optimization

- Implementing compiler optimizations using the generic programming approach allows reuse
- Optimizations either in compiler, library, or individual program
- Reuse allows:
  - Higher-quality optimizations
  - Reduced effort
  - Optimizations by users

Concept-based optimization



Meta-level concepts and models

- Meta-level concepts are requirements for fragments
- Meta-level models provide the fragments
  - Code run within a larger optimization
- Optimizations are generic programs at the meta-level
- Can be implemented via Haskell-style dictionaries

Monoid meta-level concept
• Find identity elements ➔ Set of program expressions • Find binary operation ➔ Set of program expressions and pairs of arguments

Optimization fragments

- Analysis and transformation fragments contain parts of a full optimization
- Fragments are customized for each type in program
- Analysis fragments locate program points
  - That do a particular operation, modify a variable, etc.
- Transformation fragments modify the program
  - Change an operation found by an analysis fragment, etc.

$$\begin{array}{l} \mathrm{x} = \mathrm{y}; \\ \mathrm{z} = \mathrm{w}; \end{array} \quad \Longrightarrow \quad \begin{array}{l} \langle s_1, \mathrm{x}, \mathrm{y} \rangle \\ \langle s_2, \mathrm{z}, \mathrm{w} \rangle \end{array}$$

Optimizing a program

- Optimizations applied for each combination of input types and operations in the program
- Changes are applied after all optimizations
  - To avoid invalidating analysis results

Identity removal	**int**, $+$ **double**, $*$ matrix, $+$
Copy propagation	**int**

```
int x, y;
double z;
matrix m;
x = nrows(m + matrix(0));
y = x;
z = (double)y * 1.;
```

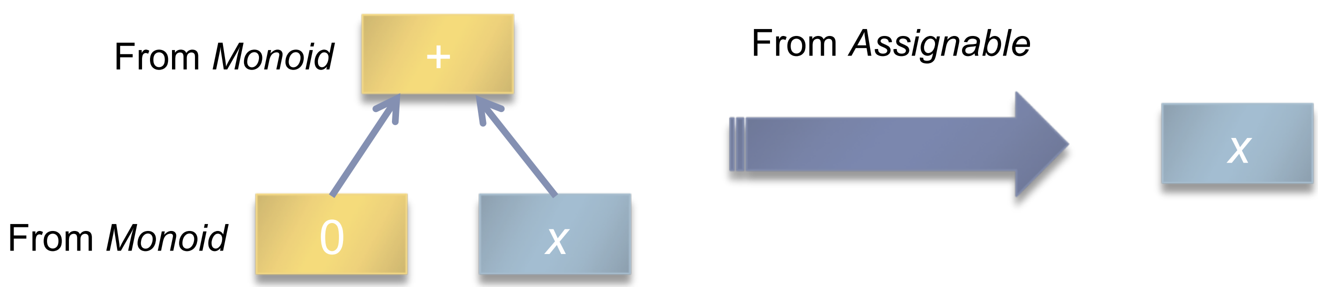
```
// ...
x = nrows(m);
y = x;
z = (double)x;
```

Proofs of concept

- Feasibility demonstrated with prototypes
  - Regular-expression-based optimization specification language
  - Traditional flow equations
- Both are embedded into Scheme and apply to simple C++ programs (using the ROSE framework)

Identity operation removal

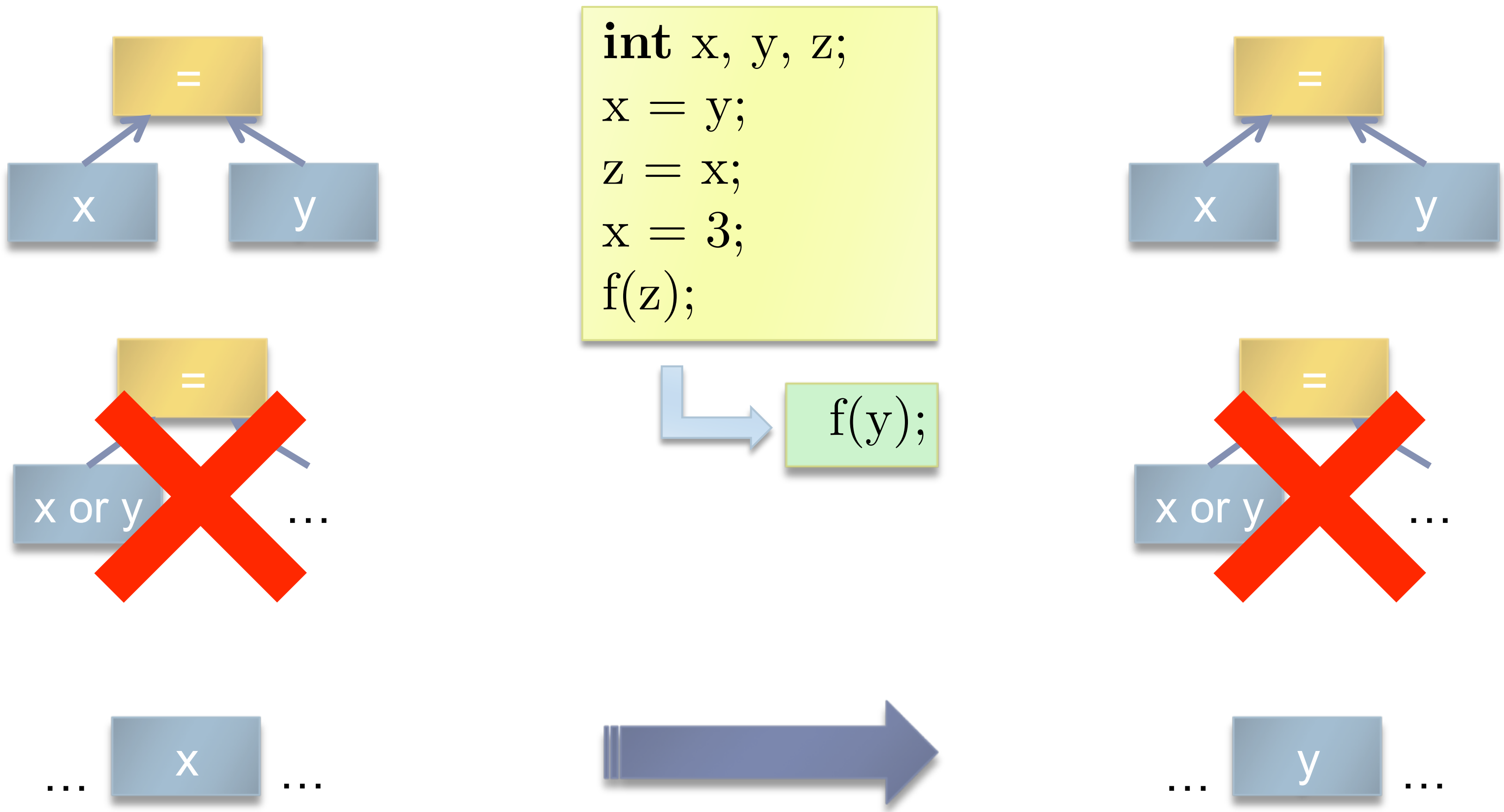
- $0 + x \to x$ and $x + 0 \to x$ (for generalizations of 0 and $+$)
- Applies to any monoid
- Two meta-level concepts required: **Monoid** and **Assignable**



- Transforms $\textbf{int}\ \mathrm{w} = 0 + (\mathrm{x} + 3 * \mathrm{y});$ to $\textbf{int}\ \mathrm{w} = \mathrm{x} + 3 * \mathrm{y};$

Generic copy propagation

- Only **Assignable** is required



Conclusions

- Generic optimizations allow optimizations to be applied to entire classes of types
- Optimizations can be encoded in library to extend compiler
- Optimizations can be reused
- Feasibility demonstrated with implementation

Future work

- Analysis and transformation fragments that work on many types at once
- Ordering and profitability of generic optimizations
- Using axioms or a different high-level specification language
- Generic transformations in MetaOCaml
- User-defined type optimization in Haskell or other languages