Trials and Tribulations of Designing a Modelling Language

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Outline

1. Design Goals for Zinc
2. Modelling Combinatorial Optimization Problems
3. Natural Modelling
4. Extensible Modelling
5. Software Engineering
6. Practical Solver-Independence
7. Conclusion
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Problem Solving Process

- **Problem**
  - “Find 4 different integers between 1 and 5 that sum to 14”

- **Conceptual Model**
  - Precisely specify the problem without describing how to solve it
  - $S \subseteq \{1, 2, 3, 4, 5\} \land |S| = 4 \land \sum S = 14$

- **Design Model**
  - Correct efficient algorithm
  - Specified using some solver technology and search strategy
  - 
    \[
    [W, X, Y, Z] :: 1..5, \text{alldifferent}([W, X, Y, Z]), W + X + Y + Z \neq 14, \text{labeling}([X, Y, Z, T])
    \]

- **Solution**
  - $W = 2 \land X = 3 \land Y = 4 \land Z = 5 \Rightarrow S = \{2, 3, 4, 5\}$
- Designed to mimic the problem solving process
- **Zinc**: Conceptual modelling language
- **Cadmium**: Mapping language
- **Mercury**: Solver backends
Design Goals for Zinc

- **Natural Modelling**: clear and concise high-level mathematical models
- **Extensible Modelling**: support modelling for a wide-variety of applications by extending the modelling language
- **Software Engineering**: support the development of correct and maintainable models
- **Practical Solver-Independence**: allow a single conceptual model to be mapped to many design models
Designing Zinc

- Three years of work
- Many refinements and clarifications
- Many Zinc models written and reviewed
- Reconsidered decisions in light of experience
- Still refinements to be made!
- Highlighting some of the important decisions made/discovered
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Specification Languages

- Generic specification languages: e.g. Z, B
  - More expressive than Zinc
  - Turing-complete, require theorem proving
  - Too powerful for combinatorial optimization

DIMACS SAT representation

- Designed for solvers, not for modelling
- Application and algorithm independent
- Difficult to encode some problems: pigeonhole

MPS (lower level mathematical programming specification)

- Again designed for solvers, not for modelling
- Application and algorithm independent
- Difficult to encode some problems: zebra

CSP $\langle V, D, C \rangle$ variables $V$, domains $D$, constraints $C$

- Expressive, algorithm independent
- Limited modelling features (extensive constraint defn!)

No separation of data and model
**Modelling Languages**

- Mathematical modelling languages: MOLGEN, AMPL, GAMS
  - Support a range of mathematical programming solvers
  - Arrays of variables, iteration, separation of model and data
  - Restricted to linear arithmetic

- Constraint logic programming languages: Eclipse, CHIP
  - Solver independence (Eclipse)
  - Full programming languages
  - Untyped and procedural

- Comet
  - Procedural Turing-complete language
  - Allows specification of conceptual and design models
  - Currently restricted to local search
Modelling Combinatorial Optimization Problems

- **Modelling Languages**
  - **OPL**
    - Inherits good features from math modelling languages
    - Enumerated domains, type declarations, data structures, reification
    - Discrete and continuous variables
  - **ESRA**
    - Very high level: set and relation variables
    - Discrete variables only
  - **Essence**
    - Very high level: set, multiset, relation and function variables
    - Strongly typed
    - Discrete variables only
### Modelling Combinatorial Optimization Problems

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- **Decidable:** all models are solvable.
- **Typed:** language is typed.
- **High-level:** admits data structures such as records and sets.
- **Con-types:** constraints can be associated with (all variables/values of) a type.
- **Coercions:** support for both overloading and type coercions.
- **Extensible:** core language provides extensible features.
- **Sep-model:** model and data can be provided separately.
- **Platforms:** models can be mapped to different underlying platforms.
- **Domains:** supported constraint domains—continuous arithmetic (C), discrete arithmetic (D), discrete symbolic (E), Booleans (B), sets (S).
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Example: Perfect Squares \texttt{perfsq.zinc}

type \texttt{PosInt} = (\texttt{int}: x \text{ where } x > 0);  
\texttt{PosInt}: \texttt{base};

type \texttt{Square} = \text{record}(\text{var} 1..\texttt{base}: x, \text{var} 1..\texttt{base}: y, \texttt{PosInt}: \text{size});

\text{list of} \texttt{Square}: \texttt{squares};

predicate \texttt{nonOverlap}(\texttt{Square}: s, \texttt{Square}: t) =
\begin{align*}
& s.x + s.size \leq t.x \lor t.x + s.size \leq s.x \lor \\
& s.y + s.size \leq t.y \lor t.y + s.size \leq s.y;
\end{align*}

constraint \texttt{forall}(s \text{ in} \texttt{squares}) ( 
\begin{align*}
&s.x + s.size < \texttt{base} \lor s.y + s.size < \texttt{base} 
\end{align*} );

constraint \texttt{forall}(i, j \text{ in} 1..\text{length}(\texttt{squares}) \text{ where } i < j) ( 
\texttt{nonOverlap}(\texttt{squares}[i], \texttt{squares}[j])
);

constraint \texttt{assert}(\texttt{sum}(s \text{ in} \texttt{squares})(s.size \times s.size) = \texttt{base*base},
\text{"Squares do not cover the base exactly"});

\texttt{solve satisfy;}
\texttt{output show(\texttt{squares});}
Example: Perfect Squares `perfsq.zinc`

- Constrained type item: `type PosInt = (int: x where x > 0);`
- Parameter declaration item: `PosInt: base;`
- Record type declaration item
  `type Square = record(var 1..base: x, var 1..base: y, PosInt: size);`
- (Array) Variable declaration item: `list of Square: squares;`
- Predicate definition item

```plaintext
predicate nonOverlap(Square: s, Square: t) =
  s.x + s.size <= t.x \/
  t.x + s.size <= s.x \/
  s.y + s.size <= t.y \/
  t.y + s.size <= s.y;
```
Example: Perfect Squares \textit{perfsq.zinc}

- Constraint items

\[
\text{constraint } \forall (s \in \text{squares}) \left( s.x + s.size < \text{base} \land s.y + s.size < \text{base} \right) ;
\]
\[
\text{constraint } \forall (i, j \in 1..\text{length(squares)} \text{ where } i < j) \left( \text{nonOverlap(squares}[i], \text{squares}[j]) \right) ;
\]

- Assertion

\[
\text{constraint assert} \left( \sum (s \in \text{squares})(s.size \times s.size) = \text{base} \times \text{base} , \right.
\]
\[
\text{"Squares do not cover the base exactly"} \);\]

- Solve item: \text{solve satisfy};

- Output item: \text{output show(squares)};
Example: Perfect Squares Data `perfsq6.data`

- Problem instance defined by separate data file
- Example
  ```
  base = 6;
  squares = [ (x:_, y:_, size:s) | s in [3,3,3,2,1,1,1,1,1] ];
  ```
  _ represents anonymous variable.
- Result
  ```
  [(x:1, y:1, size:3), (x:4, y:1, size:3),
   (x:1, y:4, size:3), (x:4, y:5, size:2),
   (x:4, y:4, size:1), (x:5, y:4, size:1),
   (x:6, y:4, size:1), (x:6, y:5, size:1),
   (x:6, y:6, size:1)]
  ```
Types and Insts

- **Types**
  - **Base**: Booleans, integers, floats, strings
  - **Constructors**: sets, arrays, tuples, records, variant records, enumerated types

- **Instantiations (Insts)**
  - **par**: parameter — fixed by the data
  - **var**: decision variable
  - default is **par**

- **Type-Inst** (pairing of type and instantiation)

**Design Decision: Type-Insts**

- Modellers must distinguish between parameters and decision variables
- Allows: checking of parameter initialization, translation simplification
- Improves: readability, error checking
Base types

- Numbers
  - integers 23 and floats 2.3e-05, 0.0067
  - built-in arithmetic: +, *, round, ...

- Booleans
  - true, false
  - built-in operators: \/, /\, ->, ...

**Design Decision: Booleans**

- Don't represent Booleans as 0..1 integers
- Better error checking, easier to map to different solvers

- Strings
  - "one two three \n"
Enumerated types and Sets

- Enumerated types
  - `enum Colour = {Red, Green, Blue};`
  - `array[Colour,Colour] of var Colour: Clashing;`

Design Decision: Enumerated types

- Name space for elements is global
- Type name is a set expression
- Can be declared in a model and defined in data file
  - `for(i,j in Colour)(Clashing[i,j] != i)`
Sets and Comprehensions

**Sets**
- sets literals \{1.0, -5.3\} and ranges 1..4
- built-in operators: in, card, union, intersect, ...
- Only sets of **par** instantations
- Var sets must have finite type
  - **Yes**: var set of Colour, set of tuple(int,int)
  - **No**: set of var Colour, var set of tuple(int,int)
- set comprehensions
  - \{i * j | i, j in 1..10 where i != j \}

**Design Decision: Comprehensions**
- Generator sets of arrays must be **par**
- Ensures finiteness, some confusion

- **No**: var set of 1..10: p; constraint sum(i in p)(i) > 0;
- **Yes**: constraint sum(i in 1..10)(bool2int(i in p)*i) > 0;
Arrays

Arrays

- Elements with any instantiation
- Indices must be \texttt{par}, arrays are never \texttt{var}

Design Decision: Arrays

- Arrays of variable length are disallowed (finiteness)
- Multi-dimensional arrays are actually arrays indexed by tuple
- Lists are syntactic sugar for arrays

- \texttt{for(i,j in Colour)(Clashing[(i,j)] != i)}

Explicit and implicit indices

- By default integral beginning at 0
- array[1..3] of int: \texttt{a1 = [5, 6, 7]; \% explicit-index}
- array[int] of int: \texttt{a2 = [0:8, 1:9]; \% implicit-index}
- array[1..100] of int: \texttt{a3 = [1:1, 2:2] default 0;}

array comprehensions

- \texttt{[i * j | i,j in 1..10 where i != j]}

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Zinc

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Tuples, Records and Variant Records

- **Tuples**
  - Elements of any instantiation
  - `tuple(int, float, bool): x = (1, 4.56, true);`
  - Field numbers: `x.3 \ y \geq 0`

- **Records**
  - Elements of any instantiation
  - `record(x:int, y:float, z:bool): y = x;`
  - Field access: `y.1 \geq 8`
  - Coercion from tuples of correct type.

- **Variant Records**
  - Non-recursive
  - `variant_record thing = {
      integer(int:x),
      boolean(bool:b),
      pair(int:x, int:y)
    }`
Let Expressions

- Let expressions
  - Introduce local variables and parameters
  - `let { int:x = z*z, var int:y = u*u } in x + y`

**Design Decision: Let**

- Let expressions in negative contexts must functionally define variables
- Otherwise: requires universal quantification

- **No**: `not (let {var int:z } in x == 2 * z)`
- **Yes**: `not (exists(z in 1..10)(x == 2 * z))`
- **Yes**: `not (let {var int:z = floor(x / 2) } in x == 2 * z)` is equivalent to
  `let {var int:z = floor(x / 2) } in not(x == 2 * z)`
Items

- **Assignment items**
  - \(x = 3;\)
  - Joint variable declarations are sugar: e.g. \(\text{int}:x = 3; \Rightarrow \text{int}:x; x = 3;\)

- **Include items**
  - \(\text{include } "\text{globals.zinc}"\)
  - Textually insert file into including file

**Design Decision: Items**

- Items can appear in any order (helps include)
- Data files are just Zinc (complex expressions allowed)

```zinc
enum Colour;
Colour: None;
int: x;
var Colour: y;
include "test.data"
constraint y != None;
```

```zinc
enum Colour = { Empty, Red, Blue };
Colour: Empty;
int: x;
x = card(Colour) - 1;
test.data
```
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Extensible Modelling

- Rich type language
  - Define a new type for some application domain
- User-defined predicates and functions
  - Define the operations (functions) for the new type
  - Define the constraints (predicates) for the new type
- Constrained types
  - Enforce certain constraints on all members of the type
Predicates and Functions

- Predicates are simply functions with return type `var bool`
- Functions can be overloaded on type-inst
- Types can use type parameters `$T$

```plaintext
function var bool: between($T: x, $T: y, $T: z) =
  (x <= y \and y <= z) \or (z <= y \and y <= x);
function par bool: between(par $T: x, par $T: y, par $T: z) =
  (x <= y \and y <= z) \or (z <= y \and y <= x);
```

Second version gives more accurate type-inst on return `par bool`

Design InDecision: Overloading

- Currently body is duplicated for overloading
- Later perhaps we allow sharing of bodies
foldl and foldr

- Two higher-order built-in functions
  - `foldl(fun, init, array)`
    - Apply binary function `fun` to each element in `array` starting from `init`

```plaintext
predicate forall(array[int] of var bool: xs) =
  foldl(’/\’, true, xs);

function var int: sum(array[int] of var int: xs) =
  foldl(’+’, 0, xs);

function var float: sum(array[int] of var float: xs) =
  foldl(’+’, 0, xs);
```

Design Decision: Fold

- Provide powerful building blocks `foldl`, `foldr`
- Preferable to many built-in iteration constructs `forall`, `sum`
In order to define functions and predicates

**Reflection functions**

- **index_set**: returns index of array argument
- e.g. **index_set_1of2**: first index of 2d array
- **lb**: returns declared lower bound of var int, var float
- **dom**: returns declared domain of var int, var float
- **ub**: returns declared upper bound of var int, var float, var set of ..

%----------------------------------------------------------%
% Requires the image of function 'x' (represented as array) on set of values 's' is 't'
%----------------------------------------------------------%

predicate range(array[int] of var int:x, var set of int:s, var set of int:t) =
    forall(i in ub(t))(i in t -> exists(j in ub(s))(j in s -> x[j] == i));
Constrained Types

- All elements of the type must satisfy a certain constraint
  
  ```plaintext
  type PosInt = (int: i where i > 0);
  type Interval = (record(var int: start, var int: end):
      r where r.end >= r.start);
  ```

- ranges `1..n` are a special case

- **Constraint view**: syntactic sugar, e.g. 
  ```plaintext
  var PosInt: y; ⇒
  var int: y;
  constraint y > 0;
  ```

- **Type theoretic view**: subtype not active constraint
  - should not affect execution of type correct program

- The constraint view and subtype view are **incompatible!**
Constrained Types Difficulties

- predicate ge(var PosInt:x, var PosInt:y) = x >= y;

  var int: x = 5; var int: y = -6; var int: z;
  constraint ge(x,y) \/ z = 1;

- subtype view: type error!

- constraint view: z = 1 since equivalent to
  constraint (x > 0 \/ y > 0 \/ x >= y) \/ z = 1;

- Problematic with negation!
  constraint (ge(x,y) \/ z = 1) \/ (not ge(x,y) \/ z = 2);

  Constraint view: x = 5 \(\land\) y = -6 \(\land\) z = 2
  subtype view: type error

Design Decision: Constrained types

- Check statically whether formal types implied by actual types
- Warn if not so, and use constraint viewpoint
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Zinc designed to support good software engineering practices

- Conciseness and readability
- Strong static error checking
- Avoiding code duplication (parametricity)

**Problem instance evaluation**

1. *model checking*: data-independent check of model
2. *instance checking*: checking once the data is combined with the model
3. *instance evaluation*:

Zinc checks errors as soon as possible in the pipeline

**Design Decision: Variable Declarations**

- All variables except generator variables must have a declared type-inst
- Complete inference impossible with separate data files
Type-Inst Checking

- Main static check
- Type system: Hindley-Milner with coercions and overloading
- Type-inst lattice
Coercions

- Integers can be coerced to floats
- Sets $S$ of type $t$ can be coerced to arrays indexed by $0..\text{card}(s)$ of type $t$
- Tuples can be coerced to records (if type appropriate)
- $\text{par}$ values can be coerced to $\text{var}$ values
- Anonymous variable _ (type-inst $\text{var} _$) can be coerced to any $\text{var}$ type-inst.

Algorithm

- Bottom-up inference: determine type-inst
- Top-down: add appropriate coercions
Type-Inst Checking Example

- array[int] of var float:  \( x = [1,2,\_] \)
- array element type: lub of \( \text{par int, var } \bot = \text{var int} \)
  
  \[
  [ \coerce(\text{par int}, \text{var int}, 1), \\
  \coerce(\text{par int}, \text{var int}, 2), \\
  \coerce(\text{var bottom, var int}, _) ]
  \]

- Assignment means coerce array[int] of var int to array[int] of var float

  array[int] of var float:  \( x = \\
  \coerce(\text{array[int] of var int, array[int] of var float}, \\
  [ \coerce(\text{par int}, \text{var int}, 1), \\
  \coerce(\text{par int}, \text{var int}, 2), \\
  \coerce(\text{var bottom, var int}, _) ]
  \]

- Coercions are pushed down as far as possible

  array[int] of var float:  \( x = \\
  [ \coerce(\text{par int}, \text{var float}, 1), \\
  \coerce(\text{par int}, \text{var float}, 2), \\
  \coerce(\text{var bottom, var float}, _) ]
  \]
Overloading interacts dangerously with coercion!

\[
\text{function int: } f(\text{int: } x, \text{float: } y) = 0; \\
\text{function int: } f(\text{float: } x, \text{int: } y) = 1;
\]

Type of \(f(3,3)\) determines result 0 or 1!

Type-inst checking with overloading and coercion may be expensive

\[
\text{function int: } g(\text{int: } x, \text{float: } y); \\
\text{function float: } g(\text{float: } x, \text{int: } y);
\]

Checking \(g(g(g(1,2),g(3,4)),g(5,g(6,7)))\) is combinatorial

Design Decision: Overloading

- Overloaded versions of functions should be semantically equivalent wrt coercion: Not statically checkable
- Overloaded functions must be closed under type conjunction
- Overloaded functions must be monotonic
Array access, Domain checking, Assertions

- **Array access** (*verifying*)
  - `array[int] of par int: x = [1,2,3];`
  - `var int:i; then a[i] has type-inst var int`

- **Domain checking**
  - Set solvers require sets to range over finite domains
  - *finite type*: enumerated type, range, Boolean: tuples, records, sets of finite types.

- **Assertions**
  - Two assertion functions
    - `function $T: assert(par bool: c, par string: s, $T: val);`
    - `function par bool: assert(par bool: c, par string: s);`
  - Check `c`, if false print `s` else return `val` (or true)

**Design Decision: Assertions**

- Originally assertion item, expressions are more flexible, particularly for functions
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Zinc is designed to allow the mapping of a conceptual model to different design models.

Features to support this are:
- Annotations
- Decomposable Global Constraints
- Implementability
Annotations can be used to control the translation of conceptual models.

Solver dependent information (this includes search!)

Can be ignored by a solver

Declared with types:

```cpp
template enum SolverKind = { Lp, Ip, Fd, Sat };
template annotation solver(SolverKind);
template annotation bounds;
```

Attached to expressions and items with `::`

```cpp
template var array[int] of var int: x :: bounds;
template constraint all_different(x) :: solver(Fd) :: bounds;
template constraint sum(i in S)(a[i] * x[i]) <= 10 :: solver(Lp);
```
Decomposable Global Constraints

- Global constraints are simply **predicates**
- Low-level logical definition means they can be used for any solver!
- Example: sequence constraints: in each sequence of length \( k \) in \( x \) there are between \( l \) and \( u \), 1s:

\[
\text{predicate sequence_among(int: l, int: u, int: k, array[int] of var 0..1: x) =}
\]
\[
\text{let } \{ \text{int: n = max(index_set(x))} \} \text{ in}
\]
\[
\text{assert(min(index_set(x)) == 1 /\ card(index_set(x)) == n,}
\]
\[
\text{"array x must be indexed 1..n",}
\]
\[
\text{forall(i in 1..n-k+1)(}
\]
\[
\text{among(l, u, [x[j] | j in i..i+k-1])};
\]

\[
\text{predicate among(int: l, int: u, array[int] of var 0..1: x) =}
\]
\[
\text{let } \{ \text{var int: s = sum(x)} \} \text{ in l <= s /\ s <= u;}
\]

- Supports experimentation with different decompositions, e.g. **sequence_cumul**
Implementability

Zinc is designed so that the features are mappable to modern CP solvers

- Evaluate parameters
- Determine initial domain for all decision variables
- Simplify records to tuples, flatten tuples, replace field accesses
- Replace enumerated types by integer range types
- Unfold built-in and defined predicates and functions
- Insert constraints arising from constrained types
- Lift lets to be global (rename variables)
- Simplify arrays to be one dimensional integer indexed from 0
- Translate variables sets on structured types to var set of int
- Reify to separate logical combinations of constraints
Implementations

- Two implementations
  - Prototype Full Zinc compiler
    - 12000 Mercury LOC, 5000 C LOC
    - Generates simplified Zinc using translation on previous slide
    - Maps simplified Zinc to Eclipse: 3 solver
      - Complete tree search with FD propagation
      - (Repair-based) Local search maintaining some hard constraints
      - Mapping to MIP and branch and bound search
  - In progress “Industrial Strength” Zinc compiler
    - 25000 Mercury LOC
    - Syntax and semantics checks
    - Transformation using Cadmium of a subset of Zinc, MiniZinc, to FlatZinc
    - FlatZinc interpretable by LP/FD solvers, and Gecode, Eclipse
Outline

1. Design Goals for Zinc
2. Modelling Combinatorial Optimization Problems
3. Natural Modelling
4. Extensible Modelling
5. Software Engineering
6. Practical Solver-Independence
7. Conclusion
Conclusion

Zinc

- Allows clear and concise high-level mathematical models
- Extensible with constrained types, and user-defined predicates and functions
- Supports the development of correct and maintainable models
- Allows a single conceptual model to be mapped to many design models

Future

- Many mapping of Zinc to solvers to explore
- Specifying search in Zinc
- Direct mapping of Zinc to Mercury

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