Object-Oriented Modeling of Programming Paradigms

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Abstract

For the right application, the use of programming paradigms such as functional or logic programming can enormously increase productivity in software development. But these powerful paradigms are tied to exotic programming languages, while the management of software development dictates standardization on a single language.

This dilemma can be resolved by using object-oriented programming in a new way. It is conventional to analyze an application by object-oriented modeling. In the new approach, the analysis identifies the paradigm that is ideal for the application; development starts with object-oriented modeling of the paradigm. In this paper we illustrate the new approach by giving examples of object-oriented modeling of dataflow and constraint programming. These examples suggest that it is no longer necessary to embody a programming paradigm in a language dedicated to it.

1. Introduction

What programming language should we use? The answer to this question has changed over the decades. In the 1970s the answer was: “The Right One”. Since then it has become: “What Everyone Else Is Using”. For example, in the 1970s one company embarked on the design and implementation of a language that was to be ideal for developing telephone switch software. Although they were successful, in the 1990s they judged it more important to use a standardized language with multiple and competing vendors. Accordingly, the ideal language was replaced by C and C++, much to the detriment of their subsequent software development.

Not only in this company, but in almost every other organization, a similar shift has occurred. In this paper, we want to re-examine the now discarded answer, “The Right One.” Why was this ever considered the right answer?

We believe it was based on the observation that with the languages such as Prolog, Scheme or ML, some problems become miraculously easy to program. But that depends on the problem: if it is easy in Scheme or ML, it may not be so in Prolog, and vice versa. Thus, the effect depends on the programming paradigm on which the language is based: functional programming in the case of Scheme and ML; logic programming in the case of Prolog.

The fact that, with the right choice of language some problems become miraculously easy to program we call the Whitehead effect, inspired by the following quote from Alfred North Whitehead (1861-1947):

“By relieving the brain of unnecessary work, a good notation sets it free to concentrate on more advanced problems, . . .”

Whitehead goes on to claim that the effect is to increase the mental capacity of those who use the notation.

In this connection one should also note the Sapir-Whorf hypothesis, stating that what one can think is determined by one’s language. In this form the hypothesis is vague in the extreme. Though various attempts at making it concrete have been discredited, the hypothesis may have something to do with the fact that, with the right language, some things become miraculously easy to program.

1.1. Radical Software Development

The Whitehead effect suggests that one first determines the programming paradigm that makes the application miraculously easy to program and that one then uses a language that embodies the paradigm. This we call Radical Software Development.

It is easy to see why this approach is not practical: Radical Software Development tends to lead to different paradigms, as required by the different applications. As it is, paradigms are locked up in programming languages. As a result Radical Software Development requires writing modules in several programming languages.

1.2. A One-Language World

Meanwhile, in the real world, companies are increasingly under pressure to “stick to their knitting”. For example, this means that a company making telephone switches
gets out of developing and maintaining its own ideal programming language. Managers want to cut costs of training new hires and insist on a widely used, standardized language. For further economies, such a language should come with tools and multiple, competing vendors. This explains why the world of programming has become a one-language world, or at least has been trying to.

It is not just managers who are opposed to multiple programming languages. The Right Language tends to be an exotic one, and does not sit well on the resume of the programmer who may soon need to look for another job. Another problem with The Right Language is what we call the Ninety-Percent Phenomenon, which we will now explain by an example.

Suppose one finds that logic programming is the paradigm that makes the application miraculously easy. At present, this means using Prolog. A browse of the manual shows that ninety-percent of it is taken up by matters that have nothing to do with logic programming. This ninety-percent is taken up with the mundane infrastructure that all languages seem to require, regardless of paradigm: what characters are allowed in names, what kind of numbers are there, how you write them, strings, characters, I/O, and so on. To their credit, the designers of C++ and Java have been careful to do this as much as possible as it has been done in C. In Prolog it has been done independently of C, or of any other language. As a result, Prolog does it sometimes the way you guess it will do it, and sometimes not. Rather time consuming, and frustrating.

2. OO modelling of the paradigm

In object-oriented programming (OOP) it is routine to model an application from the ground up in terms of objects. In one widely used approach [24], one notes the nouns and the verbs of a description of the application in English. The nouns are then considered as candidates for the classes, the verbs as candidates for the methods. If one can do this for transactions, invoices, customers, . . . , why not for the key concepts that make a particular programming paradigm miraculously effective for the application? In this paper we argue that OOP can be used to do this for programming paradigms.

Let us consider functional programming. In procedure-oriented languages, numbers are privileged in that one can (1) give them names, (2) assign them to variables, and (3) return them as function results. In these languages, functions are underprivileged in that they share with numbers property (1), but not (2) and (3). The motivation for functional programming languages is to accord to them all the privileges of numbers, and thus make them “first-class objects”, as was the going terminology in functional programming [20].

Thus it was apparently common to regard functions as objects before 1977. It was only a matter of time to work out the consequences of this view. In fact, it happened twenty years later in Friedman and Felleisen’s A Little Java, A Few Patterns [5]. However, it took the form of a cryptic one-page appendix.

From this page, it is apparent that the absence of generics in Java makes the modelling of higher-order functional programming a tiresome exercise. To overcome this limitation, one could have followed C++ and added templates. However, Wadler and Odersky judged the Hindley-Milner type system, used in ML, as a superior alternative. They extended Java to include this type system. This resulted languages such as Pizza and GJava [15, 2] that directly allow higher-order functional programming, without the need for object-oriented modelling in the sense of this paper. The Java extended in this way became the standard in 2004 under the name “Java 2 Platform, Standard Edition 5”.

Pizza and GJava are examples of Multi-Paradigm Object Oriented Programming Languages. Here the object-orientation of Java is used to extend it to include another programming paradigm. Several other projects in this direction were reported at MPOOL 2001 [3], a workshop in conjunction with the ECOOP conference.

As we explained, there is a strong tendency for one language to dominate practical programming. Although a multi-paradigm OO language can be more elegant and powerful, it is unlikely to be accepted in practice in the foreseeable future. It is therefore of interest to see how far one can go in the direction of multiparadigm programming within a programming language that is widely used in practice. In this paper we show by worked examples in C++ that multi-paradigm programming is not only possible, but can be quite simple and elegant. To fit the paper’s format, we need to restrict ourselves to small paradigms. As we will see, dataflow and constraints are small enough to exhibit as worked examples here.

3. Dataflow programming

In the dataflow paradigm all computation happens in a network consisting of nodes connected by unidirectional datapipes. Thus each node has zero or more input pipes (when the output end of the pipe is connected to the node), and zero or more output pipes (when the input end of the pipe is connected to the node). A pipe is used by repeatedly placing data items at its input end. These items can be retrieved from its output end in the same order in which they entered at the opposite end. Abstractly viewed, the pipes behave like the abstract data structure referred to as a queue.

The dataflow paradigm is justified by the class of problems that it makes easy to solve. For example, such prob-
lems arise in business process re-engineering. Such processes are naturally analyzed and re-designed in terms of workflow [9]. The automation of workflow then naturally translates to dataflow.

An older method is Structured Systems Analysis (also called SADT, for Structured Analysis and Design Technique), which was at one time widely applied in commercial dataprocessing [8]. However, Structured Systems Analysis was a world unto itself, apparently not aware of the larger context of dataflow programming. However, Structured Systems Analysis was a world unto itself, apparently not aware of the larger context of dataflow programming.

Structured Systems Analysis discovered dataflow by inspired thinking about commercial dataprocessing applications. Ashcroft and Wadge [22] arrived at the idea starting from studies in semantics of programming languages. Dennis, Arvind and others at MIT have arrived at the dataflow paradigm from computer architecture [21]. Dataflow has been identified as a Software Architecture [19].

As early as 1977 the paradigm was already sufficiently compelling that a programming language was designed to make dataflow programming as natural as possible [13]. The paper just mentioned also contains some simple and widely appealing examples showing the paradigm at its best. Note that the paradigm was independently arrived at from disparate areas: business applications, semantics, and architecture (hardware and software). This suggests that it’s “real” in some sense.

### 3.1. Hamming’s problem solved in dataflow

A good introduction to the dataflow paradigm is Hamming’s problem [13]:

> to print out in increasing order all positive integers that have no prime factors other than 2, 3, or 5.

Thus, the sequence starts with 1, 2, 3, 4, 5, 6, 8, 9, 10, 12, 15, … This problem is attributed to R.W. Hamming by Dijkstra [4], who provided an ingenious solution. It is more efficient than, but is not as easy to understand as, the dataflow version given by Kahn and McQueen [13], which we follow here.

One approach to a solution starts with the observation that the infinite sequence $x$ of numbers required by Hamming’s problem satisfies the following equation:

$$ x = 1 \circ \text{merge}(\text{merge}(t_2(x), t_5(x)), t_5(x)) $$

where

- $\circ$ is the result of merging its two sorted input sequences into a sorted output sequence, suppressing duplicates
- $t_2$ is result of multiplying by 2 its input sequence, element by element; similarly for $t_3$ and $t_5$

The question whether the solution to Hamming’s problem is the only solution to the equation is addressed by the methods developed in Kahn [12].

To turn this observation into a dataflow network, we take the above equation with a complex expression and turn it into a system of simple equations by introducing auxiliary variables. We do this in two steps. In the first step, we get rid of nested expressions:

$$ a = t_2(x_2) \quad b = t_3(x_2) \quad d = t_5(x_2) $$
$$ c = \text{merge}(a, b) \quad x_1 = \text{merge}(c, d) $$
$$ x_2 = 1 \circ x_1 $$

The resulting equations can, if considered in isolation, each be translated directly into a node of a dataflow network. Each of $a, b, c, d,$ and $x_1$ correspond to a datapipe because, in the above set of equations, they have exactly one occurrence in a left-hand side and exactly one occurrence in a right-hand side. An occurrence on the left-hand (right-hand) side corresponds to the output (input) side of the datapipe.

However, $x_2$ has too many occurrences in right-hand sides. We can avoid this problem by making these occurrences into different variables, say $f, g,$ and $h$. But how do we tell that these are the same sequence? To do that, we introduce a node type, with one input and two output pipes, that outputs two identical copies of each item that it receives from the input pipe. Let us call this node $\text{split}$.  

$$ i = x_2 \quad h = x_2 \quad f = i \quad g = i $$
$$ a = t_2(f) \quad b = t_3(g) \quad d = t_5(h) $$
$$ c = \text{merge}(a, b) \quad x_1 = \text{merge}(c, d) $$
$$ x_2 = 1 \circ x_1 $$

The entire top two lines each correspond each to a $\text{split}$ node; the remaining six equations correspond to a node each. This makes eight nodes in all. See the network diagram in Figure[1]

### 3.2. An object-oriented implementation of Hamming’s problem

The most widely known principle of object-oriented modelling is to consider the nouns of the specification as candidates for classes.
In any dataflow network, particularly conspicuous nouns are node and datapipe. As observed before, datapipes behave like queues, a commonly used class.

According to the principle just mentioned, we should consider a class suitable for creating all required nodes as instances. The principle, though a good first approximation, needs some refinement. This is because objects of the same class should have states of the same form, though not necessarily of the same content. The state of a node object includes the states of the abutting datapipes. And of course, instances of the same class should have the same behaviour.

These considerations suggest that the merge nodes are instances of the same class (merge; the individual instances are m1 and m2), as are the split nodes (of the class split, with instances sp1 and sp2), as are the nodes t2, t3, and t5 (of the class times, with instances t1, t2, and t3).

Lines 3–5 create instances of class queue to act as datapipes, each with a maximum size arbitrarily set at 10. Given these pipes, lines 6–10 create the nodes, with the correct pipe connections. These lines seem the most succinct possible textual representation of the diagram in Figure 1. In so far as this is true, C++ comes close to the best possible dataflow programming language.

Lines 3–10 create the dataflow network; they do not cause it to execute its computation. The attraction of the dataflow paradigm is to avoid the difficulty of conventional programming, namely to ensure that events happen in the right sequence. To execute a dataflow network, each node executes, independently of the others, the following simple computation:

```cpp
01: int main() { 
02:   const int MaxTimes = 50; 
03:   queue a(10), b(10), c(10), d(10), 
04:       x1(10), x2(10), 
05:   f(10), g(10), h(10), i(10); 
06:   merge m1(&a,&b,&c), m2(&c,&d,&x1); 
07:   times t2(2,&f,&a), t3(3,&g,&b), 
08:       t5(5,&h,&d); 
09:   split sp1(&x2,&h,&i), sp2(&i,&f,&g); 
10:   print p(&x1,&x2); 
11: 
12:   node* ar[] = { &m1, &m2, &t2, &t3, 
13:                  &t5, &sp1, &sp2, &p }; 
14:   int arSz = sizeof(ar) / sizeof(node*); 
15: 
16:   x1.add(1); 
17:   for ( int i=0; i < MaxTimes; i++ ) 
18:     for ( int j=0; j < arSz; j++ ) 
19:       ar[j]->run(); 
20:   return 0; 
21: }
```

Figure 1. Dataflow network for Hamming’s problem in the initial state, where all pipes are empty except a 1 in x1.

Figure 2. C++ code for the dataflow network for Hamming’s problem. The node print has been added to allow the solution to be printed.
If any of the input datapipes is empty, or if any of the output datapipes is full, do nothing. Otherwise, remove the next item from each of the input pipes, perform on them the specialized computation characteristic for the type of node, and place the results, if any, on the output pipes.

The computation just described is invoked by a method called run, which is defined for each of the classes merge, times, and split.

To execute the entire network, one invokes the run method for each node, as in lines 18–19 of Figure 2. Typically several of these invocation have no effect because of full output or empty input pipes. But if the network can do anything at all, then at least one node will do something. In large networks it is worth optimizing the invocations of the run method. One can keep track of which nodes are blocked. A blocked node connected to a pipe of which the content changed may no longer be blocked and becomes a candidate for being run. Such an optimization is reminiscent of the constraint propagation algorithm of D. Waltz [23].

Note that in lines 12–13 the nodes of the dataflow are placed into an array. The order of the nodes in this array gives the order in which the run methods are called (line 19). However, this order does not matter, since in dataflow the order in which things are done matters less than it does in conventional programming.

Space limitations prevent us from listing the entire program, which is about a hundred lines, including the queue implementation. We just add some representative code:

class node {
public:
    virtual void run() = 0;
};

class times : node {
private:
    int mult; queue *in, *out;
public:
    times(int Mult, queue *In, queue *Out) {
        mult = Mult;
        in = In;
        out = Out;
    }
    void run() {
        if (in->empty() || out->full())
            return;
        out->add(mult*(in->next()));
        in->remove();
    }
};

An attractive characteristic of dataflow is that the nodes can run concurrently subject to mutual exclusion on the datapipes. We have considered doing this example in Java to make it easy to have every instance of node run in its own thread. But although threads are simple to use, the result is still not as simple as doing without. To find Hamming numbers, threads are not essential. So we make our point better by showing a simpler program that just gets the numbers.

4. Constraint programming

Many problems in resource planning and numerical computation can be solved in a declarative way: one states the relations that are to hold between the unknowns; a suitable solver then finds values such that all relations are satisfied. The relations are referred to as constraints; the method is known as constraint programming [14,11].

Constraint programming is useful because systems can be solved that contain thousands of constraints. Here we will of course illustrate with a very small example.

4.1. Complex constraints

A particular constraint programming method is interval constraints. Specific for interval constraints is that the unknowns are real numbers and that their domains are intervals. As an example consider the problem of finding the intersection points of the circle \(x^2 + y^2 = 1\) and the parabola \(y = x^2\). This means finding values for \(x\) and \(y\) such that both relations are satisfied.

Of course a student in secondary school will identify \(y = (\sqrt{5} - 1)/2\), and \(x\) accordingly. The point here is to develop a system that determines solutions directly from the set of constraints as given, for a wide class of constraints.

Suppose that initially all we know is that \(x\) and \(y\) are in \([-\infty, +\infty]\). Considering each of the two given relations separately would already remove some values for \(x\) or \(y\) from consideration. For example, it is clear from the constraint \(x^2 + y^2 = 1\) that \(x\) and \(y\) have to be in \([-1, +1]\). Whatever it is that allows us to reduce the original intervals \([-\infty, +\infty]\) to \([-1, +1]\) we call a contraction operator. It is an operator associated with the constraint that allows one to make such an inference. In constraint programming, one applies in turn the contraction operators associated with the constraints until no more contraction results. The remaining intervals for the variables then give all information about the solutions of the problem that this method can give.

To make this method practical, contraction operators have to be widely applicable and efficiently implementable. Such operators have only been discovered for a relatively small repertoire of primitive constraints. These include constraints with binary relations such as \(x \leq y\), \(x = y\), and...
and $y = x^2$. There are also constraints with ternary relations such as $x + y = z$ and $x \times y = z$. The primitive constraints do not include the constraint $x^2 + y^2 = 1$, as it does not occur sufficiently often to justify its presence in a general-purpose solver. This complex constraint is therefore decomposed into primitive constraints with the aid of auxiliary variables. In this way the circle-and-parabola problem is expressed by the system

$$x^2 = x_2, \quad y^2 = y_2, \quad x_2 + y_2 = 1, \quad x_2 = y \quad (1)$$

### 4.2. Contraction operators

To introduce contraction operators, let us look at an example of one in action: the one for primitive constraints of the form $x + y = z$. Such a constraint expresses that the variables are in a ternary relation that we call sum. If it is known initially that $x$ and $y$ are in $[0, 2]$ and that $z$ is in $[3, 5]$, then it is clear that neither $x$ nor $y$ can be near 0 and that $z$ cannot be near 5. In fact the contraction operator reduces the intervals for $x$ and $y$ to $[1, 2]$ and the one for $z$ to $[3, 4]$.

This is optimal and can be computed in a few floating-point operations. One can solve complex systems of nonlinear equations and inequalities by first reducing them to primitive constraints, and by then applying contraction operators until nothing changes. Typically, the remaining intervals are too large to be useful, in which case one interval is split and the constraint propagation is repeated.

### 4.3. OO modelling of interval constraints

Let us now do a perfectly straightforward exercise in object-oriented modelling in the spirit of [24]. Clearly, “constraint” is an important noun, so justifies a class of that name. The same holds for “variable”. However, this is a dangerously ambiguous concept: in programming languages, in logic, and in calculus it means different things. The role of $x$ in the example can be stated precisely: it is the name of a real number that we do not know. Thus $x$ is an instance of a class of which the instances represent real numbers. This suggests the following class definition:

```cpp
class real {
private:
  FLPT lb, ub;
public:
  real();
  real(FLPT lb, FLPT ub);
};
```

FLPT is a generic floating-point number type; it could be of single or double length. The class real is a classic example of object-oriented modelling. It stands for an abstract concept, in this case a real number. It hides the representation, which is the description of a set of real numbers to which the real number belongs. The set is restricted to the form of an interval $[lb, ub]$, which has the floating-point numbers $lb$ and $ub$ as lower and upper bounds.

In the case of real numbers this distinction between the abstract concept, which is public, and its hidden representation is especially valuable because most real numbers do not even have a finite representation. So far, this perfectly ordinary piece of object-oriented modelling has been, as far as we know, the only practical way to directly compute with mathematical models involving continuously varying quantities.

The zero-argument constructor creates a real of which nothing is known. Accordingly it is represented by the interval $[-\infty, +\infty]$, which is the set of all real numbers. If more is known about the real number, then it is represented by a smaller interval. In our example we need the real numbers 1 and 0.5, which are represented by the intervals only containing these numbers and are created by the constructor calls real _1(1.0,1.0) and real _0(0.5,0.5).

To model constraints, we note that their identity is determined both by the relation and by the variables connected by the relation. Each instance of a constraint needs to record the variables of that instance. It is essential that different constraints be able to share reals. This sharing is modelled by members that are pointers to instances of class real. The relation is represented by ensuring that constraints are instances of the same class if, and only if, they have the same relation. In this way the contraction operator for that relation can be a method of that class. This method is named `shrink()`. As all constraints need to go into the same container, and as they all have a `shrink()` method, all constraint classes derive from an abstract class named constraint. These considerations are embodied in the code in Figure 3.

Now that we have the interface with the interval constraint machinery, let us use it to express the system (1) for the circle-and-parabola problem; see Figure 4.

In line 3 the variables of system (1) are created. Lines 7 through 11 create the constraints of this system and place them in a container. At the same time, this specifies the interconnections of the constraints via the shared variables.

After the constraint system has been built, contraction operators are applied. This is done in a simplistic way in lines 13 through 18. In actual practice, it is done by means of a constraint propagation algorithm. These algorithms have a long and interesting history; see [1] for recent contributions and a history.

The result of the propagation is printed on lines 18 and 19 with the result: $x \in [-1, 1]$ and $y \in [0, 1]$. This result

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1 It is intended to shrink intervals. Moreover, the class is part of a system called “Sound High-Resolution Interval Numeric Calculator”.

\[ y = x^2 \]
is large enough to contain both solutions to \( (1) \). If one is interested in one solution, say, with positive \( x \), then one can add a constraint as in line 10, using a constant created as in line 4. In that case there is one solution, enclosed in a narrow interval:

\[
\begin{align*}
  x & \in [0.78615137777574229, 0.78615137777574236] \\
  y & \in [0.6180339887498944, 0.6180339887498954]
\end{align*}
\]

We include this example because we believe that it shows that a special-purpose constraint programming language would not be able to specify the system \( (1) \) in a clearer or more succinct way. At the same time, a special-purpose language would probably not have any original insights on how to do containers, nor on how to do control primitives, so that these aspects of the program would be the same or gratuitously different. Hence, this straightforward exercise in object-oriented modelling of constraint programming is probably as well as one can do in the form of text.

5. Object-oriented frameworks

The foregoing examples suggest that a distinctive programming paradigm need not have a language of its own. It is adequately supported by a suitable class library. Both our examples include an abstract class and a generic algorithm expressed in terms of that class. Programming in the paradigm requires one to define derived class suitable to the application. In our dataflow example, each type of node and its specific activity becomes a class derived from node. Similarly, in the constraint example, each type of constraint and its specific contraction operator becomes a class derived from constraint.

But the library, with its abstract classes and generic algorithms is not enough. If it indeed embodies a distinctive programming paradigm, it comes with a view of how to do things, a mindset. This can be expressed by a set of tutorial examples. The collection of these things is what is called a framework by Gamma, Helm, Johnson, and Vlissides [7].

The trend towards frameworks rather than dedicated programming languages may have started with Puget’s approach to constraint programming. At first, constraint programming followed the conventional route with a dedicated programming language. It grew out of logic programming, which had Prolog as dedicated programming language. Accordingly, constraint programming was implemented in various dialects of Prolog: Prolog II and III, CHIP and its descendants, BNR Prolog, and Prolog IV. However, Puget adopted Saraswat’s comprehensive view of constraint programming [18] called Concurrent Constraint Programming, dropped the concurrency, and based a C++ class library on it [16] [17].

Design Patterns and object-oriented frameworks seemed equally promising when these ideas first arose. Design patterns found wide acceptance. However, to quote Erich Gamma [6]

> When we wrote “Design Patterns” we were excited about frameworks and forecast that there would be lots of them in the near future. Time has shown, however, that frameworks aren’t for everyone. Developing a good framework is hard and requires a large up-front investment that doesn’t always pay off.

Originally, frameworks were intended to help specific applications, such as graphical user interfaces or document processing. Like design patterns, object-oriented frameworks are defined as systems of customizable co-operating classes. What one obtains as a result of modelling a programming paradigm also answers to this description, but is not a design pattern. Instead, it is useful as a new way of discovering useful systems of customizable co-operating classes.

One of the most important advantages of design patterns is as an aid to documentation: just because the pattern has a name, the use of this name in the documentation speeds up understanding of the part of the code concerned. The object-oriented frameworks arising from programming paradigms have this same advantage.

6. Conclusions

So far there has been little scope in practice for the Whitehead effect to ease software development. Applying the paradigm that’s right for the application seemed to require switching to a different programming language. Practical concerns necessitate sticking to a single language.

This situation has changed since the single language is object-oriented. Programming paradigms such as dataflow or constraints, which once were thought to need a dedicated language, are easily modelled in an object-oriented language. In fact, as easily as the textbook example of object-oriented modelling of simple applications. Thus it is not overly ambitious to model the ideal programming paradigm, rather than the application. This modelling typically takes the form of an OO framework.

In this we can distinguish between minor and major paradigms. The minor ones are those that can be modelled in one of the few languages most widely accepted in industry. We saw that dataflow and constraint programming fit in this category. Järvi and Powell [10] implement partial function application in this way in C++. The fact that functional programming can be characterized by functions being first-class objects, suggests that functional programming is no harder to do. It has turned out that it is and that it seems to require a new programming language. Apparently, functional programming is a major paradigm. However, even in this case OO programming has made a difference. The
new language turned out to be an extension of Java that was needed anyway, independently of functional programming.

The question remains whether logic programming, so far sequestered in Prolog and other dedicated languages, is a major paradigm requiring a language extension or a minor one that can easily be modelled in an existing OO language. The work of combining Smalltalk with logic programming by symbiotic reflection seems to transcend the simplistic criterion used to distinguish between minor and major paradigms.

It used to be that not only paradigms, but certain applications got their own programming languages. We have argued that this is something of the past. It was even the case that one application, namely simulation, had several languages devoted to it. One of these was Simula, and the rest is history.

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class constraint {
  public:
    virtual bool shrinc() = 0;
    virtual ~constraint {}  // Applies contraction operator.
    // Returns false iff
    // an empty interval results.
};
// constraint is x <= y
class leq: public constraint {
  real *x, *y;
  public:
    leq(real *x, real *y);
    bool shrinc();
};
// constraint is x == y
class eq: public constraint {
  real *x, *y;
  public:
    eq(real *x, real *y);
    bool shrinc();
};
// constraint is x+y = z
class sum: public constraint {
  real *x, *y, *z;
  public:
    sum(real *x, real *y, real *z);
    bool shrinc();
};
// constraint x^2=y
class square: public constraint {
  real *x, *y;
  public:
    square(real *x, real *y);
    bool shrinc();
};

Figure 3. Definitions for the constraint classes.
int main () {
    //solve \( x^2 = x2, y^2 = y2, x2+y2 = 1, y = x2 \)
    //create variables:
    real x, y, x2, y2, _1(1.0,1.0);
    //real _0(0.5,0.5);

    //create constraint system:
    constraint* array[] = {
        new square(&x,&x2), new square(&y,&y2),
        new sum(&x2,&y2,&_1), new eq(&y,&x2)
        //, new leq(&_0,&x)
    };

    //propagate:
    const int MAX = 1000;
    int size = sizeof(array)/sizeof(constraint*);
    for (int i=0; i < MAX; i++)
        for (int j=0; j < size; j++)
            array[j].shrinc();
    cout << "x: " << x << endl;
    cout << "y: " << y << endl;
    for (int j=0; j < size; j++)
        delete array[j];
}

Figure 4. C++ code for finding the intersection of a circle with a parabola using the interval constraints method.