A NEW PARADIGM FOR COMPUTER USERS

by

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Date Transmitted: July 1995

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ABSTRACT

Why is it that mathematical results are useful for centuries, yet computer programs suffer tumultuous changes of technology? Can one write programs that will be useful in fifty years? Extreme efforts to preserve “dusty deck” programs have confused the roles and responsibilities of four participants: the end user, application programmer, system software designer, and hardware engineer. Users feel they must know hardware details like word size and megahertz rate – yet are oblivious to error in the output. Application programmers try to guess compiler behavior, often obtaining high performance only by trickery. With new hardware, that old guess is often wrong. The result is “high-performance code” that is slower than the original code. The hardware engineer tries to maintain compatibility through many generations, sacrificing performance and hardware affordability to meet presumed needs of the other three participants. We propose that the respective roles and responsibilities be clearly delineated via a *three-stage contract* between the four participants. The result is a new interaction paradigm that should allow programs to share the longevity of mathematical results and absorb technical advances gracefully.

A NEW PARADIGM FOR COMPUTER USERS

1 Introduction

There have always been four identifiable groups, or *participants* that use computers: the end user, the application programmer, the system software designer (including the compilers, libraries, and operating systems), and the hardware engineer. In many scientific environments, the end user and the application programmer are the same person; the end user is also expected to be the author and maintainer of the source code. In other environments, such as business computing and personal computing, the end users are distinct from and far more numerous than the application programmers.

But mostly because of performance motivations, there has been a trend to blur roles and responsibilities for one another's traditional tasks. The tendency to "pass the buck" between the four participants regarding who should make performance higher has led to problems that were never anticipated or intended by the computing community. Part of our solution will be to redefine and disentangle the roles using definitions given in Section 3. We propose that the roles of each participant be made explicit via a *three-stage contract*, described in Section 4, as an approach to solving these problems. Section 4 also steps the reader through a simple but nontrivial example. This is followed by a section containing concluding remarks, along with our long-term vision of future research. To summarize, this technical report presents the problems with the current use of computers that have arisen, why they have arisen, and what might be done to solve them.

2 Background and Motivation

2.1 History of Entanglements

In recent years, the roles of the four classes of computer participants have become confused and entangled to the detriment of everyone. These four types of participants are: the end user, application programmer, system software designer, and hardware engineer. A watershed was in 1975, when FPS successfully commercialized a wide-instruction word computer, the AP-120B [3]. That computer shifted the burden of raising performance from the hardware engineer to the designers of subroutine libraries that did "software pipelining." It also put a burden on the application programmer, who had to rewrite applications in terms of those library routines. The CRAY-1 [18], introduced in 1977, forced the issue of "vectorization" on disgruntled application programmers. Those who accepted the new burden were (sometimes) rewarded with much higher performance, at the price of having to learn a new set of skills, reduced portability, and increased code development time. By about 1982, "parallel processing" was beginning to be debated as the unavoidable next advance in computer architecture [2, 6, 8, 10, 11].

Parallel processing has been with us for many years. Computer architectures of the 1950's had parallel functions (for example, the IBM 7094 [14] fetched data and instructions in parallel), and even the use of n -bit words implies $\mathcal{O}(n)$ parallelism at the finest grain. Yet "parallel processing" is treated as a recent revolution in computing. Why?

The difference now is that the application programmer is being asked to recognize parallelism and make use of it, whereas in the past the parallelism had always been the province of the hardware engineer, or beginning in the 1980's, the compiler designer [1, 7, 9, 16, 17, 20]. As the term is used today, "parallel processing" means only *that type of parallelism that cannot be disguised from the application programmer*. The need for the application programmer to know so much about computer architecture is viewed by some as a major calamity, and the cost of rewriting the serial software in existence is enormous. Even the end user is no longer insulated from changes in computer architecture. In parallel computing environments, users are expected to specify how many processors they need, for example.

A popular school of thought is that we must find ways to exploit parallelism at the application level that are gradual and painless. Others feel that only revolutionary change is the solution and that we must discard old software and start over with some assumption about what "all" future computers will have in common. There is no agreement about what that future will be and the result is paralysis.

The debate is often couched in terms of computer languages. Those who oppose all changes at the application level want to lock in existing definitions of languages like C and Fortran. Others look to extensions to languages by compiler directives and new keywords, asking the application programmers and compiler designers to do the "dirty work." The High Performance Fortran (HPF) [13] initiative belongs to this category. Still other want to invent entirely new languages like Sisal or Occam, that can express parallelism or data flow, requiring a complete rewrite of every application.

It is not our intent to offer, in this technical report, a new language definition. We see the choice of computer language as neither the problem nor the solution. The problem lies in the correct assigning of responsibility for tasks among the four participants. Computer languages are inherently ephemeral. Consider Knuth's series *The Art of Computer Programming* [12]. His "assembly language" examples written in MIX are of little value today; however, the English and mathematical examples are still relevant and useful. A combination of English and standard mathematical notation to delineate tasks and responsibilities seems likely to remain readable over many decades of technological change and is the focus of this technical report.

2.2 Failures of the Current Approach

In this section, we provide three examples illustrating the failure of the currently-used programming paradigm. The first example deals with assumptions by certain system software designers regarding end user input accuracy and output error. The second example illustrates how low performance can result when the application programmer tries to guess the compiler behavior. The last example notes how personal computer purchasers (end users) often use irrelevant hardware

criteria in making their purchase decisions.

2.2.1 Uncertain Accuracy

In the 1980's, the DEC and Unix C libraries for trigonometric functions, assumed that the end user's input is *exact*. Because a number like 10^{300} expressed to fifteen decimals is really uncertain to $\pm 10^{285}$, it is absurd to insist that the sine or cosine of that number be exact. Who knows where, on the unit circle, the angle really lies? But without permission from the end user to treat the input as approximate, the only way to unwind the number around the circle accurately is to use multiple-precision arithmetic with π stored to thousands of decimals! The resulting performance, needless to say, is abysmal. The fault lies in the misplacement of responsibility in the implicit contract between the end user and the application programmer. A concession (by the end user) of inaccurate input can greatly improve performance that one can reasonably demand.

2.2.2 Loop Unrolling

In the 1980s' LINPACK benchmark report [4], there is the annotation "(rolled BLAS)" after many of the numbers in the table. What does this cryptic comment mean? Well, the BLAS are Basic Linear Algebra Subroutines [5] like dot product and vector scaling for which the LINPACK benchmark supplies Fortran subroutines. The loop operation $y_i = a \cdot x_i + y_i$ is given two pages of Fortran with the loop unrolled 2-fold, 4-fold, 8-fold, and 16-fold. A portion of this code is given in Figure 1. Unrolling is done to avoid the overhead of loop management. In more recent machines and compilers, there is a higher performance penalty associated with unrolled code than there is with rolled code. So people "roll" the unrolled loop back up. Then LINPACK goes faster.

What went wrong in these events? The application programmer was guessing both compiler and hardware behavior. What the programmer wanted to accomplish was to multiply a row of a matrix by a constant and then to add the result to another row. Conventional Fortran forces the programmer to write a "DO" loop to perform this sequentially, even though the order of the i subscripts does not matter. There is plenty of parallelism in the operation and opportunity for vector arithmetic also. Compilers for vector and parallel computers have to do some extra work figuring out if the serial ordering the programmer specified is safe to ignore. All the unrolling does is make that analysis more difficult.

2.2.3 Word Size

In 1993, one could eavesdrop on 10-year-olds debating the merits of 8-bit versus 16-bit NintendoTM [3] video game systems. One wonders whether those arguers had much understanding of register sizes, data bus widths, and the technical merits and costs. It seems more likely that the number 16 was considered to be twice as good as the number 8.

Long ago, one of the authors witnessed a marketing executive insisting he needed a 16-bit personal computer to do word processing, because an 8-bit PC simply would not do the job.


```

c  main loop - groups of sixteen vectors
c
      jmin = j+16
      do 60 j = jmin, n2, 16
        do 50 i = 1, n1
          y(i) = (((((((((((((( (y(i))
$           + x(j-15)*m(i,j-15)) + x(j-14)*m(i,j-14))
$           + x(j-13)*m(i,j-13)) + x(j-12)*m(i,j-12))
$           + x(j-11)*m(i,j-11)) + x(j-10)*m(i,j-10))
$           + x(j- 9)*m(i,j- 9)) + x(j- 8)*m(i,j- 8))
$           + x(j- 7)*m(i,j- 7)) + x(j- 6)*m(i,j- 6))
$           + x(j- 5)*m(i,j- 5)) + x(j- 4)*m(i,j- 4))
$           + x(j- 3)*m(i,j- 3)) + x(j- 2)*m(i,j- 2))
$           + x(j- 1)*m(i,j- 1)) + x(j)      *m(i,j)
50      continue
60      continue

```

Figure 1: Unrolled LINPACK Code

When asked to explain, the depth of understanding of 8-bit versus 16-bit proved no different than that of your average 10-year old.

Why are computer customers concerned only with hardware specifications instead of actual *delivered* performance? Similarly, the megahertz rating is often cited as though it were a sure indicator of application speed. The point of this example is that end users have involved themselves in hardware choices that are only weakly correlated to their actual needs.

3 Participants

In much the way that a building is constructed through contracts, contractors, bids, materials, and labor, a computer application may be thought of in a similar light with the final product being desired information. In this section we concentrate on the four participants involved with executing a computer application: the end user, the application program, the system software, and the hardware specification file. Of course, the application program, system software, and hardware specification file are created by application programmers, system software designers, and hardware engineers, respectively. But when the contract between the end user and application program is being negotiated, it is the software entities that are participating, not the people. The only human that is directly involved is the end user. After the participants have been described, we describe in Section 4 the interactions between the four participants in terms of the three-stage contract.

3.1 End User

An **end user** is a person wishing to execute some application but is not assumed to know or care about the architecture, topology, or *any* machine-specific details. Hence, the end user should only have to specify the task in terms of goals. Perhaps more importantly, the end user should *not be allowed* to specify anything but the goals. The primary goal of the end user is to obtain “accurate answers” in “a reasonable time” and at “a reasonable cost”. In practice, we observe two disturbing trends away from this common goal: a naive disregard for accuracy issues and focus on extraneous machine-dependent details instead of on time and cost.

Typically, when an end user executes a numerical application, end user assumes that the output accuracy is sufficient to meet his needs. On the few occasions when he feels uncomfortable with the answer, the common response is to switch from single precision representation to double precision. In fact, most end users of applications have no idea how accurate their output really is. Even in the cases where an output error estimate is supplied by an application, the output error is calculated under the assumption that the *input* is exact and error-free.

We propose that the end user focus on accuracy, elapsed time, cost, and reliability (tolerance for machine/software failure rates) by passing a set of *demands* and *concessions* to the application program¹. For example, the end user can say, “I need three digits of accuracy in my answer.” However, the end user should *not* be allowed to say, “I want you to use the ‘double precision’ data type because on this computer I think it will be good enough. I do not trust single precision.”

Demands that an end user can specify include placing upper limits on:

- how long the job may run in wall clock time
- error in the output
- cost (preferably in *real* money)
- acceptable failure rates

Most paradigms involve demands alone. However, it is important that *concessions* be included too. Placing demands without concessions allows one to make wild and unrealistic requirements without consideration to their cost or feasibility. In terms of the construction analogy, an example would be asking for a mile high skyscraper in a day at no cost. Obviously, this would be impossible without conceding several points. Suppose one said that they would like the same skyscraper but would be willing to settle for a building of 80 floors in 5 years in exchange for \$200,000,000. This is a contract that at least has a fighting chance. So accordingly, here are some concessions that an end user can give:

- a worst-case estimate of error in the input data
- a willingness to tolerate faults in hardware or system software

¹Depending on your point of view, virtually any attribute may be thought of in terms of demands or concessions. The point is that the end user must be willing to endure certain penalties or forfeit use of the computer.

- a willingness to pay for a run
- a willingness to wait for a run
- a list of lower priority goals that may be sacrificed (if necessary) in order to meet other more important goals

Of the demands and concessions listed above, the three most important may be specifying a maximum of wall clock time and output error while admitting the amount of input error. Yet our generation of end users is accustomed to having little control over these issues. Scientific simulations are typically done with inputs assumed to be exact, very unscientific confidence in the numerical validity of the answers, and execution times determined by trial-and-error for each system with no guarantees of repeatability.

It seems possible to create a first-stage contract² between the end user and the application program that demands a minimum performance for execution time and answer quality, yet frees the application programmer to achieve these things by any method that works. Note that the acknowledgment of possible error in the input is a concession made by the end user that helps the application programmer. This subcontract makes up the first stage of the three-stage contract.

3.2 Application Program

The next participant is the **application program**. Currently, when an application programmer develops an algorithm, he or she passes to the **compiler** a great detail of information which is not only irrelevant, but is also damaging to the efforts of obtaining good performance. For example, in conventional languages like C or Fortran, the sequential ordering of instructions usually results in unnecessary and spurious data dependencies from one instruction to the next. Also, application programmers are notorious for introducing extraneous details like loop unrolling (Section 2.2.2) in order to obtain better performance. Later, when a computer is replaced by a newer computer, the relative performance of the same program suffers as a result of these extra details.

We believe that “an application program” should actually be a suite of many different, *best-known* algorithms that cover a wide range situations. For example, some algorithms would be targeted to a SIMD machine with a two-dimensional mesh. In addition, separate algorithms would exist depending on bits of precision, register availability, and the number of floating point adders. We propose that the algorithms be written in an English-like format with dependencies, suggestions, and shortcuts stated explicitly.

As the application program is downloaded to a particular machine, it should be sent to the system software for extraction of those algorithms suited to the particular hardware. At this point, much of the software is omitted due to incompatible topological or timing or precision requirements. However, the subset of algorithms that remain can confidently be believed to be the currently “best known” approaches to meeting certain goals within the concession/requirements for this particular machine.

²Henceforth, referred to only as the “contract” when the context makes it clear which stage is applicable.

After the remaining algorithms have been compiled, they would be individually tagged by the system software with timing and error estimates. When an end user submits a contract, it can be processed at submission time against this tagged information to locate the appropriate algorithm (if one exists at all) or to determine that the contract is not feasible. When a contract is not acceptable, alternative contract stipulations should be offered to the end user for consideration.

So what should an application program legitimately specify in its “contract”? The answer is: whatever it needs from the compiler to satisfy the goals set by the end user. The application divides the end user’s goals into subtasks, which sounds like top-down design but is something very different. The end user’s goals involve time and accuracy. The application program specifies an algorithm, with guaranteed performance at every step. That algorithm can be constructed by top-down, bottom-up, or whatever method one likes, so long as the final result can be read by a human as a proof of the achievability of the overall goal. The best way is by example and is given in Section 4.2.

There are two important features in this particular part of the contract that are not found in other approaches. One is to place a bound on the speed, latency, and precision of every data item. The second is to express as much parallelism as possible, understanding that there is generally more parallelism in the data dependency of an algorithm than can be exploited by a compiler. The compiler’s task is now discarding parallelism instead of trying to derive it.

These two details are the ones compilers are currently burdened with guessing about, and programmers have avoided specifying these things. So traditional programming languages tell the compiler extraneous information that it must work to ignore (like spurious sequential ordering of operations) and deny it essential information that it must work to guess or derive (*e.g.* which variables belong in registers).

Another useful piece of information the application programmer should supply is branch probability. Any time a conditional statement is made, some indication should be given about which way it goes most of the time, or that no such prediction can be made. Similarly, minimum, average, and maximum expected passes through a loop should be specified. Then, in addition to maximum execution time, average execution time could also be predicted. This example illustrates why this paradigm is new. Current paradigms insist that the compiler or other tools somehow derive these probabilities and bounds. It is little burden for the application programmer to specify this information. Often, it is the case that the programmer knows this information far better than the tools will ever be able to derive.

If the application programmer declines to supply this information, then the compiler is not obligated to be “clever” or go beyond what is patently explained in the program. The time for a sequence of operations is the sum of their times. The time for parallel operations varies with available parallelism in the hardware. The trade-off between porting to a wide number of computers and asking for the maximum performance is made explicit.

3.3 The Compiler

The third stage of the contract is between the compiler and the hardware. The compiler will examine, say, a block of application source code as well as its timing and precision requirements. It then consults a table that is specific to a computer system that describes the hardware: the number of functional units and the restriction on using them simultaneously, the size of each memory regime, and any other feature that must be known to establish timing and error estimates. Alternately, a microcode simulator can be used instead of a table, but it should still be able to give a maximum wall clock time and output error estimate for the conditions of the contract.

If the compiling of the block of an application program fails to meet performance requirements, then the compiler can:

- try alternatives, limited by the application programmer to compile within a certain time
- quickly give up and report where and why the problem occurred so that the end user can alter the terms of the contract or find a different host.

The compiler should not be burdened with $\mathcal{NP}$ -hard optimization problems of resource allocation. If someone finds a clever solution to a common optimization problem, then that should be placed in the standard library of routines. That standard library can contain, say, all the best known methods for performing the $y(i) = a * x(i) + y(i)$ operation for the whole spectrum of computer architectures. That library function might be lengthy and complicated, but would be attached to a simple performance specification usable by the compiler to see if a contractual obligation to the application programmer can be met.

3.4 Hardware Specifications

The hardware specification file was already mentioned in the previous section. This file does not need to contain everything there is to know about the hardware. Rather, it should contain only the information necessary to the compiler for determining timing, cost, precision, range, and reliability requirements. Optionally, a hardware simulator could be used in place of the hardware specification file. Note that such hardware simulators already exist and are used by the manufacturer during the design phase of a new architecture. The simulator would be useful in many different situations. The first is to give an overall maximum wall clock time for a block of application code. Another is to select the fastest code among alternatives in an algorithm where machine dependent details matter.

For example, consider the quadratic equation. The denominator is the term '2a'. For many years, it has been standard practice in a situation like this to calculate the value $1/(2a)$ once and place it in a temporary variable. Then every time a division is called for, a multiplication by the inverse is used instead. The rationale is that a floating point multiplication is typically faster than a division. We believe that the application programmer should accommodate as many alternative hardware possibilities as is manageable.

Rather, this is a feature that can and should be tested at compile time and the application programmer should supply two versions of the code: one using the temporary variable and one

that does the division every time. Then after the compiler has done its speed test for division versus multiplication, it can decide which alternative section of code to use. We can extend this idea even further by having the compiler time both branches of code (*i.e.* an entire section of code) and then select the quicker of the two.

In summary, we have shifted the burden off of the compiler and onto the application programmer. This is contrary to the prevailing academic goal. We believe this approach has the benefit of reducing long term development costs - even though it is at the expense of greater short-term cost.

4 Contracts

In this section we describe, in detail, our new three-stage contract paradigm that:

1. forces the end user to specify practical goals without being allowed to specify implementation details
2. forces the application programmer to specify performance in the algorithm description without being able to assume target hardware
3. enables the compiler to use a local hardware specification or microcode simulator to determine whether or not the application programmer's specifications are feasible - and if not, to provide feedback and alternatives to the application programmer. The compiler is *not* allowed to make clandestine changes to the code. This is a marked departure from current programming methodology.

As an example, we provide a *generic* contract except in part of the second-stage contract where specific contract information for solving a quadratic equation is provided. In the generic contract, the notation is loosely based on the Backus-Naur Form (BNF) specification and is defined as follows:

<code>##</code>	comment follows to end of line
<code>itemlist</code>	required item or items
<code> </code>	alternation - pick one from this itemlist
<code>[]</code>	enclosed optional item

We hope that all other notation is self-explanatory.

4.1 End User to Application Program

In this section, we discuss the first stage of the three-stage programming contract. Recall that the first-stage contract is between the end user and an application program. Please refer to Figure 2 throughout the following discussion.

```

TIME ( {average | maximum | confidence n%} wall clock time):           ##demand
    n {seconds | minutes | hours | days} [excluding user interaction]

COST:
    The total cost of this run is:                                     ##demand
        not to exceed n {dollars | units} when successful
        not to exceed n {dollars | units} when not successful

NEGOTIATION:
    if contract fails, the user [is |                                ##concession
        is not] willing to engage in a dialog                       ##demand

DATA REPRESENTATION:
{
    <variable-list> :
        source: {user-supplied | computed}

        error: {exact |                                           ##demand
            fixed error n | relative error on nonzero n%}         ##concession

        numeric format: {{decimal | binary} digits | not applicable}

        ## specify digits of precision and absolute or relative error
        ## the number of placeholders can be varied by the end user

        [+|-]d.dd...d E[+|-]dd...d +/-d.dd...d E[+|-]dd...d [%]    ##demand/output
                                                                    ##concession/input
    }* ## repeat as needed

GOAL: {speed | accuracy | thrift | reliability}

INTERFACE:                                                             ##demand
    [ <input data variable-list> : <machine location> ]
    <output data variable-list> : <machine location>
    notifications : <machine location>

```

Figure 2: 1st Stage Contract Template

Time Clause

The time clause in the contract is to specify the maximum wall clock time that the end user is willing to wait for the completed execution of the application. The decision to use wall clock time instead of CPU time was not arbitrary. Under our new paradigm, the end user is insulated from hardware and system details. Therefore, it makes no sense to have the end user think about such things as time sharing, job swapping, and all the other events that cause CPU and wall clock times to differ. Rather, we view the end user as having little if any prerequisite computer science background; all that the end user cares about is reliable obtainment of accurate answers in a reasonable time and cost. Since human interaction can have a major impact on wall clock time especially when input is entered from the keyboard), we give the end user the option of excluding that interaction time in the wall clock time. We also give the option of specifying time as an average over many runs, a hard maximum, or a degree of confidence that it will finish within that time.

Cost Clause

In the cost clause, the end user states requirements for maximum cost for submitting a job. These costs are subdivided into two cases: a successful run and an unsuccessful run. These cases are analogous to other human contracts that specify a cost in case of failure to deliver, ranging from nothing to full cost.

Negotiation Clause

The negotiation clause represents the willingness to negotiate the contract. The application program contains the logic for assisting the user to relax requirements until they can be met.

Data Representation Clause

The data representation clause of the contract specifies the *source*, type of *error*, and *format* of input and output data. There are two choices for *source* which are “user-supplied” and “computed”. User-supplied means that the data is input by user. Computed means that the value is output from the application program. This information is necessary for the computation of output error.

The term *error* applies to both input and output values. When an error of zero is explicitly demanded on either input or output for an numerical algorithms, the user incurs the sometimes high price of that demand. Otherwise, the error can be stated or calculated in either absolute or relative amounts. One way to calculate error is by use of interval arithmetic techniques [12, 15]. Ordinarily, error is applied only to numeric values. However, the term can be generalized. For example, a misspelled word in text may be thought of as a correctable and/or measurable error.

In the next subclause, the end user specifies the *format* of numeric values. The end user has the option of working in the binary or decimal number system. A wide variety of non-numeric formats can also exist. For now, we are choosing to ignore the variety of choices; however, in the future the non-numeric values may need to be developed.

Finally, the range, precision, and uncertainty of numeric values are specified by the user through a length adjustable, number template which is in exponential form. Absolute error is specified by omitting the trailing percent sign; relative error is specified with the percent sign.

All of the specifications in the data representation clause are applied to one or more variables specified in a variable list. Use of the clause may be repeated any arbitrary number of times for different variable lists.

Goal Clause

In the *goal* clause, the end user must state whether the primary goal is to reduce wall clock time, increase output accuracy, minimize cost, or to increase chances for a successful run. Since these goals are diametric to one another, this information is useful for selecting the correct algorithm to execute.

Interface Clause

Finally, the *interface* clause requires that the end user specify the source and destination for input data, output data, and side interactions with the system (such as error messages). In this respect, our contract paradigm is similar to that of UNIXTM. This clause interacts with the time clause. If human interaction is selected, then no guarantees can be made regarding time.

Figure 3 illustrates the process that an end user experiences in submitting a job. In practice, the user will rarely have to go through such an elaborate process since defaults are associated with all contract terms. Nevertheless, contract terms are always available for perusal.

4.2 Application Programmer to Compiler

The *second-stage contract* negotiations are between the application programmer and the compiler. These negotiations occur while the algorithm suite is being developed. In many ways, this contract is similar to but much more detailed than the first-stage contract. The application program creates a set of machine independent algorithms. These algorithms are written in an English-like style and all data dependencies are explicitly stated. Included are a set of requirements, namely: speed, cost, accuracy, and reliability of the algorithm and hardware. These same requirements may also be applied to the compilation process itself.

The application programmer bases these estimates on estimates of a hypothetical machine. If the programmer demands too high a performance, all users will be satisfied, but no compiler will agree to the contract. If the programmer is too conservative, every compiler will agree to the terms, but end users' demands will not be met. In this way we make explicit what is currently implicit. Note also that this allows the application programmer to track decades of hardware change simply by altering performance demands without making any changes to the set of algorithms.

The algorithms and requirements are then passed to the compiler. In addition to the usual syntactical checks and translation, the compiler also uses its knowledge about the target hardware to determine whether or not the application programmer's performance requirements are feasible. If they are, the object code is generated and *tagged* with the various performance values. If the

Figure 3: Life cycle of a First Stage Contract Submission

requirements are not feasible, then the compiler rejects the contract and notifies the application programmer of the reasons for rejection.

In general, low effort by the application programmer will usually result in a failed contract. As the application programmer expends more effort in writing efficient code and in giving the compiler more information on how portions of the code should be compiled, the more likely a successful compilation will be.

Consider the quadratic equation as an example. One way to express this equation is as:

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

Suppose that the application programmer does not give the compiler any information about the placement of values in memory leading to a contract failure. The compiler might respond back by suggesting that the timing requirement be relaxed. Suppose that the application programmer decides that the timing requirement **not** be changed. Then extra effort must be expended to help the compiler find a way to do the same equation in less time. One way to achieve this would be for the application programmer to suggest to the compiler that the values of a and b be stored in registers. Another suggestion to the compiler could be to calculate b^2 as $b * b$ instead of by invoking a power function. Yet another suggestion would be to inform the compiler of the various parts of the equation to calculate in parallel.

The point is that we expect the application programmer to do most of the “dirty work” – not the compiler. As more and more details and suggestions are given to the compiler, the more tenable the contract becomes.

In the Second-Stage contract (see Figure 4), the following items included:

- variable latency hierarchy
- the application algorithm including looping probabilities and loop bounds
- data dependencies

The application program should give the compiler information of true utility. Included is a section containing suggestions for variable placements. Currently, we see two different approaches in which this can be done. The first is called the *relative memory distance approach*. In this approach, variables are ranked from fastest access needs down to those of slowest access needs. This is done by declaring *levels* so that variables of like access speed can be grouped together under a common level.

The second approach to specifying variable latencies is in terms of absolute distance as measured by elapsed wall clock time for access. For certain kinds of applications, this approach is more useful as it places definite, real-time limits on the system. However, this very precision also makes this approach more tied to current technological levels in its specification without anticipation of future improvements. We believe that this information could be changed from a suggestion to a requirement, if need be, but could be counter productive to overall speed obtainment.

VARIABLE ACCESS PRIORITIES

--Relative memory distance approach

Level 0: (fastest access) a b : same type as specified by End User

Level 1: (next fastest) temp0 temp1 : same type as 'a' and 'b'

--Absolute memory distance approach

{All of the INPUT and OUTPUT information comes from the End User.

INPUT

a, b are (floating_point, integer)

range: [m1E-e1, m2E+e2] /* These values are obtained from the end user */

relative error: [x-x*p1, x+x*p2]

maximum distance: 3 uSec (4 uSec total for both a and b brought in together)

OUTPUT

<generic> are (floating_point, integer)

range: [m1E-e1, m2E+e2]

relative error: [x-x*p3, x+x*p4]

maximum distance: 3 uSec

Temporary

temp0, temp1 are <same_as_INPUT>

maximum distance: 2 uSec

ALGORITHM

1. READ input values a, b, and c from source and store them in registers: temp0, temp1, temp2
2. see if temp0 = 0
3. see if temp1 = 0
4. see if temp2 = 0

\$\$EXECUTE ANY OF THE FOLLOWING SEGMENTS HAVING A TRUE ASSERTION

5. (2%) temp0 = temp1 = temp2 = 0 ==>
6. WRITE "Ill-posed equation - Infinite solutions" to destination
7. (2%) temp0 = 0, temp1 = 0, temp2 <> 0 ==>
8. WRITE "Ill-posed equation - Zero roots" to destination
9. (8%) temp0 = 0, temp1 <> 0, temp2 = 0 ==> { a=c=0 --- 1 real root }
10. WRITE "1 real root = " 0.0 to destination { Solution: x = 0 }
11. (8%) temp0 = 0, temp1 <> 0, temp2 <> 0 ==> { a=0 --- 1 real root }
12. temp3 = -temp2 { -c } { Solution: x = -c/b }
13. temp4 = temp3 / temp1 { -c/b }
14. WRITE "1 real root" temp4 to destination
15. (8%) temp0 <> 0, temp1 = 0, temp2 = 0 ==> { b=c=0 --- 1 real root }
16. WRITE "1 real root = " 0.0 to destination { Solution: x = 0 }
17. (25%) temp0 <> 0, temp1=0, temp2 <> 0 ==> { b=0 --- 2 real roots when ac<0 }
18. \$\$EXECUTE ANY OF THE FOLLOWING SEGMENTS HAVING A TRUE ASSERTION
19. (50%) unlikesign(temp0,temp2) ==> { --- 2 imag. roots when ac>0 }
20. temp5 = -temp2 { -c } { Solution: x = (+/-)sqrt(-c/a) }
21. temp6 = temp5 / temp0 { -c/a }
22. temp7 = sqrt(temp6) { sqrt(-c/a) } { First real root }
23. temp8 = -temp7 { -sqrt(-c/a) } { Second real root }
24. WRITE "2 real roots = " temp7 temp8 to destination
25. (50%) likesign(temp0,temp2) ==>
26. temp9 = temp2 / temp0 { c/a }
27. temp10 = sqrt(temp9) { sqrt(c/a) } { First imaginary root }
28. temp11 = -temp10 { -sqrt(c/a) } { Second imaginary root }
29. WRITE "2 imaginary roots = " temp6 temp7 to destination
29. \$\$END OF 'EXECUTE ANY' CLAUSE

Continued next page...

Figure 4: 2nd Stage Contract
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30. (10%) temp0 <> 0, temp1 <> 0, temp2 = 0    ==>          { c=0 --- 2 real roots }
31.   temp12 = -temp1          { -b          }          { Solution: x = 0, -b/a }
32.   temp13 = temp12 / temp0  { -b / a    }
33.   WRITE "2 real roots = " 0.0 temp13 to destination
34. (37%) temp0<>0,temp1<>0,temp2<>0    ==>      {none=0 --- 1 real root  when b^2-4ac=0 }
35.   temp14 = temp1 * temp1    { b^2      } {          --- 2 real roots when b^2-4ac>0 }
36.   temp15 = 4.0 * temp0      { 4a       } {          --- 2 complex rt when b^2-4ac<0 }
37.   temp16 = temp15 * temp2   { 4ac      }
38.   temp17 = temp14 - temp16  { b^2 - 4ac }
    $$IF_QUICKER
      { calculate reciprocal of the denominator once }
39.   temp18 = 1.0 / (2.0 * temp0) { 1 / 2a   }
    $$EXECUTE ANY OF THE FOLLOWING SEGMENTS HAVING A TRUE ASSERTION
40.   (10%) temp17 = 0.0    ==>    { discriminant of zero }          { 1 real root }
41.     temp19 = -temp1      { -b          }
42.     temp20 = temp19 * temp18 { -b / 2a   }
43.     WRITE "1 real root = " temp20 to destination
44.   (45%) temp17 > 0.0 ==> { positive discriminant }          { 2 real roots }
      { Avoid cancellation of significant digits }
45.     temp21 = -temp1      { -b          }
46.     temp22 = sqrt(temp17) { sqrt(b^2 - 4ac) }
    $$EXECUTE ANY OF THE FOLLOWING SEGMENTS HAVING A TRUE ASSERTION
47.   (50%) temp1 < 0.0 { if b < 0 } ==>
48.     temp23 = temp21 + temp22 { -b + sqrt(b^2-4ac) }
49.     temp24 = temp23 * temp18 { (-b - sqrt(b^2-4ac))/2a }          { 1st real sol. }
50.     temp25 = temp0 * temp24 { a * <1st solution> }
51.     temp26 = temp3 / temp25 { c / a * <1st solution> } { Second real solution }
52.     WRITE "2 real roots = " temp24 temp26 to destination
53.   (50%) temp1 > 0.0 { if b > 0 } ==>
54.     temp27 = temp21 + temp22 { -b + sqrt(b^2-4ac) }
55.     temp28 = temp27 * temp18 { (-b - sqrt(b^2-4ac))/2a }          { 1st real sol. }
56.     temp29 = temp0 * temp28 { a * <1st solution> }
57.     temp30 = temp3 / temp29 { c / a * <1st solution> } { Second real solution }
58.     WRITE "2 real roots = " temp28 temp30 to destination
59.   $$END OF 'EXECUTE ANY' CLAUSE
60.   (45%) temp17 < 0.0 ==> { negative discriminant }
61.     temp31 = -temp1      { -b          }
62.     temp32 = temp31 * temp18 { -b / 2a   }          { Both real solutions }
63.     temp33 = -temp17      { -(b^2-4ac)   }
64.     temp34 = sqrt(temp33) { sqrt(-(b^2-4ac) }
65.     temp35 = temp34 * temp18 { sqrt(-(b^2-4ac) / 2a }          { 1st imag solution }
66.     temp36 = -temp35      { -sqrt(-(b^2-4ac) / 2a }          { 2nd imag solution }
67.     WRITE "2 complex roots = (" temp32 temp35 ")
      (" temp32 temp36 )" to destination
68.   $$END OF 'EXECUTE ANY' CLAUSE
    $$ELSE_QUICKER
      { calculate the denominator once }
69.     temp37 = 2.0 * temp0      { 2a       }

```

Continued next page...

Figure 4: 2nd Stage Contract

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    $$EXECUTE ANY OF THE FOLLOWING SEGMENTS HAVING A TRUE ASSERTION
70.    (10%) temp17 = 0.0 ==> { discriminant of zero } { 1 real root }
71.    temp38 = -temp1 { -b }
72.    temp39 = temp38 / temp37 { -b / 2a }
73.    WRITE "1 real root = " temp39 to destination

74.    (45%) temp17 > 0.0 ==> { positive discriminant } { 2 real roots }
    { Avoid cancellation of significant digits }
75.    temp40 = -temp1 { -b }
76.    temp41 = sqrt(temp17) { sqrt(b^2 - 4ac) }
    $$EXECUTE ANY OF THE FOLLOWING SEGMENTS HAVING A TRUE ASSERTION
77.    (50%) temp1 < 0.0 ==> { if b < 0 }
78.    temp42 = temp40 + temp41 { -b + sqrt(b^2-4ac) }
79.    temp43 = temp42 / temp37 { (-b + sqrt(b^2-4ac))/2a } { 1st real sol. }
80.    temp44 = temp0 * temp43 { a * <1st solution> }
81.    temp45 = temp3 / temp44 { c/a * <1st solution> } { Second real solution }
82.    WRITE "2 real roots = " temp43 temp45 to destination
83.    (50%) temp1 > 0.0 ==> { if b > 0 }
84.    temp46 = temp40 - temp41 { -b - sqrt(b^2-4ac) }
85.    temp47 = temp46 / temp41 { (-b - sqrt(b^2-4ac))/2a } { 1st real sol. }
86.    temp48 = temp0 * temp47 { a * <1st solution> }
87.    temp49 = temp3 / temp48 { c/a * <1st solution> } { Second real solution }
88.    WRITE "2 real roots = " temp47 temp49 to destination
89.    $$END OF 'EXECUTE ANY' CLAUSE

90.    (45%) temp17 < 0.0 ==> { negative discriminant }
91.    temp50 = -temp1 { -b }
92.    temp51 = temp50 / temp37 { -b / 2a } { Both real solutions }

93.    temp52 = -temp17 { -(b^2-4ac) }
94.    temp53 = sqrt(temp52) { sqrt(-(b^2-4ac)) }
95.    temp54 = temp53 / temp37 { sqrt(-(b^2-4ac)) / 2a } { 1st imag solution }
96.    temp55 = -temp54 { -sqrt(-(b^2-4ac)) / 2a } { 2nd imag solution }
97.    WRITE "2 complex roots = (" temp51 temp54 "
    " (" temp51 temp55 ")" to destination

98.    $$END OF 'EXECUTE ANY' CLAUSE
    $$END_QUICKER

99.    $$END OF 'EXECUTE ANY' CLAUSE

DEPENDENCIES
1->[2-4]->[5,7,9,11,15,17,30,34] 5->6 7->8 9->10 11->14 15->16 17->[23,28]
30->33 34->43 1->12->13->14 1->31->32->33 1->[18,19,24,25,35,36,39,41,45,47,49]
18->23 19->20->21->22->23 24->28 25->26->27->28 etc etc

```

Figure 4: 2nd Stage Contract

Next comes the application program itself. Our goal here is to provide just the basic algorithm without supplying any unnecessary dependencies or extra "tricks" to circumvent the compiler. As a rule, we never reuse any variable on the left hand side of an assignment statement. Also note that each line is numbered for later use in the dependency specification. To aid the compiler in making timing and error estimates, we also require that probability estimates be included for conditional statements. If a probability is not known in advance, this should also be stated. Also, for loops, we recommend that bounds be included in the form of a triple containing: the guaranteed least number of times through the loop, the average expected number of times through the loop, and the guaranteed maximum number of times through the loop. With this information, both average and worst case timing estimates can be calculated. Finally, the application programmer is permitted and *strongly encouraged* to use library subroutines when possible. The idea is to keep a collection of "best known solutions to date" on line to help ensure maximum performance or accuracy while freeing the application programmer from having to continuously "reinvent the wheel". In some sense, this would be like keeping existing BLAS routines on line but it is also very different in many ways. For example, instead of having one routine to do a particular task, there would be several versions emphasizing difference precision, performance, and architectural requirements. Also, these routines would come with attached error and performance ratings so that the system software could easily match the appropriate version to meet the end user's needs. Again, these details and the fact that a collection of similar routines exist need not be known by the application programmer. Finally, the subroutines would have to pass strict requirements before being added to the system and would absolutely be forbidden from having extra "tricks" embedded in them. After all, it was these extra tricks that lead to the problem example described in Section 2.2.2.

Then, to make life easier for the compiler, we require that a data dependency specification be included that explicitly states which line of code is dependent on another line of code. However, some dependencies can be omitted due to their transitive nature. For example, if line 1 is dependent on lines 2 and 3 and line 2 is also dependent on line 3, we could denote this as $\langle 1 \rightarrow 2 \quad 1 \rightarrow 3 \quad 2 \rightarrow 3 \rangle$ or alternatively as $\langle 1 \rightarrow [2, 3] \quad 2 \rightarrow 3 \rangle$. However, since the dependency $\langle 1 \rightarrow 3 \rangle$ is implied by the other two dependencies, it is safe to omit it and simply say that $\langle 1 \rightarrow 2 \quad 2 \rightarrow 3 \rangle$. Furthermore, we permit the shorthand notation of combining dependencies into the form: $\langle 1 \rightarrow 2 \rightarrow 3 \rangle$. Finally, we also permit multiple source to destination or source to multiple destinations to be expressed with ranges of lines use combinations of commas, hyphens, and square brackets. Hence, the expression $\langle 1 \rightarrow [2, 3] \rightarrow [4, 6, 8, 13] \rangle$ is actually shorthand for $\langle 1 \rightarrow 2 \quad 1 \rightarrow 3 \quad 1 \rightarrow 4 \quad 1 \rightarrow 6 \quad 1 \rightarrow 8 \quad 1 \rightarrow 13 \quad 2 \rightarrow 4 \quad 2 \rightarrow 6 \quad 2 \rightarrow 8 \quad 2 \rightarrow 13 \quad 3 \rightarrow 4 \quad 3 \rightarrow 6 \quad 3 \rightarrow 8 \quad 3 \rightarrow 13 \rangle$.

Figure 5 illustrates the process that an end user experiences in order to submit a job. Figure 6 illustrates the process that an end user experiences in order to submit a job.

Figure 5: Traditional Compilation of an Application Program

Figure 6: (Second level) Compilation of an Application Program with Contract

4.3 Compiler to Hardware Contract

The third-stage contract is between the compiler writer and the hardware. It is at this stage that specific details (like timing, reliability, and topology) are specified. This information can be specified in a *hardware specification file* or determined from a microcode simulator. A preliminary example is given in Figure 7³. Its contents must include sufficient detail and information to provide the compiler with the resources it needs to estimate wall clock time and output error for the application at hand. In addition, the compiler must know about parallel features in the likelihood that an optimization is needed or requested. Hence, the essential features to be included in the file include, but are not limited to:

- clock cycle time
- time to execute the various arithmetic and logic functions for both INTEGER and FLOATING POINT representations under the different precisions that are available
- precisions and ranges for the INTEGER and FLOATING POINT representations including information on how the values are stored (*e.g.* biased format for exponents)
- the number of and types of functional units including chaining information and restrictions
- a full description of the memory regime including the cache policies in use
- parallel topology (if any)
- communication network information

The idea is that the front end of a compiler should still be robust enough and adaptable enough to obtain good performance for a variety of platforms.

5 Conclusions and Future Work

In this technical report, we have presented a new programming paradigm involving a three-stage contract between four participants. The participants are: the end user, the application program, the system software, and the hardware specification file. An **end user** is a person wishing to execute some application but is not assumed to know or care about the architecture, topology, or *any* machine-specific details. The *application programmer* engages in a dialog with the compiler to produce an “application program” – a suite of many different, *best-known* algorithms that cover a wide range situations. Each application program is *tagged* by the compiler with timing, accuracy, cost, and reliability estimates. This information is used in turn to match the

³This work is still VERY sketchy and is subject to substantial change in future papers. Suggestions and comments are solicited from the reader on this and any other section of this technical report.

Clock Cycle: 50 ns

Operations:	Time in clock Cycles
Logical:	
1-bit	2
8-bit	2
16-bit	2
32-bit	1
64-bit	2
Arithmetic:	
Integer (16-bit):	
add	1
subtract	2
multiply	2
divide	13
square root	7
x ^y	5
negation	1
Integer (32-bit):	
add	2
subtract	3
multiply	3
divide	24
square root	13
x ^y	9
negation	1
Floating Point (32-bit):	<similar to above>
Note: division uses 34 bits	
Floating Point (64-bit):	<similar to above>
Precision:	
Integer (8-bit):	
Unsigned representation	
Range: [0..255]	
Integer (16-bit):	
Two's complement representation	
Range: [-32768..-32767]	
Integer (32-bit):	
Two's complement representation	
Range: [-2147483648..2147483647]	
Floating Point (32-bit):	
Mantissa: 15-bit normalized in Two's complement	
Exponent: 7-bit in Biased format with zero= 0111111	
Overflow representation:	
Underflow representation:	
Absolute error: 0.00000005	

Continued next page...

Figure 7: Hardware Specification File

... continued from previous page.

Functional Units:

2 16-bit integer ALU (IU1 IU2)

may be used simultaneously for a single 32-bit operation

3 32-bit floating_point ALU (FPU1 FPU2 FPU3)

Cascading: IU1 -> IU2 FPU1 -> FPU2 -> FPU3 FPU1, FPU2 -> FPU3

Memory Regime:

Registers:

32 32-bit registers (or 16 64-bit registers)

1cc refresh rate

Cache:

1024 32-bit 8-way etc etc associate cache

minimum block size: 128 words

warm start on swapping

write back on write policy

cache hit: 1cc

cache miss: 12cc

Main Memory:

32 MByte in 8 modules with 4 byte stride

1.75cc refresh rate per module

Figure 7: (Continued) Hardware Specification File

end user with the most appropriate algorithm. It may be the case that no such algorithm exists that can meet the end user's requirements. In such a case, contract negotiations may ensue to relax end user requirements. Finally, the hardware specification file contains all of the information specific to a particular platform. This information is used to help determine timing, cost, and reliability estimates. The file's topological details also help in the selection of the appropriate algorithm for a particular machine.

Obviously, we cannot give all the details of our scheme in this summary. Rather, we would like to reiterate that the main contribution here is the new way in which interactions with the computer are thought of. Now, the user cares only about obtaining acceptably good answers in a reasonable amount of time and within a particular (cash or time) budget. The application program can now focus on the underlying algorithm without presuming compiler and hardware behavior. Finally, the compiler is given the information it really needs: what can be run in parallel and what types of hardware are necessary to do the job.

In the short term, we hope to develop a working prototype. The hardest part will be finding a universal, hardware specification. The compiler is also expected to take a great deal of time. Then, once the prototype is working, a library of routines for a variety of precisions and timing can be developed. Gradually, more target hardware will be incorporated with an emphasis on parallel platforms. The creation of a robust system capable of handling a wide variety of machines is likely to take ten years or longer.

If we are successful, application programs will be thought of in an entirely new way. For one thing, they will not be dependent on any given language. More importantly, though, the application program (by *not* specifying any trick code for higher performance) will become immortal as it locks in the essence of the algorithm while ignoring techniques and technology. Such a program could, in theory, need never be rewritten except in the case where the underlying algorithm itself is improved. Then, as these immortal programs are developed, an international clearing house or repository can be set up providing on line access to the code.

Authors' Note:

This *Technical Progress Report* summarizes some of the work done during the Summer of 1994 and in May 1995. In many cases, our thoughts and views have undergone substantial changes making portions of this report obsolete. In particular, we no longer hold the view that the compiler should be expected to perform any sort of clever optimization or be expected to find alternate solutions. In fact, the third participant is now referred to as the system software and not just the compiler. Many aspects of the contracts have also changed. For the latest version of our work, we refer the reader to a pending publication [19].

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