Next-Paradigm Programming Languages: What Will They Look Like and What Changes Will They Bring?

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Abstract

The dream of programming language design is to bring about orders-of-magnitude productivity improvements in software development tasks. Designers can endlessly debate on how this dream can be realized and on how close we are to its realization. Instead, I would like to focus on a question with an answer that can be, surprisingly, clearer: what will be the common principles behind next-paradigm, high-productivity programming languages, and how will they change everyday program development? Based on my decade-plus experience of heavy-duty development in declarative languages, I speculate that certain tenets of high-productivity languages are inevitable. These include, for instance, enormous variations in performance (including automatic transformations that change the asymptotic complexity of algorithms); a radical change in a programmer's workflow, elevating testing from a near-menial task to an act of deep understanding; a change in the need for formal proofs; and more.

CCS Concepts • **Software and its engineering** → **General programming languages**; • **Social and professional topics** → *History of programming languages*;

> [W]e've passed the point of diminishing returns. No future language will give us the factor of 10 advantage that assembler gave us over binary. No future language will give us 50%, or 20%, or even 10% reduction in workload.
>
> *Robert C. Martin [17]*

1 Introduction

Since the 1950s, high-level programming languages have resulted in orders-of-magnitude productivity improvements compared to machine-level coding. This feat has been a great enabler of the computing revolution, during a time when computer memories and conceptual program complexity have steadily grown at exponential rates. The history of computing is testament to language designers' and implementers' accomplishments: of the 53 Turing awards to present (from 1966 to 2018) a full 16 have been awarded for contributions to programming languages or compilers.[1]

At this time, however, the next steps in programming language evolution are hard to discern. Large productivity improvements will require a Kuhnian *paradigm shift* in languages. A change of paradigm, in the Kuhn sense, is a drastic reset of our understanding and nomenclature. It is no surprise that we are largely ineffective at predicting its onset, its nature, or its principles.

Despite this conceptual difficulty, the present paper is an attempt to peer behind the veil of next-paradigm programming languages. I happen to believe (on even days of the month) that a change of paradigm is imminent and all its technical components are already here. But you do not have to agree with me on either point—after all, the month also has its odd days.

Reasonable people may also differ on the possible catalysts of such a paradigm shift. Will it be machine learning and statistical techniques [21], trained over vast data sets of code instances? Will it be program synthesis techniques [9], employing symbolic reasoning and complex constraint solving? Will it be mere higher-level language design combined with technology trends, such as vast computing power and enormous memories?

Regardless of one's views, I hope to convince the reader that there is reasonable clarity on *some* features that next-paradigm programming languages will have, *if* they ever dominate. Similarly, there is reasonable clarity on what changes next-paradigm programming languages will induce in the tasks of everyday software development.

For a sampling of the principles I will postulate and their corollaries, consider the following conjectures:

- Next-paradigm programming languages will not display on the surface the computational complexity of their calculations. Large changes in asymptotic complexity (e.g., from $O(n^4)$ to $O(n^2)$) will be effected by the language implementation. The language will not have loops or explicit iteration. The programmer will often opt for worse asymptotic complexity factors, favoring solution simplicity and

[1]The count is based on occurrences of "programming language(s)" or "compiler(s)" in the brief citation text of the award, also including Richard Hamming who is cited for "automatic coding systems" (i.e., the L2 precursor of Fortran). Notably, the number does not include John McCarthy or Dana Scott, who are well-known for languages contributions yet the terms do not appear in the citation.

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countering performance problems by limiting the inputs of algorithms (e.g., applying an expensive computation only locally) or accepting approximate results.

- Next-paradigm programming languages will need a *firm mental grounding*, in order to keep program development manageable. This grounding can include: a well-understood cost model; a simple and clear model on how new code can or cannot affect the results of earlier code; a natural adoption of parallelism without need for concurrency reasoning; and more.
- Development with next-paradigm programming languages will be significantly different from current software development. Minute code changes will have tremendous impact on the output and its computation cost. Incremental development will be easier. Testing and debugging will be as conceptually involved as coding. Formal reasoning will be easier, but less necessary.

In addition to postulating such principles, the goal of the paper is to illustrate them. I will use examples from real, deployed code, written (often by me) in a declarative language—Datalog. My experience in declarative programming is a key inspiration for most of the observations of the paper. It is also what makes the conjectures of the paper "real". All of the elements I describe, even the most surprising, are instances I have encountered in programming practice. I begin with this personal background before venturing to further speculation.

I've seen things, that's why I'm seeing things.

—*me*

2 Where I Come From

In the past decade, I have had the opportunity to write declarative, logic-based code of uncommon volume and variety, under stringent performance requirements. This experience underlies my speculation on the properties of next-paradigm programming languages.

Declarative code—lots of it. Most of my research (and the vast majority of my personal coding effort) in the past decade has been on declarative program analysis [22]. My group and a growing number of external collaborators have implemented large, full-featured static analysis frameworks for Java bytecode [4], LLVM bitcode [2], Python [13], and Ethereum VM bytecode [6, 7]. The frameworks have been the ecosystem for a large number of new static analysis algorithms, leading to much new research in the area.

These analysis frameworks are written in the Datalog language. Datalog is a bottom-up variant of Prolog, with similar syntax. "Bottom-up" means that no search is performed to find solutions to logical implications—instead, all valid solutions are computed, in parallel. This makes the language much more declarative than Prolog: reordering rules, or clauses in the body of a rule, does not affect the output. Accordingly, computing all possible answers simultaneously means that the language has to be limited to avoid possibly infinite computations. Construction of new objects (as opposed to new combinations of values) is, therefore, outside the core language and, in practice, needs to be strictly controlled by the programmer. These features will come into play in later observations and conjectures.

The Datalog language had been employed in static program analysis long before our work [10, 14, 20, 27]. However, our frameworks are distinguished by being almost entirely written in Datalog: not just quick prototypes or "convenient" core computations are expressed as declarative rules, but the complete, final, and well-optimized version of the deployed code, as well as much of the scaffolding of the analysis. As a result, our analysis frameworks are possibly the largest Datalog programs ever written, and among the largest pieces of declarative code overall. For instance, the Doop codebase [4] comprises several thousands of Datalog rules, or tens of thousands of lines of code (or rather, of logical specifications). This may seem like a small amount of code, but, for logical rules in complex mutual recursion, it represents a daunting amount of complexity. This complexity captures core static analysis algorithms, language semantics modeling (including virtually the entire complexity of Java), logic for common frameworks and dynamic behaviors, and more.

Emphasis on performance, including parallelism. The Datalog code I have contributed to in the past decade aims for performance at least equal to a manually-optimized imperative implementation. That is, every single rule is written with a clear cost model in mind. The author of a declarative rule knows, at least in high-level terms, how the rule will be evaluated: in how many nested loops and in what order, with what indexing structures, with which incrementality policy for faster convergence when recursion is employed. Optimization directives are applied to achieve maximum performance. Shared-memory parallelism is implicit, but the programmer is well aware of which parts of the evaluation parallelize well and which are inherently sequential. In short, although the code is very high-level, its structure is anything but random, and its performance is not left to chance. Maximum effort is expended to encode highest-performing solutions purely declaratively.

Many domains. My experience in declarative programming extends to several domains, although static analysis of programs has been the primary one. Notably, I have served as consultant, advisor, and academic liaison for LogicBlox Inc., which developed the Datalog engine [1] used in Doop until 2017. The company built a Datalog platform comprising a language processor, JIT-like back-end optimizer, and specialized database serving as an execution environment. All applications on the platform were developed declaratively—even UI frameworks were built out of a few externally-implemented primitives and otherwise entirely logic-based rules. The company enjoyed a lucrative acquisition, mostly based on the value of its deployed applications and customers. All applications were in the domain of retail prediction—about as distant from static analysis as one can imagine. For a different example, an algorithm for dynamic race detection developed in the course of my research [23] was implemented in Datalog and all experiments were over the Datalog implementation. An imperative implementation would be substantially more involved and was never successfully completed in the course of the research.

"Declarative languages aren't good for this." A repeat pattern in my involvement with declarative languages has been to encode aspects of functionality that were previously thought to require a conventional (imperative or functional) implementation. The possibility of the existence of the Doop framework itself was under question a little over a decade ago—e.g., Lhoták [15] writes: *"[E]ncoding all the details of a complicated program analysis problem [...] purely in terms of subset constraints [i.e., Datalog] may be difficult or impossible."* In fact, writing all analysis logic in Datalog has been a guiding principle of Doop—extending even to parts of the functionality that might be *harder* to write declaratively. Very few things have turned out to be truly harder—it is quite surprising how unfamiliarity with idioms and techniques can lead to a fundamental rejection of an approach as "not suitable". Most recently, we got great generality and scalability benefits from encoding a decompiler (from very-low-level code) declaratively [6], replacing a previous imperative implementation [26]—a task that the (highly expert) authors of the earlier decompiler considered near-impossible.

Design declarative languages. Finally, I have had the opportunity to see declarative languages not just from the perspective of a power user and design advisor, but also from that of a core designer and implementer [18, 19]. This dual view has been essential in forming my understanding of the principles and effects of next-paradigm languages.

> [A]ll programming languages seem very similar to each other. They all have variables, and arrays, a few loop constructs, functions, and some arithmetic constructs.
>
> *Patrick S. Li [16]*

3 Principles of Next-Paradigm Languages

Before going on, I will emphasize again that the reader does not need to agree with me on the usefulness of declarative languages. Next-paradigm programming languages could be based on any of several potential technologies—e.g., perhaps on machine learning and statistical techniques, or on SMT solvers and symbolic reasoning. Regardless of the technology, however, I think that some elements are near-inevitable and these are the ones I am trying to postulate as "principles". I will illustrate these principles with examples from declarative programming, because that's the glimpse of the future I've happened to catch. But other glimpses may be equally (or more) valid.

3.1 Programming Model: Cost

Principle 1 (Productivity and Performance Tied Together)**.** *If a language can give orders-of-magnitude improvements in productivity*
then *its implementation has the potential for orders-of-magnitude changes in performance.*

Large variations in both productivity and performance are functions of a language being *abstract*. Neither is possible with the current, ultra-*concrete* mainstream languages. If one needs to explicitly specify "loops and arrays", neither large productivity gains, nor large performance variations are possible. Instead, the language implementation (or "compiler" for short[2]) of a high-productivity, next-paradigm language will likely be able to effect orders-of-magnitude performance differences via dynamic or static optimization. For performance variability of such magnitude, the asymptotic complexity of the computation will also likely change.

Corollary 1.1. *Programs ≠ Algorithms + Data Structures.* Instead:
Compiler(Program) = Algorithms + Data Structures.

Programs in next-paradigm languages will likely *not* be the sum of algorithms and data structures, contradicting Wirth's famous equality. Instead, programs will be specifications—carefully written to take into account an execution model that includes a search process (done by the compiler) over the space of implementations. Major algorithmic elements and key data structure decisions will be determined automatically by this search. The compiler will be a mere function from programs to concrete implementations, consisting of algorithms and data structures.

Example: Choice of Algorithm. Language optimization that can affect the asymptotic complexity of the computation is hardly new. Relational query optimization is a prime realistic example.[3] In our setting, we can revisit it, with Datalog syntax, before building further on it. A common static analysis rule, responsible for interpreting calls as assignments from actual to formal arguments, is shown below:

[2]A language implementation consists of an interpreter or compiler (ahead-of-time or just-in-time) and a runtime system. The term "compiler", although not always accurate, seems to encompass most of the concepts we are used to in terms of advanced language implementations.
[3]Relational database languages, such as SQL, are a limited form of declarative programming. Due to the simplified setting and commercial success, many ideas we discuss have originated in that domain.

```
Assign(formal, actual) :-
  CallGraphEdge(invocation, method),
  FormalParam(index, method, formal),
  ActualParam(index, invocation, actual).
```

The logic just says that if we have computed a call-graph edge from instruction `invocation` to a `method`, then the *i*-th (`index`) actual argument of the call is assigned to the *i*-th formal parameter of the method.

In terms of declarative computation, this rule is evaluated via a relational join of the current contents of (conceptual) tables `CallGraphEdge`, `FormalParam`, and `ActualParam`. But it is up to the compiler to decide whether to start the join from table `CallGraphEdge` or one of the others. This decision may be informed by dynamic statistics—i.e., by current knowledge of the size of each of the three tables and of the past selectivity of joining each two tables together. It could well be that our input consists of overwhelmingly zero-argument functions. Thus, the join of `CallGraphEdge` and `FormalParam` will be small. It is wasteful (up to asymptotically so) to start by iterating over all the contents of `CallGraphEdge`, only to discover that most of them never successfully match a method with an entry in table `FormalParam`. Instead, the join may be much quicker if one starts from functions that do take arguments, i.e., from table `FormalParam`. The LogicBlox Datalog engine [1] performs precisely this kind of dynamic, online query optimization, based on relation sizes and expected selectivities.

Example: Choice of Data Structures. Data structure choice is already standard practice in relational languages. For instance, the Soufflé [11] implementation of Datalog automatically infers when to add indexes to existing tables, so that all rule executions are fast [25]. In our earlier example, Soufflé will add an index (i.e., a B-tree or trie) over table `FormalParam`, with the second column, `method`, as key, and similarly for `ActualParam`, with either column as key. Then, if computation starts from an exhaustive traversal of `CallGraphEdge`, only the matching subsets of the other two tables will be accessed, using the index to identify them. We illustrate below, by denoting the partial, indexed traversal by a Π prefix on the accessed-by-index tables, and by underlining the variables bound by earlier clauses during the evaluation:

```
Assign(formal, actual) :-
  CallGraphEdge(invocation, method),
  ΠFormalParam(index, method, formal),
  ΠActualParam(index, invocation, actual).
```

Note that such choice of data structure is not based on local constraints, but on all uses of the table, in any rule in a (potentially large) program. However, per our discussion of trends, it is typically fine for the compiler to maintain an extra data structure, if this will turn an exhaustive traversal into an indexed traversal, even if the benefit arises in very few rules.

Generally, I believe it is almost a foregone conclusion that next-paradigm programming languages will perform automatic data structure selection. The language will likely only require the programmer to declare data and will then automatically infer efficient ways to access such data, based on the structure of the computation. Both technology trends and data structure evolution conspire to make this scenario a near certainty:

- Although many potential data structures exist, a logarithmic-complexity, good-locality, ordered structure (such as a B-tree or trie) offers an excellent approximation of most realistic data traversals. Both random access and ordered access are asymptotically fast, and constant factors are excellent. (Accordingly, most scripting languages with wide adoption in recent decades have made a standard "map" their primary data type.) If one adds a union-find tree, abstracted behind an "equivalence class" data type, there may be nearly nothing more that a high-productivity language will need for the vast majority of practical tasks.
  Of course, the are glaring exceptions to such broad generalizations—e.g., there is no provision for probabilistic data structures, such as bloom filters, cryptographically secure structures, such as Merkle trees, or other classes of structures essential for specific domains. However, the use of such structures is substantially less frequent. Additionally, a theme for next-paradigm languages will be escaping the language easily—as I argue later (Section 3.3).
- Adding an extra data structure vs. not adding a data structure is no longer a meaningful dilemma, under current memory and speed trends. The cost of additional ways to organize data only grows linearly, while the speed benefit can be asymptotic. Therefore, when in doubt, adding an extra B-tree or trie over a set of data is an easy decision.

Example: Auto-Incrementalization. Another realistic example of asymptotic complexity improvements offered routinely in declarative languages is automatic incrementalization. Our earlier example rule is, in practice, never evaluated as a full join of tables `CallGraphEdge`, `FormalParam`, and `ActualParam`. The reason is that other rules in a typical program analysis will use the resulting relation, `Assign`, in order to infer new call-graph edges (e.g., in the case of virtual calls). This makes the computation of `Assign` mutually recursive with that of `CallGraphEdge`. Therefore, the rule will be evaluated incrementally, for each stage of recursive results. The rule, from the viewpoint of the Datalog compiler looks like this:

```
ΔAssign(formal, actual) :-
  ΔCallGraphEdge(invocation, method),
  FormalParam(index, method, formal),
  ActualParam(index, invocation, actual).
```

This means that the new-stage (denoted by the Δ prefix) results of `Assign` are computed by joining only the newly-derived results for `CallGraphEdge`. Tuples in `CallGraphEdge` that existed in the previous recursive stage do not need to be considered, as they will never produce results not already seen. (The other two tables involved have their contents fixed before this recursive fixpoint.) In practice, such automatic incrementalization has been a major factor in making declarative implementations highly efficient—often much faster than hand-written solutions, since incrementalization in the case of complex recursion is highly non-trivial to perform by hand.

Incrementalization also exhibits complex interplay with other algorithmic optimizations. For instance, the latest delta of a table is likely smaller than other relations, in which case the exhaustive traversal of a join should start from it.

Corollary 1.2 (Cheapest is hardest.). *"Easy" in terms of (sequential) computational complexity may mean "hard" to express efficiently in next-paradigm languages.*

The shortcomings of next-generation languages may be more evident in the space where human ingenuity has produced incredibly efficient solutions, especially in the low-end of the computational complexity spectrum (i.e., linear or near-linear algorithms). In the ultra-efficient algorithm space, there is much less room for automated optimization than in more costly regions of the complexity hierarchy.[4]

Example: Depth-First Algorithms and Union-Find Structures. Current declarative languages are markedly bad at expressing (without asymptotic performance loss) efficient algorithms based on depth-first traversal. For instance, declarative computation of strongly-connected components in directed graphs is asymptotically less efficient than Tarjan's algorithm. Also, union-find trees cannot be replicated and need special-purpose coding.

Generally, algorithms that are hard to parallelize (e.g., depth-first numbering is P-hard) and data structures that heavily employ imperative features (both updates and aliasing) are overwhelmingly the ones that are a bad fit for declarative programming. It is reasonable to speculate that this observation will generalize to any next-paradigm programming language. After all, a high-productivity language will need to be abstract, whereas imperative structures and non-parallelizable algorithms rely on concrete step ordering and concrete memory relationships (i.e., aliasing). If this speculation holds, it is a further argument for the inevitability of next-paradigm programming languages. In most foreseeable technological futures, parallelism and non-random-access memory are much more dominant than sequential computation and a shared, random-access memory space. The algorithms that will dominate the future are likely amenable to general automatic optimization in a high-productivity language.

[4]This general conjecture may be easily violated in specialized domains where symbolic search already *beats* human ingenuity. E.g., program synthesis has already exhibited remarkable success in producing optimal algorithms based on bitwise operators [8].

Corollary 1.3 (Even Asymptotics May Not Matter). *Asymptotically sub-optimal computations may become dominant, for limited, well-supervised deployment.*

Asymptotic performance degradation factors are impossible to ignore, since they typically turn a fast computation into an ultra-slow or infeasible one. However, in next-paradigm languages, a programmer may routinely ignore even asymptotic factors and favor ultra-convenient programming. To avoid performance degradation in a realistic setting, the applicability of inefficient computations may be limited to a local setting, or approximate results may be acceptable [5].

Example: Inefficient Graph Computations. In Datalog code I have often favored quadratic, cubic, or worse solutions, as long as they are applied only locally or other constraints ensure efficient execution. Graph concepts offer generic examples. (In practice the computation is rarely about a literal graph, but binary relations are often convenient viewed in graph terms.) For instance, I have often used code that computes all pairs of predecessors of a graph node, generically written as:

```
BothPredecessors(pred1, pred2, next) :-
  Edge(pred1, next),
  Edge(pred2, next),
  pred1 != pred2.
```

As long as the in-degree of the graph is bounded, the "wasteful" all-pairs concept costs little to compute and can be quite handy to have cached.

Similarly, a wasteful but convenient concept is that of directed graph reachability without going through a given node:

```
ReachableExcluding(node, node, notInPath) :-
  IsNode(node),
  IsNode(notInPath),
  node != notInPath.

ReachableExcluding(source, target, notInPath) :-
  Edge(source, target),
  IsNode(notInPath),
  source != notInPath,
  target != notInPath.

ReachableExcluding(source, target, notInPath) :-
  ReachableExcluding(source, interm, notInPath),
  Edge(interm, target),
  target != notInPath.
```

Note that the computation is worst-case bounded only by a n^4 polynomial, for n graph nodes—e.g., the last rule enumerates near-all possible node 4-tuples, source, target, interm, and notInPath.

Written as above, the computation would be infeasible for any but the smallest graphs. However, if we limit our attention to a local neighborhood (for whatever convenient definition, since this pattern applies in several settings) the computation is perfectly feasible, and, in fact, common in production code:

```
ReachableExcluding(node, node, notInPath) :-
  InSameNeighborhood(node, notInPath),
  node != notInPath.

ReachableExcluding(source, target, notInPath) :-
  Edge(source, target),
  InSameNeighborhood(source, target),
  InSameNeighborhood(source, notInPath),
  source != notInPath,
  target != notInPath.

ReachableExcluding(source, target, notInPath) :-
  ReachableExcluding(source, interm, notInPath),
  Edge(interm, target),
  InSameNeighborhood(source, target),
  target != notInPath.
```

Generally, I believe that programmers will be quite inventive in reshaping a problem in order to employ ultra-high-level but inefficient computations. Coding simplicity and correctness clarity are excellent motivators for questioning whether a full, exact answer is strictly needed.

Corollary 1.4 (Implicit Parallelism)**.** *In any high-productivity setting, parallelism will be pervasive but implicit.*

A next-paradigm programming language, offering orders-of-magnitude productivity improvements, will very likely heavily leverage parallelism, yet completely hide it! There is no doubt that shared-memory concurrency correctness is among the thorniest programming challenges in existence. High-productivity and explicit synchronization, of any form, are very unlikely to be compatible. High levels of abstraction also seem to mesh well with automatic data partitioning and replication solutions, as does the earlier observation about sacrificing even asymptotic optimality on the altar of programming productivity.

Example: Implicit Shared-Memory Parallelism. Declarative languages already auto-parallelize programs. All the Datalog logic we have seen is executed by a modern engine (e.g., Soufflé) in parallel, by multiple threads over partitionings of the input data. A join operation is naturally massively parallel, so, the larger the input data, the more parallelism one can easily attain.

3.2 Programming Model: Semantic Invariants

In addition to a cost model, a next-paradigm PL programmer's mental model should include semantic guarantees.

Principle 2 (Need For Firm Mental Grounding)**.** *The programming model of next-paradigm languages will offer strong semantic guarantees (about what code can do and how new code can affect old).*

A language that will offer orders-of-magnitude improvements in productivity will necessarily enable the programmer to express more with less. A highly concise specification will yield a detailed optimized implementation, with the compiler playing a huge role in searching the space of potential algorithms and data structures. Keeping one's sanity will not be trivial. A one-word (or even one-character) change has the potential to completely alter program output or its performance. I am not giving examples from my declarative programming experience because anecdotes don't do justice to the magnitude of the issue. After all, small changes with large effects can also arise in conventional programming practice. However, what is currently an extreme case will be common, everyday experience in next-paradigm languages. Changes that the programmer considers completely innocuous may result in vastly different program implementations.

Faced with such complexity, the language will need to provide firm, sanity-keeping semantic guarantees. What can these guarantees be? It is hard to speculate on specifics without knowing the exact technology behind a language. Most likely, semantic invariants will guarantee what the program can or cannot do, what effect code in one part of the program can have on others, how the program output can change once new code is added, etc. Current examples give a glimpse of the possibilities.

Example: Monotonicity. The top sanity-preserving semantic invariant in Datalog is monotonicity. Computation is (dominantly) monotonic—other rules can only *add* to the output of a rule, never invalidate previous outputs. This gives excellent properties of code understanding via local inspection. It also helps with understanding the updated program semantics upon a code change—code addition is overwhelmingly the most common change in program development. Consider the earlier example of an Assign inference from established instances of CallGraphEdge. To understand the rule, we have never needed to wonder about either other rules that inform Assign or the rules that establish CallGraphEdge, even if those themselves employ Assign. Also, we have never needed to wonder about the evaluation order of this rule relative to any others. The rule works like a pure logical inference precisely because of the monotonicity property. The same holds for the three rules we employed for ReachableExcluding: we have not needed the definition of any rule in order to understand the others.[5]

[5]In reality, Datalog programs typically use "stratified negation", allowing non-monotonic operators (i.e., negation and arbitrary aggregation) over predicates defined in a previous evaluation stratum. This means that extra rules *can* produce fewer results, but only if these extra rules affect a predicate that is conceptually "more primitive" than the extra results. The programmer needs to have a stratification of the program logic in mind. This is a fairly

Example: Termination. A guarantee of program termination is another semantic invariant of the Datalog language. Core Datalog does not include operators for inventing new values, therefore all computation can at most combine input values. This results in a polynomial number of possible combinations, more and more of which are computed monotonically during program evaluation. Therefore, a program is guaranteed to terminate.

Of course, in practice strict guarantees of termination are impossible or impractical. A guarantee of termination makes a language sub-Turing complete. Practical implementations of Datalog allow creating new values, thus no ironclad guarantee of termination exists. However, it is valuable to distinguish a core guarantee, applicable to the majority of the code, from an exception that can be effected only by use of a well-identified language feature.[6] It is much easier to reason about the possible new values invented via constructors than have potentially non-terminating computations possibly lurking behind every computation in the language.

3.3 "Known" Principles? Abstraction, Extensibility, Modularity, Interoperability

It is interesting to speculate on new design principles of next-paradigm languages, but what about current, well-established language principles? These include, at the very least:

- (module) abstraction/growing a language: packaging recurring functionality in a reusable, parameterizable module [24];
- language extensibility: the marriage of powerful module abstraction with syntactic configurability;
- modularity: having mechanisms for keeping parts of the code isolated, only visible through specific, identified interfaces;
- multi-paradigm interoperability: easy interfacing between languages so that programming tasks can be expressed in terms well-suited to the computation at hand.

There is no doubt that current, established principles of good language design will play a big role in next-paradigm language design as well. However, these principles on their own are not enough to get us to a next-paradigm language. Furthermore, the benefits the established principles afford may be only second-order effects. They may pale compared to the chief benefit of a next-paradigm language: levels of abstraction high enough to yield orders-of-magnitude productivity improvements. In fact, the first next-paradigm programming languages may well be lacking in module abstraction, extensibility, or modularity. Later incarnations will likely benefit more from these principles, as have existing languages.

manageable mental burden (given compiler support for tracking violations), even for large code bases.

[6] "Pure" functional languages do something similar. They certainly permit side effects (e.g., I/O), but encapsulate them behind a well-identified interface—a monad.

The one principle that seems a priori indispensable for next-paradigm languages is that of multi-paradigm interoperability. I already conjectured that next-paradigm programming languages will not be good at everything—e.g., see Corollary 1.2. Escaping the language is then inevitable, even if it happens rarely. The language escape mechanism should not break the fundamental high-productivity abstraction. Instead, it can encapsulate, behind a clear interface, computations best optimized by manual, lower-level coding. There are mechanisms of this nature in common current use—e.g., uninterpreted functions/external functors.

Diminishing Returns. The need to escape a language raises an interesting question. How can high productivity be sustained, if parts of the coding need to happen in a conventional setting? The law of diminishing returns dictates that dramatically speeding up one part of software development will only move the bottleneck to a different part. If, say, the core of application logic currently takes 70% of programming effort and is made 10x more efficient, with other tasks staying the same, then 37% of the original effort is still required—the overall benefit is merely a factor of 2.7x. Tasks that may not benefit much from next-paradigm languages include low-level coding, as well as bespoke code for UI/storage/other interfacing with the environment.

Indeed, this is a constraint that can limit the large benefits of high-productivity languages to some kinds of development tasks but not others. However, I believe the effect will be largely mitigated by more conventionally forms of productivity enhancement: domain-specific languages and reusable modules (i.e., module abstraction). Furthermore, many of the non-core tasks of program development parallelize a lot more easily than the core application logic itself. Building a UI, a service wrapper, or integration APIs may require effort, but the effort can be more easily split among multiple programmers. Therefore, even though the overall effort may indeed see smaller (than orders-of-magnitude) improvements, other metrics of development productivity, such as end-to-end development time, may improve more, by dedicating more programmers to the task.

> We have programs that are vastly powerful but also vastly mysterious, meaning small changes can badly destabilize the system and we don't yet know how to talk about debugging or maintenance.
>
> *Jan-Willem Maessen, in reference to Sculley et al. [21]*

4 Changes to Development Workflows

An informal axiom of the Software Engineering community is that the choice of programming language does not fundamentally change the software engineering *process*. This may be true in the sense that process stages (e.g., requirements analysis, architecture, design, coding, testing, verification) remain the same conceptual entities. However, the relative effort and emphasis of each stage may change dramatically with high-productivity, high-abstraction languages. The *practice* of software development will change.

Principle 3 (Workflows Will Change)**.** *Next-paradigm programming languages will change well-established patterns in current programming workflow.*

Orders-of-magnitude productivity improvements will, very likely, disrupt the established workflow of program development. Code will be much more terse and abstract, resembling a formal specification. Small changes will have a huge impact on both functionality and performance. It is hard to fully grasp precisely how today's common practices will evolve, so I will speculate modestly, straying little from observations from my own coding practices.

Corollary 3.1 (Incremental Development)**.** *In next-paradigm languages, it will be much easier to develop programs incrementally, and to continue from where one has left off.*

This observation may seem pedestrian, but it has been one of the most striking revelations in my everyday experience with declarative programming. The higher level of abstraction means that one can rely on highly-powerful concepts without ever looking at their definitions. Specifically for Datalog development, monotonicity in the language evaluation model means that developing more functionality is a natural extension of what is already there. However, the experience of incremental development will likely generalize to all higher-level programming settings. Programming with high-level specifications is naturally incremental. For one, at any point in development, a partial specification yields a program. The program's outputs are incomplete, but they immediately suggest what is missing and how more work can get the program closer to the desired task. Adding extra features interacts in a predictable way with earlier functionality.

Example: An Interactive Graphical Application. Imagine creating an interactive graphical application (e.g., a video game or a drawing program) in a language with high degrees of abstraction. Such a language will likely accept a logical specification of *what* should be displayed, *where* and *when*, without encoding at all the *how*. Whether a control should have an effect at a certain point, whether a graphical element is visible or obstructed, how the display adjusts to changes of the environment, etc., are all elements that the language implementation should address, and not the program itself.

Development in such a language is naturally incremental. It is straightforward to start with specifications of elements that appear on the screen, under some control conditions (which may involve timing). There is no need to specify yet what the timing or the controls are—just to declare them. It is easy to add sample inputs for these and see graphical elements displayed—the incomplete specification already yields a working program. Making progress on any front is incremental and straightforward. One can add more graphical elements, or more detail over current elements, or complex specifications to define user control, or a mechanism for storing data, or any other desired functionality. All new functionality should interact cleanly with existing functionality. The language implementation will resolve conflicts (sometimes with the programmer's help, in case of hard conflicts) and will produce vastly different low-level programs as the specification becomes more and more complete.

Corollary 3.2 (Testing Changes)**.** *In next-paradigm languages, testing will be a larger and deeper part of the programmer's workflow.*

When programming effectively becomes a collaboration between a creative human and a compiler with vast abilities in exploring an implementation space, the role of testing will change dramatically. The programmer will write highly concise code that produces very complex outputs. Continuous checking of assumptions against the implemented model will be necessary. The programmer may be spending much more time running code in complex settings than writing it.

The task of testing and debugging will also be conceptually harder. Testing may be as complicated as writing the code, and indeed writing testing specifications may be obligatory. The difficulty arises because efficiency in execution necessarily means that most intermediate results will never be part of the output. This complicates debugging enormously. For instance, the mechanism of time-travel debugging (e.g., see Reference [3]), which has captured the programming community's imagination in recent years, works only when the space of intermediate values of a computation is not that much larger from the space of final values. This is not the case for abstract programs. Both the language implementation and the program itself may be collapsing a much larger space of values in order to get a single output [12].

Example: Paths. A pedestrian but illustrative example is that of a declarative "transitive closure" computation: compute when there is a path between two nodes, given direct edges as input. The recursive rule for this is:

```
Path(source, target) :-
  Edge(source, interm),
  Path(interm, target).
```

This computation only stores the fact that there *is* a path, but not how this path was established: the `interm` value is dropped. Keeping all `interm` values will make the cost of computing and storing the `Path` relation combinatorially larger: $O(n^3)$ instead of $O(n^2)$.[7] In practice, this increase is often

[7]If one wants to be pedantic, in the worst case, the cost of computing `Path` is $O(n^3)$ anyway. But in the sparse graphs that arise in practice, the

prohibitive. Consider that the transitive closure computation shown in the above rule is the simplest possible recursive computation in a logical specification. Most real specifications that employ recursion will be much more complex, with several intermediate values used to derive results but not memorized. Therefore, completely routine computations become intractable if it becomes necessary to fully trace how the result was derived.

Corollary 3.3 (Different Balance of Formal Reasoning and Coding)**.** *For programs in next-paradigm languages, formal proofs will be easier. Yet they will also be less necessary.*

A program that is effectively an executable specification removes some of the need for formal verification. The value of verification in current coding stems partly from the assurance of formal reasoning and partly from specifying the computation in a completely different formulation, unencumbered by implementation constraints. In a next-paradigm language, the level of abstraction of the program will likely be much closer to that of a non-(efficiently-)executable specification. There will likely still be a need for formal reasoning, to establish properties of the program with confidence and in full generality. Such reasoning will be easier just by virtue of the smaller gap between the two specifications.

5 Conclusions

Next-paradigm programming languages will need a revolutionary change in level of abstraction, if they are to ever realize large productivity improvements. Such a change will necessarily have many repercussions on the role of the compiler, on the programmer’s mental model, and on development patterns. In this paper, I tried to identify these changes, looking over the future through the misty glass of the present. Necessarily, I only present the view of the future from where I currently stand. Others will likely find it too speculative or too myopic—and that’s fine. But we need a conversation about next-paradigm programming languages and I hope to help start it.

References

[1] Molham Aref, Balder ten Cate, Todd J. Green, Benny Kimelfeld, Dan Olteanu, Emir Pasalic, Todd L. Veldhuizen, and Geoffrey Washburn. 2015. Design and Implementation of the LogicBlox System. In *Proceedings of the 2015 ACM SIGMOD International Conference on Management of Data (SIGMOD ’15)*. ACM, New York, NY, USA, 1371–1382. https://doi.org/10.1145/2723372.2742796

[2] George Balatsouras and Yannis Smaragdakis. 2016. Structure-Sensitive Points-To Analysis for C and C++. In *Static Analysis*, Xavier Rival (Ed.). Springer Berlin Heidelberg, Berlin, Heidelberg, 84–104.

[3] Earl T. Barr and Mark Marron. 2014. Tardis: Affordable Time-travel Debugging in Managed Runtimes. In *Proceedings of the 2014 ACM International Conference on Object Oriented Programming Systems Languages & Applications (OOPSLA ’14)*. ACM, New York, NY, USA, 67–82. https://doi.org/10.1145/2660193.2660209

computation is typically $O(n^2)$ if intermediate nodes do not need to be kept and $O(n^3)$ if they do.

[4] Martin Bravenboer and Yannis Smaragdakis. 2009. Strictly Declarative Specification of Sophisticated Points-to Analyses. In *Proceedings of the 24th ACM SIGPLAN Conference on Object Oriented Programming Systems Languages and Applications (OOPSLA ’09)*. ACM, New York, NY, USA, 243–262. https://doi.org/10.1145/1640089.1640108

[5] Michael Carbin, Deokhwan Kim, Sasa Misailovic, and Martin C. Rinard. 2012. Proving acceptability properties of relaxed nondeterministic approximate programs. In *ACM SIGPLAN Conference on Programming Language Design and Implementation, PLDI ’12, Beijing, China - June 11 - 16, 2012*, Jan Vitek, Haibo Lin, and Frank Tip (Eds.). ACM, 169–180. https://doi.org/10.1145/2254064.2254086

[6] Neville Grech, Lexi Brent, Bernhard Scholz, and Yannis Smaragdakis. 2019. Gigahorse: Thorough, Declarative Decompilation of Smart Contracts. In *International Conference on Software Engineering (ICSE)*.

[7] Neville Grech, Michael Kong, Anton Jurisevic, Lexi Brent, Bernhard Scholz, and Yannis Smaragdakis. 2018. MadMax: Surviving Out-of-Gas Conditions in Ethereum Smart Contracts. *Proc. ACM Programming Languages* 2, OOPSLA (Nov. 2018). https://doi.org/10.1145/3276486

[8] Sumit Gulwani, Susmit Jha, Ashish Tiwari, and Ramarathnam Venkatesan. 2011. Synthesis of Loop-free Programs. In *Proceedings of the 32Nd ACM SIGPLAN Conference on Programming Language Design and Implementation (PLDI ’11)*. ACM, New York, NY, USA, 62–73. https://doi.org/10.1145/1993498.1993506

[9] Sumit Gulwani, Oleksandr Polozov, and Rishabh Singh. 2017. Program Synthesis. *Foundations and Trends in Programming Languages* 4, 1-2 (2017), 1–119. https://doi.org/10.1561/2500000010

[10] Elnar Hajiyev, Mathieu Verbaere, and Oege de Moor. 2006. CodeQuest: Scalable Source Code Queries with Datalog. In *ECOOP’06: Proceedings of the 20th European Conference on Object-Oriented Programming*. Spinger, 2–27.

[11] Herbert Jordan, Bernhard Scholz, and Pavle Subotić. 2016. Soufflé: On Synthesis of Program Analyzers. In *Computer Aided Verification*, Swarat Chaudhuri and Azadeh Farzan (Eds.). Springer International Publishing, Cham, 422–430.

[12] Sven Köhler, Bertram Ludäscher, and Yannis Smaragdakis. 2012. Declarative Datalog Debugging for Mere Mortals. In *Datalog in Academia and Industry - Second International Workshop, Datalog 2.0, Vienna, Austria, September 11-13, 2012. Proceedings (Lecture Notes in Computer Science)*, Pablo Barceló and Reinhard Pichler (Eds.), Vol. 7494. Springer, 111–122. https://doi.org/10.1007/978-3-642-32925-8_12

[13] Sifis Lagouvardos, Julian Dolby, Neville Grech, Anastasios Antoniadis, and Yannis Smaragdakis. 2019. Static Analysis of Shape in TensorFlow Programs. in submission.

[14] Monica S. Lam, John Whaley, V. Benjamin Livshits, Michael C. Martin, Dzintars Avots, Michael Carbin, and Christopher Unkel. 2005. Context-sensitive program analysis as database queries. In *Proc. of the 24th Symp. on Principles of Database Systems (PODS ’05)*. ACM, New York, NY, USA, 1–12. https://doi.org/10.1145/1065167.1065169

[15] Ondřej Lhoták. 2006. *Program Analysis using Binary Decision Diagrams*. Ph.D. Dissertation. McGill University.

[16] Patrick S. Li. 2016. Stop Designing Languages. Write Libraries Instead. http://lbstanza.org/purpose_of_programming_languages.html.

[17] Robert C. Martin. 2016. Blue. No! Yellow! - Clean Coder Blog. https://blog.cleancoder.com/uncle-bob/2016/05/21/BlueNoYellow.html.

[18] Christoph Reichenbach, Neil Immerman, Yannis Smaragdakis, Edward E. Aftandilian, and Samuel Z. Guyer. 2010. What Can the GC Compute Efficiently?: A Language for Heap Assertions at GC Time. In *Proceedings of the ACM International Conference on Object Oriented Programming Systems Languages and Applications (OOPSLA ’10)*. ACM, New York, NY, USA, 256–269. https://doi.org/10.1145/1869459.1869482

[19] Christoph Reichenbach, Yannis Smaragdakis, and Neil Immerman. 2012. PQL: A Purely-Declarative Java Extension for Parallel Programming. In *ECOOP 2012 – Object-Oriented Programming*, James Noble (Ed.). Springer Berlin Heidelberg, Berlin, Heidelberg, 53–78.

[20] Thomas Reps. 1994. Demand interprocedural program analysis using logic databases. In *Applications of Logic Databases*, R. Ramakrishnan (Ed.). Kluwer Academic Publishers, 163–196.

[21] D. Sculley, Gary Holt, Daniel Golovin, Eugene Davydov, Todd Phillips, Dietmar Ebner, Vinay Chaudhary, and Michael Young. 2014. Machine Learning: The High Interest Credit Card of Technical Debt. In *SE4ML: Software Engineering for Machine Learning (NIPS 2014 Workshop)*.

[22] Yannis Smaragdakis and Martin Bravenboer. 2011. Using Datalog for Fast and Easy Program Analysis. In *Datalog Reloaded*, Oege de Moor, Georg Gottlob, Tim Furche, and Andrew Sellers (Eds.). Springer Berlin Heidelberg, Berlin, Heidelberg, 245–251.

[23] Yannis Smaragdakis, Jacob Evans, Caitlin Sadowski, Jaeheon Yi, and Cormac Flanagan. 2012. Sound Predictive Race Detection in Polynomial Time. In *Proceedings of the 39th Annual ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages (POPL '12)*. ACM, New York, NY, USA, 387–400. https://doi.org/10.1145/2103656.2103702

[24] Guy L. Steele, Jr. 1998. Growing a Language. In *Addendum to the 1998 Proceedings of the Conference on Object-oriented Programming, Systems, Languages, and Applications (Addendum) (OOPSLA '98 Addendum)*. ACM, New York, NY, USA, 0.01–A1. https://doi.org/10.1145/346852.346922

[25] Pavle Subotic, Herbert Jordan, Lijun Chang, Alan Fekete, and Bernhard Scholz. 2018. Automatic Index Selection for Large-Scale Datalog Computation. *PVLDB* 12, 2 (2018), 141–153. http://www.vldb.org/pvldb/vol12/p141-subotic.pdf

[26] Various. 2018. Vandal – A Static Analysis Framework for Ethereum Bytecode. https://github.com/usyd-blockchain/vandal/ Accessed: 2018-07-30.

[27] John Whaley, Dzintars Avots, Michael Carbin, and Monica S. Lam. 2005. Using Datalog with Binary Decision Diagrams for Program Analysis. In *Proc. of the 3rd Asian Symposium on Programming Languages and Systems*. 97–118.