

An environment that works the way nonprogrammers expect is more inviting and helps users become more confident and productive.

NATURAL PROGRAMMING LANGUAGES AND ENVIRONMENTS

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OVER THE LAST SIX YEARS, WE HAVE BEEN WORKING TO CREATE PROGRAMMING languages and environments that are more natural, or closer to the way people think about their tasks. Our goal is to make it possible for people to express their ideas in the same way they think about them. To achieve this, we have performed various studies about how people think about programming tasks, both when trying to create a new program and when trying to find and fix bugs in existing programs. We then use this knowledge to develop new tools for programming and debugging. Our user studies have shown the resulting systems provide significant benefits to users. _____

It is somewhat surprising that in spite of over 30 years of research in the areas of empirical studies of programmers (ESP) and human-computer interaction (HCI), the designs of new programming languages and debugging tools have generally not taken advantage of what has been discovered. For example, the C#, JavaScript, and Java languages use the same mechanisms

for looping, conditionals, and assignments shown to cause many errors for both beginning and expert programmers in the C language. Systems such as MacroMedia's Director and Flash, Microsoft's Visual Basic, and general-purpose programming environments like MetroWerks' CodeWarrior and Microsoft's Visual C++, all provide the same debugging tech-

niques available for 60 years: breakpoints, print statements, and showing the values of variables.

Our thorough investigation of the ESP and HCI literature revealed many results that can be used to guide the design of new programming systems, many of which have not been utilized in previous designs. However, there are many significant gaps in our

knowledge about how people reason about programs and programming. For example, there has been very little study about which fundamental paradigms of computing are the most natural or what questions people ask when debugging. We are performing user studies which investigate these questions.

It is in this context that we developed the Natural Programming design process, that treats usability as a first-class objective by following these steps:

- Identify the target audience and the domain, that is, the group of people who will be using the system and the kinds of problems they will be working on.
- Understand the target audience, by studying the actual language, techniques, and thinking they naturally use when trying to solve problems. This includes an awareness of general HCI principles as well as prior work in the psychology of programming and empirical studies. When issues or questions arise that are not answered by the prior work, conduct new user studies to examine them.
- Design the new system based on this information.
- Evaluate the system to measure its success, and to understand any new problems the users have. Redesign the system based on this evaluation, and then reevaluate it, following the standard HCI principle of iterative design.

Thus, the Natural Programming approach is an application of the standard user-centered design process to the specific domain of programming languages and environments.

This article provides an overview of some of the work of the Natural Programming project.¹ We explore why naturalness might be better for developers and what might be more natural in programs for graphics and data processing based on initial user studies. The results were used in the design of a new language and environment called Human-centered Advances for the Novice Development of Software (HANDS). We also discuss our survey of programmers creating small and medium-size programs using a different environment called Alice (see www.alice.org).

Why Natural Might Be Better

The premise of our research project is that programmers will have an easier job if their programming tasks are made more natural. By “natural,” we mean “faithfully representing nature or life,” which here

implies it works in the way people expect. By “natural programming” we are aiming for the language and environment to work the way that nonprogrammers expect.

Why would this make programming easier? One way to define programming is the process of transforming a mental plan in familiar terms into one compatible with the computer [3]. The closer the language is to the programmer’s original plan, the easier this refinement process will be. This is closely related to the concept of directness that, as part of *direct manipulation*, is a key principle in making user interfaces (UI) easier to use. UI designers and researchers have been promoting directness at least since Ben Shneiderman identified the concept in 1983, but it has not even been a consideration in most programming language designs.

Conventional programming languages require the programmer to make tremendous transformations from the intended tasks to the code design. For example, a typical program to add a set of numbers in C uses three kinds of parentheses and three kinds of assignment operators in five lines of code, whereas a single “SUM” operator is sufficient in a spreadsheet [2]. We argue that if the computer language were to enable people to express algorithms and data more like their natural expressions, the transformation effort would be reduced.

Similarly, debugging activities could benefit from being more natural. Research describes debugging as an exploratory activity aimed at investigating a program’s behavior, involving several distinct and interleaving activities [12]:

- Hypothesizing what runtime actions caused failure;
- Observing data about a program’s runtime state;
- Restructuring data into different representations;
- Exploring restructured runtime data;
- Diagnosing what code caused faulty runtime actions; and
- Repairing erroneous code to prevent such actions.

Current debugging tools support some of these activities, while hindering others. For example, breakpoints and code-stepping support observation of control flow but hinder exploration and restructuring, whereas visualization tools help restructure data but hinder diagnosis and observation [5]. Yet none of these tools support hypothesizing activities. The argument behind our Natural Programming approach to debugging is that support for such question-related activities will significantly improve success. If programmers have a weak hypothesis about the cause of a failure, any implicit assumptions about what did or

¹More details are available from other papers at www.cs.cmu.edu/~NatProg.

The goal is to make it possible for people to express their ideas in the same way they think about them.

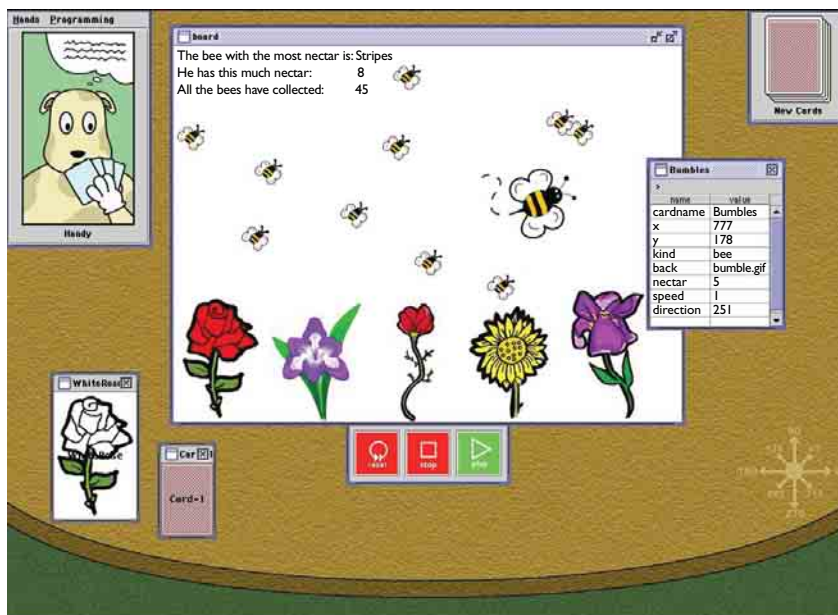


Figure 1. The HANDS system portrays the components of a program on a round table. All data is stored on cards, and the programmer inserts code into Handy's thought bubble at the upper left corner. When the play button is pressed, Handy begins responding to events by manipulating cards according to the instructions in the thought bubble.

did not happen at run-time will go unchecked. Not only do these unchecked assumptions cause debugging to take more time [12], but they also result in new errors. For example, in a study of Alice users we found that 50% of all errors were due to programmers' false assumptions in the hypotheses they formed while debugging existing errors [6].

Related work. We build on the research of many others, who have studied programming and debugging. Prior studies (see [10] for a summary) have shown that features of the programming environment are a crucial part of making a programming language effective and easy to use. For example, providing immediate feedback about problems and testing helps with problem solving. The ability to test partial solutions is an important feature for novices and experts alike, especially during testing and when reusing code. This incremental and frequent testing should be

encouraged because it is a useful debugging strategy. When novices test their code incrementally, they perform better [2].

The idea that the programming environment can help users construct programs has a long history. "Syntax Directed Editors" (also called "Structure Editors") have been used to help eliminate syntax errors at least since the Cornell Program Synthesizer [11], and there have been many variations. Modern tools like Visual Basic provide context-dependent pop-up menus that insert correctly formatted code, but do not restrict what users can type. Alice takes an extreme

stance and only allows syntactically correct statements to be entered, since all editing is performed by dragging-and-dropping statements and using pop-up menus to specify parameters. A number of environments have adapted the successful spreadsheet style of end-user programming to other domains (for example, [1, 4]).

Many tools have been created to help with debugging, but most focus on visualization of data and control flow. Research by Kehoe, Stasko, and Taylor suggests, however, that these are not particularly helpful for debugging [5]. *Communications* devoted a special section to new ideas for debugging in April 1997, but none of the systems have been user tested or widely deployed [8].

Language Studies

We conducted two studies to examine the language and structure that children and adults naturally use in solving problems before they have been exposed to programming. Participants were presented with programming tasks and asked to solve them on paper using whatever text or diagrams they wanted

to use. To avoid biasing the subjects' answers, the study materials were constructed with great care, using graphical depictions and terse descriptions of problem scenarios. One study used the PacMan video game and another used database access scenarios more typical of business programming tasks.

Some observations from these studies were:

- An event-based or rule-based structure was often used, where actions were taken in response to events. For example, "When PacMan loses all his lives, it's game over."
- Aggregate operators (acting on a set of objects all at once) were used much more often than iterating through the set and acting on the objects individually. For example, "Move everyone below the 5th place down by one."
- Participants rarely used Boolean expressions, but when they did they were likely to make errors. That is, their expressions were not correct if interpreted according to the rules of Boolean logic in most programming languages.
- Participants often drew pictures to sketch out the layout of the program, but resorted to text to describe actions and behaviors.

Additional details about these studies are reported in [9].

The HANDS Environment and Language

The next step was to design and implement HANDS, a new programming language and environment. The various components of this system were designed in response to the observations in our studies as well as prior work.

HANDS uses an event-based language that features a new model for computation, provides queries and aggregate operators that match the way nonprogrammers express problem solutions, has high visibility of program data, and includes domain-specific features for the creation of interactive animations and simulations.

In HANDS, the computation is represented as an agent named Handy, sitting at a table manipulating a set of cards (see Figure 1). All the data in the system is stored on these cards, which are global, persistent, and visible on the table.

HANDS is event-based—a programming style that most closely matches the problem solutions in our studies. It has full support for aggregate operations—all operators can accept lists or singletons as

operands. Lists can be generated as needed, by using query operators that search all of the cards for the ones matching the programmer's criteria. Queries and aggregate operations work in tandem to enable the programmer to concisely express actions that would require iteration in most languages. For example, the following is a typical HANDS statement combining queries and aggregates:

```
set the nectar of all flowers to 0
```

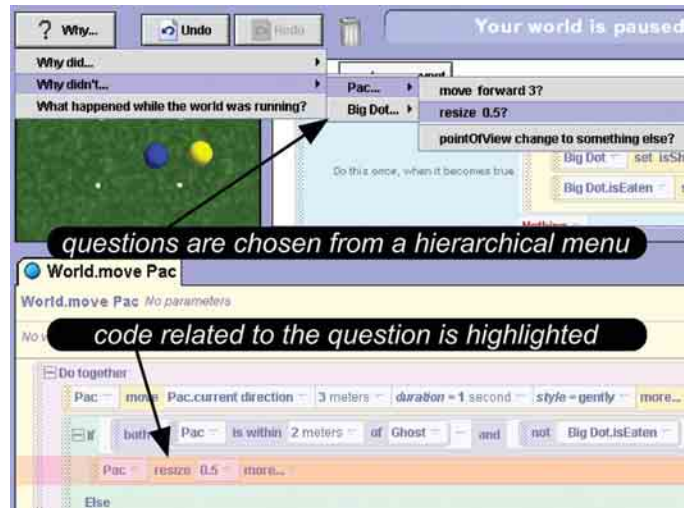


Figure 2. The Alice programming environment with a "why didn't" question in progress.

To examine the effectiveness of HANDS, we conducted a user study. Ten-year-olds were able to learn the HANDS system during a three-hour session, and then use it to solve programming problems. Children using the full-featured version of HANDS performed significantly better than their peers who used a version modified to be more like typical programming systems. Additional details about this study are reported in [9].

Debugging Studies

Our studies of the language and structure that people use helped us to design a more natural programming language. We are also performing studies of how programming environments can help programmers avoid making errors, and help them find and fix the errors they have already made. An important part of these studies is determining what causes programmers to make errors in the first place.

We have integrated many strands of prior research on human error, and have found that errors are ultimately caused by long chains of *breakdowns* that happen for one of two reasons: some breakdowns occur in the programmer's head, such as using an inappropriate

The screenshot shows the NetLogo environment with the following components and annotations:

- Top Menu Bar:** Resume, Stop, Why?, Undo, Clear, Help.
- Left Sidebar:**
 - Pac's details:** properties, methods, questions.
 - capture pose:** color, opacity, vehicle.
- Main Workspace:**
 - World.move Pac:** A block with parameters: Pac, move, Pac.current direction, 3 meters, duration, 1 second, style, ghost, more... (Annotations: "further questions can be asked", "camera focuses on subject of question").
 - Pac:** A block with parameters: Pac, is within, 2 meters, of, Ghost, and, run, Big Dot Is Eaten, more... (Annotations: "tooltips show properties' current values", "access to previous questions and answers", "code related to the selection is highlighted").
 - Big Dot Is Eaten set to true:** A block with parameters: Big Dot Is Eaten, set to, true (Annotation: "runtime actions").
 - Pac is within 2 of Ghost:** A block with parameters: Pac, is within 2 of, Ghost, and, true (Annotation: "causality arrows").
 - Questions I've asked:** A list of questions (Annotation: "access to previous questions and answers").
 - Time Slider:** A slider with a time cursor (Annotation: "time cursor traverses execution history").

to prevent breakdowns. We have recently focused on preventing breakdowns in debugging.

We observed that *all* of the programmers' questions at the time of failure were one of two types: 32% were *why did* questions, which assume the occurrence of an *unexpected* runtime action, and 68% were *why didn't* questions, which assume the absence of an *expected* runtime action. Furthermore, 50% of all errors were due to programmers' false assumptions in the hypotheses they formed while debugging existing errors, resulting in the

We performed a user study comparing the Alice environment with and without the Whyline. Subjects were Master's students with programming experience ranging from beginning Visual Basic to extensive C++ and Java. Analyzing six situations that were identical across the two conditions, the Whyline significantly decreased debugging time from an aver-

While making programming languages and environments more natural may be controversial when aimed at professional programmers, we believe it is of significant importance for end-user development. In addition to supplying new knowledge and tools directly, the human-centered approach followed by the Natural Programming project provides a model of a methodology that can be followed by other developers and researchers when designing their own languages and environments. We believe this will result in more usable and effective tools that allow both end-users and professionals to write more useful and correct programs. **C**

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