Moderated by
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literate programming

WEAVING A LANGUAGE-INDEPENDENT WEB

Polyglot Programming Literacy

Moderator's Introduction to Column 5
The mailbox fairly overflowed with responses to Eric Hamilton's program to expand generalized regular expressions (*Communications*, December 1988, p. 1376). Every letter said that it would have been more appropriate to solve Mark Kahrs's problem in another programming language. The introduction should have pointed out that Kahrs's program, which needed a string-expansion function, was itself written in C; thus, the requirement that it be possible to plug any solution into the larger program without much fuss practically demanded that Hamilton write in C.

Although correspondents were unanimous that another language would have been a better choice for the solution, they disagreed almost completely about the choice of that language: I received solutions written in APL, APL2, Icon, Miranda, MUMPS, and Smalltalk; two other readers suggested that it would be easy and natural to solve the problem in LISP, but neither had done so. These writers, and other readers who want to write literate programs in a language other than Pascal and C, should be interested in the following article by Norman Ramsey.

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In the fall of 1987 I started planning the implementation of a suite of tools for building verified Ada programs [5]. The first tool to be built was a verification condition generator, which was to be formally defined using the typed lambda calculus. I was eager to include the definition with the code so that it would be easy to check the code's correctness. Using WEB would have made this easy, but, unfortunately, the target programming language was SSL (a language for specifying structure editors), and the only languages for which WEB implementations were available were Pascal and C.

Writing a new WEB from scratch did not make sense, so I decided to modify Silvio Levy's implementation of WEB in C [3], to get a WEB that would be written in C, but would read and write SSL code. From my previous experiences modifying WEB, I knew that the most time-consuming job would be fine-tuning the grammar that WEAVE uses to prettyprint code. I believed I could make debugging that grammar a lot less painful if, instead of trying to make dozens of small modifications by hand, I wrote a simple program, perhaps an AWK script, that would read a description of the grammar and generate C code for WEAVE. That AWK script became SPIDER, a program that turns language descriptions into C code for TANGLE and WEAVE. I have used SPIDER to generate WEBs for C, AWK, SSL, Ada, and a couple of other languages. I will not go into the details of SPIDER; instead, I will try to describe what SPIDER does to accomplish its mission, or how to take the "essence of WEB" and make it language-independent.

When using WEB, a programmer writes a single source file, `foo.web`, that holds both code and documentation. TANGLE and WEAVE read that file. TANGLE extracts the code from the WEB file and rewrites it in a form suitable for compiling. WEAVE passes the documentation parts to a document formatter (TeX), and prettyprints the code parts. The whole process is shown in Figure 1, for C programs written in WEB. The § represents files that have to be written by hand. *Slant* type is used for the names of executable programs. *CTANGLE* and *CWEAVE* are the C-language versions of TANGLE and WEAVE, *cc* is a C compiler, and *ld* is a loader.

SPIDER is used to construct *instances* of TANGLE and WEAVE, and these instances are used to process programs as shown in Figure 1. Code for the language-dependent parts of these instances is generated by SPIDER when it reads a language description file written

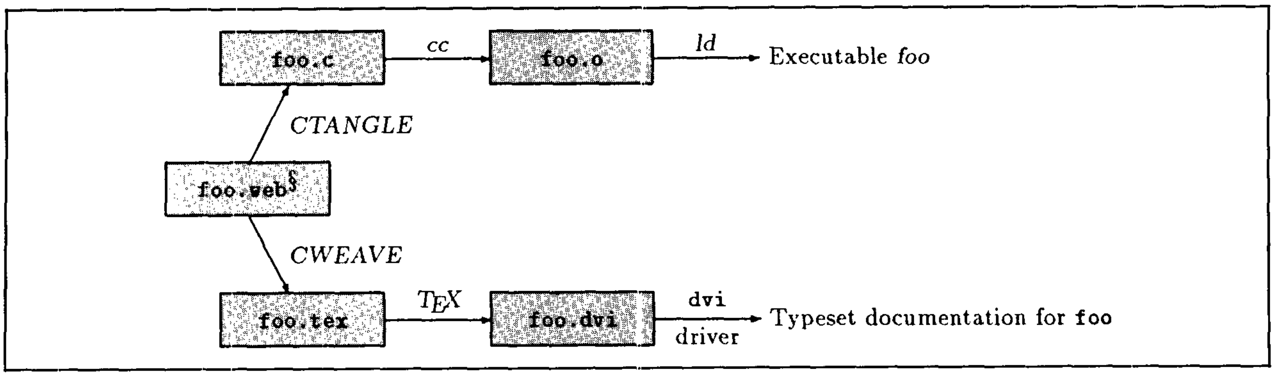

FIGURE 1. Processing a C WEB File

by a WEB designer. Figure 2 shows how instances of TANGLE and WEAVE are generated. SPIDER converts a hand-written description of a programming language into C WEB code for the language-dependent parts of TANGLE and WEAVE. In Figure 2 the target programming language is a hypothetical "X," and the description file is called "`x.spider`." CTANGLE combines the code SPIDER writes with the "master copies" of `tangle.web` and `weave.web`, which contain the language-independent parts of TANGLE and WEAVE. The result is C source code for XTANGLE and XWEAVE. After that code is compiled and loaded with WEB's I/O code, the resulting executable versions of XTANGLE and XWEAVE can be used to process X-language programs written in WEB format, as shown around the periphery of Figure 2.

The master copies of `tangle.web` and `weave.web` are about 1800 and 3200 lines long, respectively. About one-third of these lines are comments. To illustrate the other sizes, suppose X is the Ada programming language. The `ada.spider` file is about 260 lines long, and from it SPIDER generates about 1400 lines of ADATANGLE and ADAWEAVE. About one-tenth of these lines are comments. It is typical for SPIDER to generate between $5n$ and $6n$ lines of C WEB code from an n-line language description.

A WEB program is a collection of "sections," each of which has a documentation part, a definition part, and a code part. The documentation part describes what the section is supposed to do, and is intended to be processed by a formatter—my WEBs use TeX, which is especially convenient for mathematical symbols like those used in writing a formal semantics. The definition part contains macro definitions. Each macro may have parameters or not, as the programmer chooses. The code in the code part is a fragment of the whole program. It is called a "module" and can be named or unnamed. When the module is named, the module

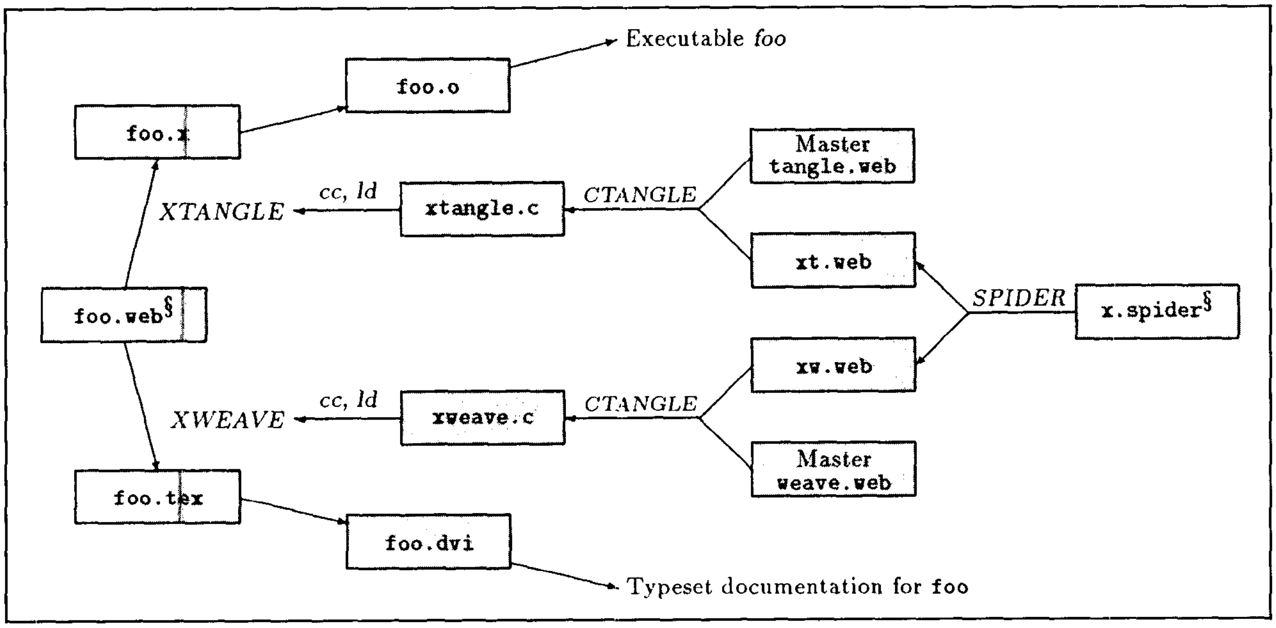

FIGURE 2. Building and Using an Instance of WEB (for Language X)

name "stands for" that code, just as a macro name stands for the code in its definition. The unnamed module is special; the code in the unnamed module is considered to be "the program."

Figure 3 shows a fragment of a WEB program; the fragment inverts an EBCDIC-to-ASCII table to obtain an ASCII-to-EBCDIC table. The target programming language is C. One module, ⟨Invert *to_ascii*, producing *to_ebcdic*⟩, uses the code defined in the other, ⟨Set *to_ebcdic*[*i*] ← *UNDEFINED_CODE* for all *i*⟩. The program, `foo`, of which this fragment is a part, can be input to CTANGLE and CWEAVE, to produce `foo.c` and `foo.tex` respectively, as shown in Figure 1.

TANGLE's job is to take a collection of sections and to produce a compilable program. TANGLE reads all the sections, skipping the documentation parts completely, but storing the macro definitions from the definition parts and the module definitions from the code parts. After it has read all the sections, TANGLE then writes out the code in the unnamed module. But whenever it encounters a module name in that code, instead of writing out the name, it writes out the code for which this name stands. That code may itself contain module names, which are replaced with the code for which they stand, and so on until TANGLE reaches code which contains no occurrences of module names. TANGLE processes macros similarly, except that macros may have parameters (modules may not).

As I have described it, the "essence of tangling" is language-independent. In the full implementation of TANGLE there are only a few language-dependent details, and almost all of them come up only in lexical analysis. During its input phase, TANGLE converts macro definitions and module definitions into token lists. The major kinds of tokens are module name tokens, identifier tokens, and ordinary tokens. Identifier tokens may be expandable (when they are macro names) or unexpandable (when they are programming-language identifiers). Module name tokens are always expandable, and ordinary tokens are never expandable. TANGLE uses a stack to write out the token list corresponding to the unnamed module, expanding expandable tokens as it goes. No token is ever expanded until the time comes to write that token on the output.

To build the language-dependent part of TANGLE, it is enough to tell TANGLE how to tokenize the input and how to write out a token list. TANGLE uses a "lowest-common-denominator" lexical analyzer to tokenize its input. The set of tokens recognized by this lexical analyzer is the union of the sets of legal tokens of many different languages. For example, different ways of delimiting string literals are recognized. Identifiers may have underscores, even though some languages (e.g., Pascal) may not permit underscores in identifiers, and others (e.g., Ada) may not permit consecutive underscores in an identifier. In general, TANGLE and WEAVE do the right thing with legal programs, but they do not detect illegalities in a program.

TANGLE's lexical analyzer recognizes a fixed set of tokens representing identifiers, string literals, and numeric literals. Any printable ASCII character which is not part of some other token forms a token all by itself. A WEB builder can specify that certain strings should be treated as single tokens, and SPIDER will convert the specifications into appropriate code for TANGLE. For example, when building WEB for C, we tell SPIDER that the strings ++, ==, and && (and many others) should be treated as single tokens, by putting the statements

```
@ The array |to_ascii| converts an EBCDIC code to
an ASCII code, or to |-1| if there is no ASCII
equivalent to the given code.
@d UNDEFINED_CODE = -1
@<Invert |to_ascii|, producing |to_ebcdic|@>=
    @<Set |to_ebcdic[i]=UNDEFINED_CODE| for all |i|@>@;
    for (i=0; i<256; i++)
        if (to_ascii[i] != UNDEFINED_CODE)
            to_ebcdic[to_ascii[i]]=i;

@ @<Set |to_ebcdic[i]=UNDEFINED_CODE| for all |i|@>=
    for (i=0; i<128; i++) to_ebcdic[i] = UNDEFINED_CODE;
```

FIGURE 3. Table Inversion

```
token ++ ...
token == ...
token && ...
```

into the language description file, `c.spider`.

TANGLE discards comments, rather than attempting to tokenize them. Comments are assumed to begin with a special string, and to end either with another string or with a newline. We specify C comment conventions by telling SPIDER

```
comment begin <"/*"> end <"*/">
```

On output, TANGLE converts tokens to text by inverting the process of lexical analysis, so, for example, the token $\boxed{++}$ is written out as "++." TANGLE's output phase inserts white space between adjacent identifiers and numeric literals, but otherwise does not write white space. This can cause problems in some cases; for example, in older C compilers the string "=–" is ambiguous. We can solve this problem by telling SPIDER to build a TANGLE that uses the text "= " when writing the $\boxed{=}$:

```
token = tangleto <"= ">
```

In sum, we can make TANGLE language-independent with almost no effort. We do this by using a lowest-common-denominator lexical analyzer whose only parameter is a description of comments, and by providing a way to fine-tune the way TANGLE writes tokens.

Unlike TANGLE, WEAVE does no rearranging of the sections; its job is to translate its input into a prettyprinted program listing. The documentation part of each section is simply copied to the output, but the definition and code parts are prettyprinted. WEAVE's output is handed to a document formatter, which is assumed to implement a prettyprinting algorithm like that described by Oppen [4]. Since my WEBs use TEX as the document formatter, the back-end prettyprinting is implemented by TEX macros.

WEAVE copies the documentation parts as texts, but it converts definition and code parts to token lists using the same lexical analyzer used by TANGLE. WEAVE's part of the prettyprinting task (as distinct from TEX's part) is converting these token lists to streams of TEX text, possibly with prettyprinting instructions intercalated between tokens. If you like, WEAVE's job is to produce the input to Oppen's algorithm. For simplicity, only three prettyprinting instructions will be discussed: *indent* (increase the level of indentation); *outdent* (decrease the level of indentation); and *force* (force a line break).

We tell WEAVE how to convert tokens to TEX text by specifying a *translation* for each token. Suppose we want the C token $\boxed{!=}$ to be printed as "≠", which is produced by the TEX text "\ne". Then we write

```
token != translation ⟨"\\ne"⟩
```

(Two backslashes appear in the translation because SPIDER uses C conventions for string literals. The angle brackets ⟨ . . . ⟩ delimit translations.) The default for translation is just as in TANGLE, so if we want "+" on input to produce "+" on output we need not specify a translation for the token $\boxed{+}$.

The process of deciding where to put line breaks and indentation is the most complicated part of WEAVE. We have to do this based on the sequence of tokens we have, but the exact details of which token is where usually are not needed to do prettyprinting. Hence we introduce the *scrap*, which abstracts away from the detail not needed to do prettyprinting. A scrap has two parts: the translation, which we have already seen, and the *category*, which corresponds to a "part of speech" or a symbol in a grammar. WEAVE uses categories to decide where to put indentation and line breaks. Since there are usually many different tokens having the same category, prettyprinting is simplified enormously.

WEAVE begins processing a program fragment by tokenizing the fragment, then converting each token in the resulting token list into a scrap. It then attempts to reduce the length of the resulting scrap list by combining adjacent scraps into a single scrap, possibly intercalating additional translations, which may include indent, outdent, and force instructions. The scraps are combined according to one of many *reduction rules*. WEAVE decides which adjacent scraps are eligible to be reduced based only on the categories of the scraps and a knowledge of the reduction rules. The reduction rules are the productions of the *prettyprinting grammar*. WEAVE's reductions of scraps are like the reductions done in bottom-up parsing.

For example, suppose that we want statements to be separated by line breaks. If we can guarantee that any scrap representing a statement has category stmt, it will be enough to specify the reduction rule

```
stmt ⟨force⟩ stmt ⟶ stmt
```

which says "two adjacent stmt scraps may be reduced to a single stmt scrap by intercalating a forced line break between them."

So we tell WEAVE how to prettyprint a language by telling how to assign a category to each token and how to combine scraps. Here is another example: the language of C expressions. Let math be the category of expressions, binop be the category of binary infix operators, and unop be the category of both unary prefix and unary postfix operators. Here are some sample tokens:

```
token identifier category math
token + category binop
token - category binop
token = category binop translation
                              ⟨"\\leftarrow"⟩
token == translation ⟨"\\equiv"⟩
                                category binop
token ( category open
token ) category close
```

Notice we print the $\boxed{=}$-token (assignment) as ←, whereas we print the $\boxed{==}$ token (comparison) as ≡. This makes it a bit easier for us to see when a programmer has mistakenly used $\boxed{=}$ instead of $\boxed{==}$.

The prettyprinting grammar for C expressions is:

```
math binop math ⟶ math
math unop ⟶ math
unop math ⟶ math
open math close ⟶ math
```

Using this grammar, WEAVE can take a long expression consisting of many scraps, and reduce it all to a single scrap of category math.

What about an operator like "*", which is both binary infix and unary prefix? This does the job:

```
token * category unorbinop
unorbinop math ⟶ math
math unorbinop math ⟶ math
```

There is a mechanism for assigning categories and translations to reserved words as well as to tokens, using slightly different syntax.

To give an idea of the complexity of the grammars, the grammar describing AWK uses 24 categories in 39 productions. The Ada grammar uses 40 categories in 65 productions, and the C grammar uses 54 categories in 129 productions.

SPIDER-generated versions of TANGLE and WEAVE differ subtly from the originals written by Donald Knuth. The most important difference is that SPIDER-generated WEB is not self-contained: where Knuth's Pascal WEB required only a Pascal compiler to bring up, SPIDER would need a C compiler and an AWK interpreter to generate a Pascal WEB, and a Pascal compiler for the resulting WEB to be of any use. Other differences are minor; for example, Knuth's TANGLE does arithmetic on constants at TANGLE time, but SPIDER-generated TANGLEs do not. Knuth's TANGLE provides three different kinds of macros, but none with more than one parameter; SPIDER-generated TANGLEs provide only one kind of macro, but macros of that kind may have from zero to thirty-two parameters.

SPIDER is a WEB generator, akin to parser generators. Both read formal descriptions of some part of a programming language, and both produce code that processes programs written in that language. Since both produce code that is part of the "compiler," using them does not introduce any extra steps into the processing of user programs. SPIDER itself is a large AWK script, written as a WEB program. `spider.web` is about 2600 lines long; about a third of these are comments.

The major cost of using SPIDER is the cost of learning yet another language. Learning this language is supposed to substitute for learning how to modify WEB, so it is probably not an exorbitant cost. Some other limitations are the need for a C compiler and an AWK interpreter, and the need to use a lowest-common-denominator lexical analyzer.

The major benefit of using SPIDER is the ease with which new WEBs can be built. The SPIDER description of a language is much smaller than the WEB implementation generated from that description, and SPIDER descriptions of similar languages are similar. Using SPIDER one can build a WEB without understanding the details of WEB's implementation, and one can easily adjust that WEB to change as a language definition changes.

SPIDER should make one literate programming tool, WEB, available to a much larger audience. I hope that, by separating the language-independent parts of WEAVE and TANGLE, SPIDER will encourage us not just to think about what the essence of tangling and weaving is, but also about what the essence of literate programming is.

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REFERENCES
1. Bentley, J.L. Programming pearls. *Commun. ACM 29*, 5 (May 1986), 364–368; 29, 6 (June 1986), 471–483.
2. Knuth, D.E. Literate programming. *The Computer Journal 27*, 2 (May 1984), 97–111.
3. Levy, S. WEB adapted to C, another approach. *TUGBoat 8*, 1 (Apr. 1987), 12–13.
4. Oppen, D. Prettyprinting. *ACM Trans. Program. Lang. Syst.* 2, 4 (Oct. 1980), 465–483.
5. Ramsey, N. Developing formally verified Ada programs. In *Proceedings of the Fifth International Workshop on Software Specification and Design*. (May 1989), pp. 257–265.
6. Van Wyk, C.J. Literate programming. *Commun. ACM 30*, 7 (July 1987), 593–599; *30*, 12 (Dec. 1987), 1000–1010.

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