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ADDING LANGUAGES TO GAME ENGINES

OK, I'll admit it. I'm a lazy programmer. Whenever I can get away with it, I love to get other people to do my job for me. And as a programmer focusing on gameplay and simulation, life keeps getting more and more complex. Just as the things we used to toil away at for hours – sound mixing, 3D rendering, interrupt processing – are getting easier and easier, simulation programming is getting harder and harder. Now that we have DirectSound and DirectDraw, when can we expect DirectGameplay?

I can remember a time not long ago when bits were the solution for everything. Back then, when a designer

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wanted some cool new feature, the solution was to write some code, find the next free bit in the CoolEffectsFlags bit vector, and recompile. Once the designer enabled the bit, the new feature emerged, ready for action. But lately, I've run out of bits.

The problem is, users are demanding more interactivity and unpredictability from their games. They aren't satisfied with 10 types of weapons when your competitor has 20. Moving platforms aren't sufficient if some other game has rotating platforms. So what's a lazy programmer to do?

Scripting languages have been an integral part of games for many years. Long before action games ran out of bits, adventure game authors recognized the need for scripting to cope with the massive number of possible interactions in their worlds. SCUMM (Story Creation Utility for Maniac Mansion), one of the original adventure game languages, has survived virtually intact until the present day, and is still used for games such as MONKEY ISLAND 3. As other game genres such as action, simulation, and strategy become more complex, they too are incorporating scripting systems.

The best way to stay competitive in the race for bigger and better games and game engines is to keep the engine as flexible, expandable, and robust as possible. An internal scripting language allows you to create a separate, crash-proof environment inside your game engine. This protected virtual machine executes the complex and frequently changing gameplay code, protected from the "real" machine running the game engine. By partitioning the code in this way, you significantly reduce the complexity of the core engine, resulting in fewer bugs and a more robust game. And since a language system is far more flexible than a collection of "canned" effects, your engine will be able to do more interesting things, even things you didn't originally anticipate.

Using a script language allows the engine programmers to focus on what is important to them — refining and optimizing the core technology of the game — while the game designers can handle the gameplay details. If the language is simple and well-designed, nonprogrammers can implement their designs directly in the script language without endangering the core engine code or involving the engine programmers. And since programmer time on a project is usually limited, recruiting designers as scriptwriters allows more of the original design to be realized, resulting in a more interesting final game. In fact, most designers jump at the opportunity to directly implement their ideas in script, even when it requires learning a new language.

The Snowball Effect

Over three years ago, the original team developing DARK FORCES (the sequel, with which this article is concerned, is shown in Figure 1) took the unconventional step of implementing some of the important game systems using a special parsed opcode language called INF. INF (which, as far as anyone on the original team can recall, doesn't stand for anything) was used for simple tasks such as moving sectors and elevators around, tracking the mission goals, and generating new enemies. INF didn't require any complex parsing because the format was simple and direct — the script equivalent of assembly language. One of the design goals in creating the sequel was to expand and enhance the INF language, making it more powerful and user-friendly.

One of the main complaints from level designers on the original project was that INF required the use of a lot of specific flags and opcodes to enable various features. A common fixture near the designer's workstation was a stack of pages affectionately known as the "Zen and the art of INF." The first draft of a replacement INF retained its basic structure, but translated the numerical codes and flags into text so this "bible" would no longer be necessary.

One day, someone suggested that if the language was expanded slightly, it could take on the added responsibility of scripting the results of powerups, which were handled in-engine in the original game. Shortly after making these extensions, someone else suggested that it would be nice to add some simple math and conditional opcodes to the language, and these were also added. And so it went, for a period of weeks, as more and more systems were absorbed into the rapidly expanding snowball that was INF 2. It became

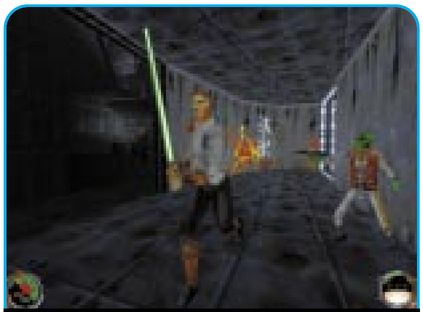


FIGURE 1. *JEDI KNIGHT: DARK FORCES 2*

clear that there was a need for a more flexible, all-purpose scripting language, and the snowball transformed into COG (which, true to the spirit of INF, also stands for nothing).

The Paths Not Taken

There were two primary goals for our language. First, the syntax should be powerful enough to offer complex loops, conditionals, and nesting, but familiar enough to be learned and used by a nonprogrammer. Second, the language must execute quickly enough to be useful in a real-time action game.

The first stop on any language shopping trip should be the catalog of free compilers at http://www.idiom.com/free-compilers/. Here, you can find dozens, if not hundreds, of existing scripting libraries that can be linked with your application. Each of these has various advantages and disadvantages. Some are very simple, such as LISP or FORTH, while others are quite complex, such as JAVA, Tcl, or LUA. Most of these languages are also completely free, the products of university or government research projects. The main disadvantage of using a ready-made language is performance. Many of the languages are at least partially interpreted, and many do not provide source code for the speed-critical execution kernel. If development time is the primary concern, or if your application is less dependent on fast execution, there are several excellent possibilities here.

Since execution speed was a primary concern, the possibility of expanding the game engine via dynamic link libraries (DLLs) instead of a script language was considered. The advantage in execution speed was clear, but using DLLs would have made it difficult for

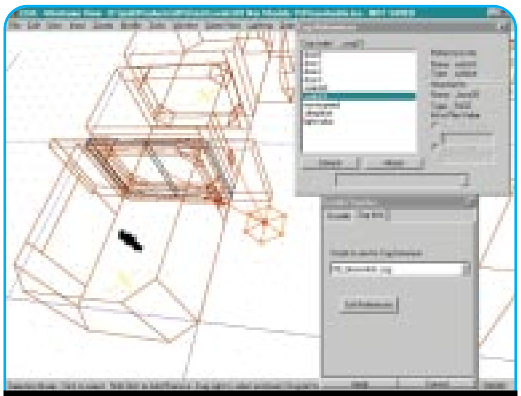


FIGURE 2. *JEDI KNIGHT's level editor LEIA.*

the game designers to use the language directly. Even though we felt comfortable introducing them to a limited C syntax and structure, we didn't want to take the further step of introducing them to the complexities of compilers, build environments, linking, and so on.

The final option, and the one that we eventually implemented, was to create a custom language execution kernel and parser. The speed issue was addressed by performing the important, time-critical operations in native code and exporting these support functions to the language system as COG library functions. These library functions could be augmented via DLLs, which gave the advantage of native-code speed with the ease-of-use of a custom language.

COG

The rest of this article focuses on the language problems and solutions that we used in creating the 3D action-adventure game JEDI KNIGHT: DARK FORCES 2 for the PC.

For the JEDI KNIGHT language, christened COG by the designers, we chose to implement a custom, compiled language that closely resembled the syntax of C. Using the C syntax as a starting point, we removed most of the obscure keywords and constructs and even removed some fairly major portions of the language dealing with function declarations and switch statements because they were significantly more complex to parse and execute than the rest of the language. We chose the C language as a starting point because of its familiarity and the wealth of books and tutorials available teach the language to nonprogrammers.

Just as in C, the syntax of the COG language is less important than library of functions at its disposal. The COG library provides about a hundred different functions to the author, ranging from environment manipulation commands to information queries. The author uses these functions to control the game environment while using the language syntax to provide branching and looping control.

The game engine executes the scripts in an event-driven manner. For example, when two objects collide with each other in the physics engine, any COG scripts linked to either object receive a "touched" event. This event contains parameters that allow the script to identify which objects were involved in the event and the type of event that occurred. Based on this information, the script can manipulate the game state in whatever manner it wishes, or can simply ignore the event. COG scripts can also contain links to each other, which enable them to exchange messages. These events make up the primary interface between the engine and the language system.

There are additional messages that are delivered directly to the COG script rather than through the objects to which a COG script is linked. A **startup** message is sent to each COG script at the start of a level, and a **respawn** message is sent each time the local player dies. Each game object also has the ability to set a repeating **pulse** event or a one-time **timer** event to be delivered at some point in the future. This allows a combination of event-driven and scheduled execution.

Because we removed the standard C syntax for function declarations from our language for simplicity, each script is organized much like a large switch statement. The entry points into the code for various types of events are labeled using the standard C label syntax. Also, because COG expanded on the standard C variable types with the addition of game-specific resource variables (sector, thing, sound, and so on), the script variables are declared in a special header. The level editor (LEIA, shown in Figure 2) also reads this header so it can display the symbols to the designers and allow them to view edit the symbol values.

Execution Model

Each script that exists in a level is linked to any number of other objects in that level: walls, enemies, doors, other COG scripts, and so on. COG scripts execute as separate virtual machines, each with its own variables, stack, and execution pointer. Because of this, COG scripts are protected from each other. One badly written COG script can only affect itself and the objects to which it is linked. Each script is a separate resource that is loaded along with a game level. A single script can be placed in a level multiple times, with each placement having its own isolated environment.

A sample COG script is shown in Listing 1. This script creates an animating neon sign which, if it is damaged, will explode in a shower of sparks. Symbols not marked local can be modified directly in level editor tool. The

TABLE 1. *Sample COG event messages.*

Message	Description
Touched	An object or surface was touched by another object. References to both collision participants can be retrieved.
Entered	For sectors, called each time a new object enters the sector
Damaged	Called whenever the object would take damage from weapons or explosions. References to the cause of the damage and the type of damage are provided to the handler.
Created	Called on a new object when it if first created
Killed	Called when the object is about to be removed from the game
Crossed	Called for an adjoin plane whenever an object crosses it
Arrived	Called when a moving object reaches its destination
Timer	A timer event set by the script has expired
Sighted	An object is seen by the player for the first time

LISTING 1. *Sample COG script.*

```
# 00_neonsign.cog
#
# this cog will cycle through frames 0-(lastFrame-1), at framerate fps
# if damaged, it will go to frame lastFrame and stop, create sparks and sound

symbols
            message     startup
            message     damaged

            surface     sign                                    mask=0x448
            float                           fps=2.0             desc=speed of anim
            template    sparks=+sparks      desc=created when shot
            sound                           exp_sound           desc=played when shot
end

code
startup:
            // Start the animation looping but skipping the first 2 frames
            SurfaceAnim(sign, fps, 0x5);
            return;

damaged:
            if (GetWallCel(sign) == 0)
                        return;

            StopSurfaceAnim(sign);

            if (exp_sound)
                        PlaySoundPos(exp_sound, SurfaceCenter(sign), 1.0, -1, -1, 0);

            SetWallCel(sign, 0);
            CreateThing(sparks, GetSourceRef());
            return;
end
```

`desc=` field tells the editor what descriptive string to display when the designer is editing that variable.

Access Control

One important decision made with COG was to disallow direct access to internal engine variables and structures from the scripts. If a COG script wishes to examine or modify these internal variables, it can do so only via library function calls. This is an important step in making the language crash-resistant. If a COG script could directly manipulate variables in the engine, there would be nothing to prevent badly written or out-of-date scripts from wreaking havoc with other systems. By requiring the use of access functions, any amount of validity checking and network synchronization can be added without affecting the scripts themselves. This requires a little extra work for the language programmer, since more functions will have to be written, but it pays off in terms of code stability down the road.

The COG library functions are actually just C function pointers that are visible to the COG scripts as global symbols. When the execution kernel encounters a call to one of these functions, it jumps to the native C code. The C code then calls language support functions to retrieve its arguments from the stack and return the results of the call back to the language. Since the functions are in native code, they execute significantly faster than the script language itself. For this reason, frequently performed tasks are written in C and called as library functions. Table 2 gives examples of the types of functions contained in the COG function library.

Compilation

For the script code to be executed as efficiently as possible, it must be translated from the text source code to some internal representation that can be executed quickly. This process is called compilation, and the compilation of our language source is just a simplified version of what a normal compiler does to translate source code into native machine code. Instead of producing Intel or PowerPC opcodes, we produce our own virtual machine opcodes.

The language's virtual machine is a type of simulated CPU. For COG, we use a very simple model called a "stack machine." The stack machine gets its name from the fact that it performs all operations on a single stack. Anyone who has used an HP calculator will be familiar with the system. To add 5 and 10 on a stack machine, we would execute the opcodes

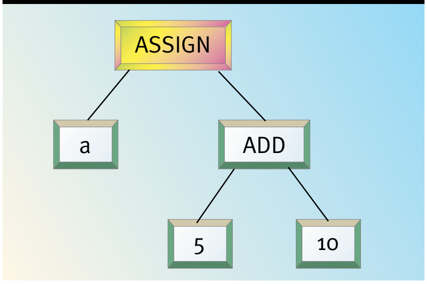
```
Push 5
Push 10
Add
```

The stack machine contains very few opcodes, making it simple to implement and efficient when executing. Our goal is to quickly compile the source code written by the designer into our custom stack machine opcodes. Any valid sequence of commands in the COG language can be broken down into these

TABLE 2. *Sample COG library functions.*

Function	Description
StartAnim	Starts a page-flipping animation on a surface, sprite, or material
SectorThrust	Sets a thrust force for a sector
SetThingFlags	Sets bits in the thing's flag field
GetCurSector	Retrieves a reference to the sector a thing is currently contained in
CreateThing	Creates a new thing in the world
PlaySoundThing	Plays a sound spatially linked to the position of a thing
SetTimer	Sets a timer event for some future time
PlaySong	Plays a redbook music track
AISetTarget	Sets the target an AI object is attacking
AISetMode	Sets the mode of an AI object
MoveToFrame	Moves an object along a path to a specified position, used for moving doors, elevators, and so on

FIGURE 3. *Simple parse tree.*



basic operations, just as normal C code can be translated into the basic opcodes of your target CPU.

The COG compilation process happens in two steps. First, the code is broken down into its relevant language parts or tokens. COG tokens, just like C tokens, include all the language keywords (**if**, **then**, **else**) and operators (**+**, *****, &&). This stage of compilation is called lexical analysis or "lexing."

The second part of the compilation process involves taking the tokens from the "lexer" and assembling them into the syntax of the language. This is a more complicated process and is based on a formal specification of the language. The formal language specification defines in detail every possible expression that can be constructed with the language in a recursive format. It seems a little awkward at first, but becomes clear after some study. For example, the formal definition of an addition operation is

```
(additionExpression) : (expression) +
          (expression).
```

This defines an addition expression as two separate expressions separated by the "+" token. Since the addition expression is just one of the many possible definitions of the more general "expression," you can see how the processing the language quickly becomes a recursive problem. The lowest level of the specification — the "atoms" of the language, so to speak — are the constants and variables.

Since parsing the language is a recursive problem, we build a tree to represent the structure of the source code as it is being parsed. As each language construct is recognized, we add it to the tree. The type of expression we recognize determines the structure of that small part of the parse tree. When the tree for the entire function or source file is completed, we can simply traverse the tree in depth-first order and create the stack machine opcodes that we will later execute.

Returning to the simple addition example, our completed parser should construct the parse tree in Figure 3 for the source code **a=5+10;**

Because the language parsing is done recursively, the parse automatically handles normally tricky problems such as nesting and order of operations automatically. When the code **a=(5*2) + (a^2)** is parsed, the parser will recognize the subexpressions **5*2** and **a^2** first, and will pass the completed parse trees for these subexpressions to the code that creates the tree for the addition expression, resulting in a single tree for the entire expression.

The most complex expressions to parse are those involving loops and branches. These expressions require the generation of code using the branching opcodes, which means the parser must know the address to which it needs to jump. For example, to generate code for **if <condition> then <expression>**, the parser must know the address of the code address immediately following the **expression** subtree in order to generate a **GOFALSE** opcode to jump to this code if the conditional fails.

The trick to generating code for these branches is to generate code in two passes rather than one. The first pass, known as "backpatching," doesn't generate code, but simply counts the number of opcodes produced by each node of the parse tree. During this first pass, as each node is encountered while traversing the tree, the code address (index into the array of opcodes) is noted both before the opcodes from the node are added and after. After this first pass, each node now contains the code address just prior to and just following its own subtree's code. Now, on the second pass, the branches that were previously expressed in terms of **end of node <expression>** can be expressed as actual code addresses.

This is obviously a complex topic that we have examined only superficially. For more information on the theory behind parsing and the use of parse trees, the standard text is *Compilers: Principles, Techniques, and Tools* by Aho, Sethi, and Ullman.

The Silver Lining

Fortunately, it's not nearly as difficult as it sounds. Writing compilers is an old and well-established science. There are numerous of tools to simplify the creation of an efficient parser. In fact, this is one of those rare computer science problems that can safely be called "solved." The parsers generated by the compiler tools are consistently more efficient than what a human programmer could create because they deal with the parsing problem as a complex state machine. Even a simple language specification results in a state machine with so many possible states and transitions that a mere mortal programmer would be driven (or bored) to tears.

One free tool called "lex" is commonly used to generate C code implementing a lexical analyzer based on a user-supplied grammar specification. Since COG follows the C syntax, we modified an existing free C lex specification file from the Internet to create the lexer for the language.This ANSI-C lex specification can be found at http://www.cis.ufl.edu/~fryman/c.lex.spec.html.

TABLE 3. *Sample COG "stack machine opcodes.*

Opcode	Explanation
Push	Pushes a constant of symbol onto the execution stack
Pop	Pops the next value off the execution stack
GoFalse	Pops the top stack value and jumps to a new execution address if it is equal to 0
Go	Jumps to a new execution address
Stop	Stops execution
CallFunc	Pops the next value from the stack as a C function pointer and calls that function
Add	Pops the next two values from the stack, adds them, and pushes the result onto the stack
Assign	Pops the next two values off the stack, and assigns the value of the second value to the variable contained in the first

Similarly, another free tool called yacc (for Yet Another Compiler Compiler) can be used to transform a formal language specification into a C module. yacc and lex are designed to work together, so the resulting source code modules can simply be compiled and linked to create a fully functional parser. For COG, the same Internet site yielded a full C grammar specification for yacc, which was trimmed down to our needs and used to create the parser module. The URL for the ANSI-C yacc framework is http://www.cis.ufl.edu/~fryman/c.yacc.spec.html.

The resulting compiler has all the tools needed to break down the source code and recognize the language syntax, but it is still your responsibility to write the "hooks" that tell the compiler what actions to perform when the language is recognized. These hooks are what enable us to build our parse tree. By inserting this parse-tree building code, along with some code to manage the allocation and definition of the language variables, we were able to create a C-subset compiler in about a day.

Both lex and yacc are available in many forms and permutations; some free, some not. And while lex and yacc are the most common compiler tools, there are several others including full-featured language construction environments such as VisualParse++ by Sandstone Technologies. Whichever tool you use, the end product is the same — a stream of opcodes that can be executed quickly and efficiently by your virtual machine. Check out the free compiler catalog mentioned earlier for links to these and other useful language tools.

For more specific information on the lex and yacc tools, check out *Lex & Yacc* by Levine, Mason, and Brown in the O'Reilly & Associates UNIX Programming Series.

Putting It All Together

The finished parser, developed using the free tools mentioned above, is incredibly fast and flexible. In a typical JEDI KNIGHT level, there are about 50 different script files that need to be parsed and compiled into our opcode format. On a typical machine, all these scripts compile in well under one second. For this reason, we decided against using an external compiler and instead load the source directly when loading the level. This improves the turnaround time for testing script changes, since the designer can quickly edit the script code and reload the level to test changes.

One aspect of the scripting system that proved critical for our project was the integration of the scripts and the level editor. The level editor not only allows the designer to place scripts into a level, but also ensures that the various links in the script are correctly assigned and remain correctly linked as the level changes. When a designer places a script resource into a level, the editor scans the header of the script to determine what variables can be assigned externally and places a graphic representation of the script resource in the level. This icon has a spatial location in the level, although its location isn't important to the script. Typically, designers place scripts near the objects to which they link. Once the script is placed, the designer can bring up the property dialog for that script and view and change its assignments. If the script contains links to other things or surfaces, these are assigned by clicking on the correct type of item in the level and clicking a link button. Links between COG scripts and world entities are shown graphically in the editor by connecting them with lines. If the script contains resources such as sounds or bitmaps, a pull-down menu displays the possible choices.

Another area that should be addressed is debugging. There are two main issues here — debugging syntax parsing problems, which normally is solved by adding better error-reporting and recovery code into the parser, and run-time debugging, which can take many forms. One possible method of run-time debugging of scripts is to allow the user to trace execution. In JEDI KNIGHT, the designer can enter a console command to turn tracing on for a specific COG script, which will cause that script to output debugging information each time it executes. A more complete system would allow for single stepping through script opcodes. The real challenge, which has not yet been addressed in COG, is to allow for "source-level" debugging, where users can watch their variables change and see the script step through the original code. This feature may seem like a lot of unnecessary work, but it was the top request made by our designers at the end of the project.

"How'd You Do That?"

Implementing and maintaining the language was a significant task, and it took the work of several programmers to keep up with the designer demand for new COG library functions. But when compared to the time that would have been spent writing specific systems for things such as mission objectives, inventory management, powerup sequencing, puzzles, doors, elevators, and so on, using a language was a definite win.

After a period of uncertainty, most of the designers started becoming comfortable with the language and began to experiment with it. Strangely enough, the key here was trust. Once the designers were convinced that the language was safe enough that they wouldn't crash the entire game by writing a bad script, they began to try more interesting things with the language. After some time, they effectively took over the majority of the gameplay programming for JEDI, as planned. Some of the designers were so enthusiastic about the use of scripting that they later took evening classes in C and C++ programming, and at least one designer is moving into programming full-time. Even those designers who preferred not to work closely with the language found it easy to place and link existing scripts written by other designers into their own levels.

Perhaps the most important effect the language had on JEDI is illustrated by an example. One day, a large group was gathered around the desk of one of the level designers on the project. It seems he had created a puzzle script where the user hits a switch on the wall causing the water level in the room to rise slowly, carrying the player along to the top of the room. It seems simple, except we had just recently decided not to support moving water levels in the game. No one, including those who had worked on the engine and the language, could figure out how he did it.

I still don't know. I'm too lazy to find out. ■

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