A *JAVA* FRAMEWORK AND DOMAIN-SPECIFIC LANGUAGE FOR MANIPULATING SOUNDS

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For my wife, Maria Inês.

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Abstract of Thesis Presented to the Graduate School
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Abstract goes here.

CHAPTER 1
LITERATURE REVIEW

Arguably the first notable attempt to design a programming language with an explicit intent of processing sounds and making music was that of *Music I*, created in 1957 by Max Mathews. The language was indented to run on an IBM 704 computer, located at the IBM headquarters in New York City. The programs created there were recorded on digital magnetic tape, then converted to analog at Bell Labs, where Mathews spent most of his career as an electrical engineer. *Music I* was capable of generating a single waveform, namely a triangle, as well as assigning duration, pitch, amplitude, and the same value for decay and release time. *Music II* followed a year later, taking advantage of the much more efficient IBM 7094 to produce up to four independent voices chosen from 16 waveforms. With *Music III*, Mathews introduced in 1960 the concept of a *unit generator*, which consisted of small building blocks of software that allowed composers to make use of the language with a lot less effort and required background. In 1963, *Music IV* introduced the use of macros, which had just been invented, although the programming was still done in assembly language, hence all implementations of the program remained machine-dependent. With the increasing popularity of Fortran, Mathews designed *Music V* with the intent of making it machine-independent, at least in part, since the unit generators' inner loops were still programmed in machine language. The reason for that is the burden these loops imposed on the computer [1, 15-17].

1.1 Software Synthesis Languages

Since Mathews' early work, much progress has been made, and a myriad of new programming languages that support sound processing, as well as domain-specific languages whose sole purpose is to process sounds or musical events, have surfaced. In [2], we see an attempt to classify these languages according to the specific aspect of sound processing they perform best. The first broad category described is that of *software synthesis languages*, which compute samples in non-real-time, and are implemented by use of a

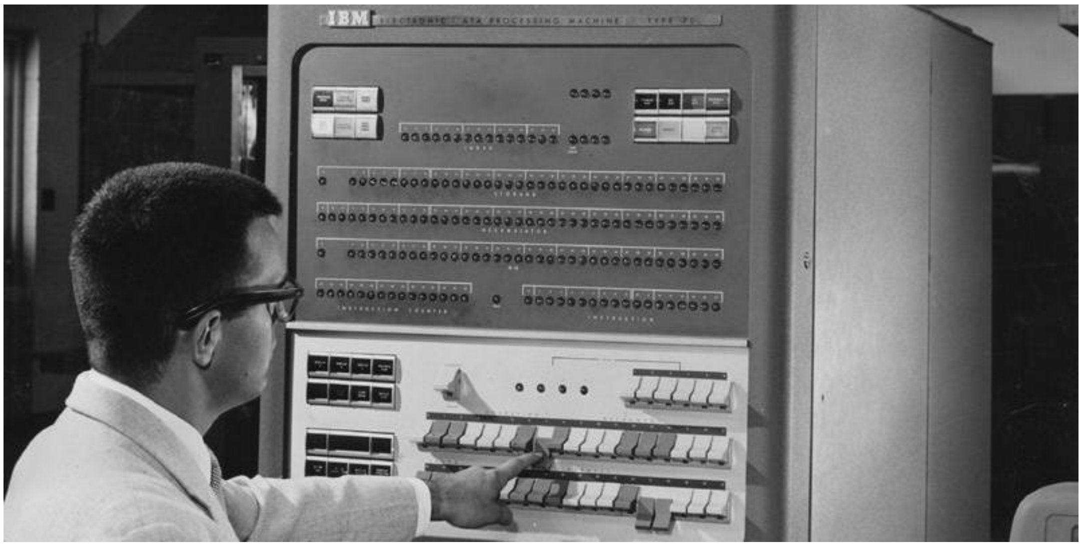


Figure 1-1. The IBM 704 computer.

text editor with a general purpose computer. The *Music N* family of languages consist of software synthesis languages. A characteristic common to all software synthesis languages is that if a toolkit approach to sound synthesis, whereby using the toolkit is straightforward, however customizing it to fulfill particular needs often require knowledge of the programming language in which the toolkit was implemented. This approach provides great flexibility, but at the expense of a much steeper learning curve. Another aspect of software synthesis languages is that they can support an arbitrary number of voices, and the time complexity of the algorithms used only influences the processing time, not the ability to process sound at all, as we see with real-time implementations. As a result of being non-real-time, software synthesis languages usually lack controls that are gestural in nature. Yet, software synthesis languages are capable of processing sounds with a very fine numerical detail, although this usually translates to more detailed, hence verbose code. Software synthesis languages, or non-real-time features of a more general-purpose language, are sometimes required to realize specific musical ideas and sound-processing applications that are impossible to realize in real time [2, 783-787].

Within the category of software synthesis languages, we can further classify those that are *unit generator languages*. This is exactly the paradigm originally introduced by *Music III*. In them, we usually have a separation between an orchestra section, and a score section, often given by different files and sub-languages. A unit generator is more often than not a built-in feature of the language. Unit generators can generate or transform buffers of audio data, as well as deal with how the language interacts with the hardware, that is, provide sound input, output, or print statements to the console. Even though one can usually define unit generators in terms of the language itself, the common practice is to define them as part of the language implementation itself. Another characteristic of unit generators is that they are designed to take as input arguments the outputs of other unit generators, thus creating a signal flow. This is implemented by keeping data arrays in memory which are shared by more than one UG procedure by reference. The score sub-language usually consists of a series of statements that call the routines defined by the orchestra sub-language in sequential order, often without making use of control statements. Another important aspect of the score sub-language is that it defines function lookup tables, which are mainly used to generate waveforms and envelopes. When *Music N* languages became machine-independent, function generating routines remained machine-specific for a period of time, due to performance concerns. On the other hand, the orchestra sub-language is where the signal processing routines are defined. These routines are usually called instruments, and basically consist of new scopes of code where built-in functions are dove-tailed, ultimately to a unit generator that outputs sound or a sound file [2, 787-794].

The compilation process in *Music N* languages consists usually of three passes. The first pass is a preprocessor, which optimizes the score that will be fed into the subsequent passes. The second pass simply sorts all function and instrument statements into chronological order. The third pass then executes each statement in order, either by filling up tables, or by calling the instrument routines defined in the orchestra. The third pass used to be the performance bottleneck in these language implementations, and during the transition between assembly and Fortran implementations, these were the parts that remained machine-specific. Initially, the output of the third pass consisted of a sound file, but eventually this part of the compilation process was adapted to generate real-time output. At that point, defining specific times for computing function tables became somewhat irrelevant.

In some software synthesis languages, the compiler offers hooks in the first two passes so that users can define their own sound-processing subroutines. In any cases, these extensions to the language were given in an altogether different language. With *Common Lisp Music*, for example, one could define the data structures and control flow in terms of Lisp itself, whereas *MUS10* supported the same features by accepting Algol code. In *Csound*, one can still define control statements in the score using Python. Until *Music IV* and its derivatives, compilation was sample-oriented. As an optimization, *Music V* introduced the idea of computing samples in blocks, where audio samples maintained their time resolution, but control statements could be computed only once per block. Of course, if the block size is one, than we compute control values for each sample, as in the sample-oriented paradigm. Instead of defining a block size, however, one defines a control rate, which is simply the sampling rate times the reciprocal of the block size. Hence a control rate that equals the sampling rate would indicate a block size of one. With *Cmusic*, for instance, we specify the block size directly, a notion that is consistent with the current practice of specifying a vector size in real-time implementations. The idea of determining events in the language that could be computed at different rates required some sort of type declaration. In *Csound*, these are given by naming conventions: variables whose names start with the character ‘a’ are audio-rate variables, ‘k’ means control rate, and ‘i’-variables values are computed only once per statement. *Csound* also utilizes naming conventions to determine scopes, with the character ‘g’ indicating whether a variable is global [2, 799-802].

1.2 Real-Time Synthesis Control Languages

Some of the very first notable attempts to control the real-time synthesis hardware were made at the *Institut de Recherche et Coordination Acoustique/Musique* in the late seventies. Many of these early attempts made use of programming languages to drive the sound synthesis being carried out by a dedicated DSP. At first, most implementations relied on the concept of a *fixed-function* hardware, which required significantly simpler software implementations, as the latter served mostly to control a circuit that had an immutable design and function. An example of such fixed-function implementations would be an early frequency-modulation synthesized, which contained a dedicated DSP for FM-synthesis, and whose software implementation would only go as far as controlling the parameters thereof. Often, the software would control a chain of interconnected dedicated DSP’s, which would in turn produce envelopes, filters, and oscillators. The idea of controlling parameters through software, while delegating all signal processing to hardware, soon expanded beyond the control of synthesis parameters, and into the sequencing of musical events, like in the New England Digital Synclavier. Gradually, these commercial products began to offer the possibility of changing how exactly this components were interconnected, what is called a *variable-function* DSP hardware. Interconnecting these components through software became commonly called *patching*, as an analogy to analog synthesizers. The idea of patching brought more flexibility, but imposed a steeper learning curve to musicians. Eventually, these dedicated DSP’s were substituted by general-purpose computers, wherein the entire chain of signal processing would be accomplished via software [2, 802-804].

Commonly in a fixed-function implementation there is some sort of front panel with a small LCD, along with buttons and knobs to manage user input. In the case of a keyboard instrument, there is naturally a keyboard to manage this interaction, as well. The purpose of the embedded software is then to communicate user input to an embedded system which contains a microprocessor and does the actual audio signal processing, memory management, and audio input/output. All software is installed in some read-only memory, including the operating system. With the creation of the *Musical Instrument Digital Interface* standard in 1983, which was promptly absorbed my most commercial brands, the issue of controlling sound synthesis hardware transcended the interaction with keys, buttons, and sliders, and became a matter of software programming, as one could easily communicate with dedicated hardware, by means of a serial interface, MIDI messages containing discrete note data, continuous controller messages, discrete program change messages, as well as system-exclusive messages. As a trend, many MIDI libraries were written at the time for general-purpose programming languages such as APL, Basic, C, Pascal, Hypertalk, Forth, and Lisp. In addition, most descendants of the *Music N* family of languages began to also support MIDI messages as a way to control dedicated hardware [2, 804-805].

The implementation of a software application to control variable-function DSP hardware is no mundane task, as it requires knowledge of digital signal processing, in addition to programming in a relatively low level language. Dealing with issues of performance, memory management, let alone the mathematics required to process buffers of audio samples, often imposes an unsurmountable burden to musicians. Many solutions were invented in order to work around this difficulties, including the use of graphic elements and controllers, but ultimately it was the concept of a unit generator, borrowed from software synthesis languages, that most influenced the creation of higher-level abstractions that were more suitable for musicians. This is notably the case of the *4CED* language, which was developed at IRCAM in 1980, and owed greatly to *Music IV* and *Music V*. The resemblance extended as far as to comprise a separate orchestra sub-language for patching unit generators, a score sub-language, and a third command sub-language for controlling effects in real-time, as well as to link both orchestra and score to external input devices such as buttons and potentiometers. The hardware these languages drove was IRCAM's 4C synthesizer. The result of nearly a decade of research at IRCAM culminated in *Max*, a visual programming language that remains to this day one of the most important real-time tools for musicians. *Max*, which will later be discussed in more detail, eventually transcended its hardware DSP and implemented itself in C the sound-generating routines. But that was not until the 2000's, ten years after it became a commercial software application, independent of IRCAM [2, 805-806].

Example 1.2.1. *[2, 809]* Music 1000 *is a descendant of the* Music N *family of languages that was designed to drive the Digital Music Systems DMX1000 signal processing computer, in which we can clearly observe the unit-generator concept in action. In Listing 1.1, a* fnctn *statement assigns to variable* func1 *an array of 512 samples using a* fourier *series of exactly one harmonically-related sine, whose (trivial) sum is* normal*-ized. The amplitude of 1000 is then meaningless, but a required argument. In fact,* func1 *takes a variable number of arguments, where for each harmonic partial, the user specifies a relative amplitude. The block that follows defines an instrument, in which the unit generator* oscil *takes as arguments the output of three other unit generators, which are respectively the wavetable previously computed, as well as amplitude and frequency parameters, whose values are in turn captured by two knobs attached to the machine. The knobs produce values between 0 and 1, and the subsequent arguments to* kscale *are scaling parameters. Finally,* out *is a unit generator that connects the output of* oscil *to the digital-to-analog converter.*

Listing 1.1. *Music 1000* algorithm that produces a sine wave.

```
fnctn func1, 512, fourier, normal, 1, 1000
instr 1
  kscale amp, knob1, 0, 10000
  kscale freq, knob2, 20, 2000
  oscil x8, #func1, amp, freq
  out x8
endin
```

1.3 Music Composition Languages

Between the 1960's and the 1990's, many programming languages were devised to aid music composition. As a noticeable trend, one can define two categories among those languages, namely those that are *score input languages*, and those that are *procedural languages*. The main difference between the two categories is that, in the former, some representation of a musical composition is already at hand, hence score input languages provide a way to encode that information. This could be a score, a MIDI note list, or even some graphical representation of music. In the latter category, the language provides, or helps define procedures that are used to generate musical material, a practice that is often called *algorithmic* music composition. One outstanding characteristic of score input languages is how verbose and complex they can become, depending on the musical material they are trying to represent. This difficulty influenced the devising of many alternatives to textual programming languages, such as the use of scanners in the late 1990's by Neuratron's *PhotoScore*, an implementation which was predicted by composer Milton Babbitt as early as in 1965. Before the advent of MIDI, however, programming languages were indeed the user interface technology of choice, or lack thereof, to design applications meant for analyzing, synthesizing, and printing musical scores. With the widespread adoption of the MIDI standard in the mid-1980's, whereby one can input note events by performing on a MIDI instrument, combined with the advancements in graphical user interfaces of the mid-1990's, the creation and maintenance of score input languages has faced a huge decline. What is even worse, the paradigm of a musical score is itself inadequate for computer music synthesis, in that a score is more often than not a very incomplete representation of a musical piece, often omitting a great deal of information. It is the job of a musical performer to provide that missing information. In this sense, *procedural languages* are much better suited for computer performance, but that comes at the cost of replacing the score paradigm altogether [2, 811-813].

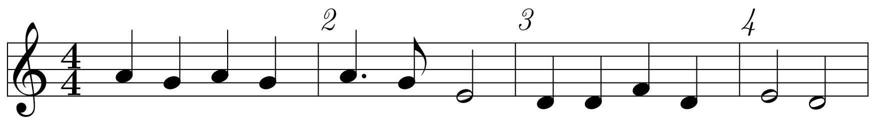
In 2018, a few *score input languages* remain, despite the vast predominance of graphical user interfaces as a means to input notes to a score. *MusiXTex* is a surviving example that compiles to LaTeX, which in turn compiles to PDF documents. It was created in 1991 by Daniel Taupin. The language has such unwieldy syntax, that often a preprocessor is required for more complex scores. One famous such processors is *PMX*, a *Fortran* tool written by Don Simons in the late 1990's. Another was *MPP*, which stands for MusiXTex Preprocessor, created by Han-Wen Nienhuys and Jan Nieuwenhuizen in 1996, and which eventually became *LilyPond*, arguably the most complete surviving score input language today. *LilyPond* has a much simpler syntax than that of *MusiXTex*, however not nearly as simple as *ABC* music notation, a language that much resembles *Musica* and which is traditionally used in music education contexts. A package written by Guido Gonzato is available in LaTeXwhich can produce simple scores in *ABC* notation. Its simplicity comes, however, at the expense of incompleteness. Finally, it is worthwhile to mention a music-notation specific standard that has emerged in the mid-2000's, namely the *MusicXML* standard. Heavily influenced by the industry, it was initially meant as an object model to translate scores between commercial applications where the score input method was primarily graphical, and whose underlying implementation was naturally object-oriented. *MusicXML* is extremely verbose, and borderline human-readable. It is, however, very complete, to the point of dictating what features an object-oriented implementation should comprise in order to be aligned with the industry standards. In recent years, many rumors have surfaced to make *MusicXML* an Internet standard, such as that of *Scalable Vector Graphics*, however nothing concrete has been established.

Listing 1.2. *Musica* algorithm that creates a simple melodic line.

```
4'AGAG / 4.A8G2E / 4DDFD / 2ED
```

Example 1.3.1. *[2, 812]* Musica *was developed at the Centro di Sonologia Computazionale in Padua, Italy, and is particularly interesting in its interpreter compiles programs into* Music V *note statements. In the snippet above, all numbers indicate note*

Figure 1-2. Typesetting music with *MusiXTex*.



duration, that is, 4 is a quarter-note, 8 is an eighth-note, and 2 is half-note, with dots indicating dotted durations. The letters indicate pitch, and the apostrophe indicates octave such that 'A $= 440Hz$*, and* "A $= 880Hz$*. Finally, the slash indicates a measure. The code below, on the other hand, shows an example of the very same musical material expressed in* MusiXTex. *One can immediately notice the difference in implementation by the sheer amount of code required to express basically the same symbols. In the code above, many commands, despite verbose, are quite self-explanatory. Some others, however, are not. The* `\qu` *command means a quarter-note with a stem pointing upward, whereas the* `\Notes` *command actually means how notes should be spaced. The more capital letters, the more spacing between the notes, that is,* `\NOTes` *is more spaced out than* `\NOtes`*. Finally, in addition to supporting the same apostrophes as* Musica *for defining octave,* MusiXTex *also supports other letters, as well as capitalizations thereof. In the example above, we have* h $= 440Hz$*, whereas* a $= 220Hz$*.*

Listing 1.3. *MusiXTex* algorithm whose output is shown in Fig. 1-2.

```
\begin{music}
  \generalmeter{\meterfrac44}
  \startextract
  \Notes \qu{h g h g} \en \bar
  \Notes \qup{h} \cu{g} \hu{e} \en \bar
  \Notes \qu{d d f d} \en \bar
  \Notes \hu{e d} \en
  \endextract
\end{music}
```

One of the greatest contributions of *procedural composition languages* to the field of music composition is arguably the concept of algorithmic composition, in particular when the realization of the musical algorithm is not restricted to human performers. In such circumstances, the composer is capable of exploring the full extent of musical ideas a computer can reproduce. Naturally, the composer must often trade off the ability to represent those ideas via a score, in which case the algorithm itself becomes the representation. If, on one hand, reading music from an algorithm is somewhat unfamiliar to most musicians, the representation is nonetheless formal, concise, and consistent. Furthermore, it lends itself to be analyzable a much larger apparatus of analytical techniques and visualization tools, hence is equally beneficial a representation to music theorists. A machine is capable of representing all sorts of timbres, metrics, and tunings that humans cannot, but it needs to be told exactly what to do. Unlike a human performer, who interprets the composer's intents, a purely electro-acoustic algorithmic composition must address a human audience without relying on a middle-man. Hence the programming language of choice becomes an invaluable tool for the composer. In addition to all that, another important aspect of algorithmic composition is how it is capable of transforming the decision-making process of a composer. Instead of making firm choices at the onset of a musical idea, a composer can *prototype* many possible outcomes of that idea before deciding. One example is assigning random numbers to certain parameters, this postponing the decision making until more structure has been added to the composition. In fact, this postponing may be final, thus an algorithmic composition may be situated within a whole spectrum of determinism. A fully stochastic piece fixes no parameter, as opposed to a fully deterministic composition. Some of the notable techniques of electro-acoustic music composition also include spatialization, where the emission of sounds through speakers positioned at specific spatial locations constitutes a major musical dimension in a composition; spectralism, where the spectral content of sounds are manipulated by an algorithm; processing sound sources in real time, very often capturing a live performance on stage; and sonification of data nor originally conceived as sound [2, 813].

1.4 Libraries

Many domain-specific languages that deal with sound synthesis, processing, and music composition are *extensible* in the sense that they provide a hook for code written in the implementation language to be executed in the context of the DSL. This feature can render a DLS a lot more flexible, at the expense of annulling the very purpose of the DSL, which can be a good trade-off if the latter's implementation is incomplete. An early example would be *Music V*, which could accept user-written subroutines in *Fortran*. *Music 4C* had its instruments written in *C*, and *Cscore* was a *C*-embedding of *Cmusic*. Other examples are *MPL*, which could accept routines written in *APL*, and *Pla*, whose first version was embedded in *Sail*, and whose second version was embedded in *Lisp*. In the particular case of *Lisp*, embeddings include *MIDI-LISP*, *FORMES*, *Esquisse*, *Lisp Kernel*, *Common Music*, *Symbolic Composer*, *Flavors Band*, and *Canon*. *Music Kit* was embedded in the object-oriented *Objective-C* [2, 814].

Besides domain-specific languages, a variety of libraries exist for general-purpose programming languages that also deal with aspects of sound synthesis, processing, and music composition. In languages like *Haskell*, these libraries may carry such syntactical weight, with so many specifically-defined symbols, that they do in fact resemble more a DSL that a library, even though such terming would not be technically correct.

CHAPTER 2
THEORETICAL FRAMEWORK

In this chapter, we present and discuss the tools and methodology utilized to build *Scandal*. We start discussing how to produce sound in the Java Runtime Environment, and particularly how it deals with real-time audio. We next give a formal presentation on how the domain-specific language was designed, and attempt to classify it among other programming languages and music-DSL's. Finally, we address the methodology involved in building its compiler, appending to the latter a short discussion on how a general-user interface was designed to provide an integrated development environment experience for the end user, as well as alternative command-line methods for compiling and running *Scandal* programs.

2.1 How *Scandal* Manages Sound

The JRE System Library provides a very convenient package of classes that handle the recording and reproduction of real-time audio, namely the `javax.sound.sampled` package. In it, we find two classes, `TargetDataLine` and `SourceDataLine`, that deal respectively with capturing audio data from the system's resources, and playing back buffers of audio data owned by the application. An instance of `SourceDataLine` provides a `write` method that takes three arguments: an array of bytes to written to a `Mixer` object, an integer offset, and an integer length. In *Scandal*, we do not specify a `Mixer` object, hence we make use of one provided by the `System`. There are two main aspects of the `write` method that need to be addressed. Firstly, it blocks the thread in which it lives until the given array of bytes has been written, from offset to length, to the `Mixer` its `SourceDataLine` contains; secondly, if nothing is done, it returns as it has no more data to write. In order to have real-time audio, one then needs to be constantly feeding this `write` method with audio samples, for as long as one wants continuous sound output, even if these buffers of audio samples contain only zeros, i.e., silence. It immediately follows that one must specify exactly how many samples are sent at a time, naturally with consequences to the system's performance. This parameter is commonly referred in the industry as the *vector size*. The trade-off is measured in terms of latency: a large a vector size helps slower systems perform better, or can allow more complex processing, or even increase polyphony. Latency, however, is bad for any live application, including the generation of MIDI notes, and the recording of live sound from a microphone. A good, low-compromise vector size is usually set to 512 samples, and normally these sizes will be powers of two. In order to specify the preferred vector size, as well as many other environment settings, *Scandal* refers to a static class named Settings, which contains a static property Settings.vectorSize.

The aforementioned two characteristics of the write method within a SourceDataLine are managed by *Scandal* by the class AudioFlow. In order to prevent write from prematurely returning, an instance of AudioFlow contains a boolean property named running, which is set to true for as long as real-time audio is desired. The fact that write blocks its thread, however, is managed by any class that contains itself an instance of AudioFlow as a property. The latter are in *Scandal* the implementors of the RealTimePerformer interface, which is a contract that contains four abstract methods: startFlow, stopFlow, getVector, and processMasterEffects. The role of the startFlow is to merely embed an AudioFlow within a new Thread object and start this new thread. This guarantees the thread that manages audio is different than the main Application thread, hence resolving the thread-blocking issue. Once a new Thread is started in *Java*, however, one cannot in general interrupt it. In order to stop the audio thread, we set the property running inside an AudioFlow to false via the stopFlow method, which causes the write method inside the AudioFlow to return. Hence one cannot resume an audio process in *Scandal* at this point, even though doing so is perfectly possible in *Java*. The reason for that is not that of a design choice, but rather the fact that the domain-specific language is at its infancy, and many important features that go beyond a proof-of-concept are yet to be implemented. The getBuffer method is called by the AudioFlow every time it needs to write another vector of audio samples. It is the responsibility then of any RealTimePerformer to timely compute the next Settings.vectorSize samples of audio data. Finally, the processMasterEffects routine is called from within getVector to further process the buffer of audio samples. This is usually done while the samples are still represented as floats, hence before converting them to raw bytes.

The constructor of an AudioFlow takes, in addition to a reference to a RealTimePerformer, a reference to an AudioFormat object. The latter is part of the javax.sound.sampled package and is how we ask the AudioSystem for a SourceDataLine. Instead of constructing AudioFormat objects, however, the Settings class contains static members Settings.mono and Settings.stereo that are instances of AudioFormat defining a mono and stereo format, respectively. In addition to a channel count argument, AudioFormat instances are constructed by specifying a sampling rate, and a bit depth (word length) for audio samples. Those are, too, static properties in the Settings class, namely Settings.samplingRate and Settings.bitDepth. Listing 2.1 gives the specifics of maintaining a SourceDataLine open inside an instance of AudioFlow. The latter implements, in turn, the Runnable interface, hence needs to override a run method. Inside this run method, we call the private play subroutine that is given below:

Listing 2.1. Writing buffers of audio data inside the play subroutine.

```
private void play() throws Exception {
  SourceDataLine sourceDataLine = AudioSystem.getSourceDataLine(format);
  sourceDataLine.open(format, Settings.vectorSize * Settings.bitDepth / 8);
  sourceDataLine.start();
  while (running) {
    ByteBuffer buffer = performer.getVector();
    sourceDataLine.write(buffer.array(), 0, buffer.position());
  }
  sourceDataLine.stop();
  sourceDataLine.close();
}
```

Inside the play subroutine, we acquire a SourceDataLine object from the AudioSystem with the specific format that the RealTimePerformer passed while constructing this AudioFlow. In order to open the data line, we need specify a buffer size in bytes, hence we multiply the vector size by the word length in bits, divided by eight, as there are eight bits per byte. We then start the data line and keep writing to it for as long as the RealTimePerformer maintains the running property inside its AudioFlow set to true. At each call to write, we ask the performer for a new vector. Filling the vector causes its position to advance until its length, hence the position method inside the ByteBuffer class will in fact return the length value we desire. The rest of the play subroutine simply releases resources before returning, at which point the audio thread is destroyed.

2.2 How *Scandal* Handles MIDI

2.3 The Structure of the Compiler

In a broad perspective, the compilation process of *Scandal*'s DSL has the following steps:

1. A path to a *.scandal* file is passed as an argument to the constructor of the compiler and a linker subroutine is called, in order to resolve any dependencies;
2. The code is passed through a scanner, which removes white space and comments while converting strings of characters to tokens. Any illegal symbol will cause the scanner to throw an error, interrupting the compilation process;
3. The tokens are parsed and converted into an abstract syntax tree, during which many tokens are discarded. If the order of the tokes does not match any of the constructs that *Scandal* understands, the parser throws an error and interrupts the compilation process;
4. The root of the AST begins the process of *decorating* the tree, in which name references are resolved, types are checked, and variable slot numbers are assigned, whenever applicable. To keep track of names, a LeBlanc-Cook symbol table is kept. If types do not match, or names cannot be referenced, the offending node in the AST throws an error, aborting the compilation;
5. Again starting from the root of the AST, each node generates its corresponding bytecode, making use of the org.objectweb.asm library as a facilitator. For any node that is a subroutine, its body is added following its declaration. No errors are thrown in

this phase, and the root node returns an array of bytes containing the program's instructions in *Java* bytecode format;

6. Every *Scandal* program implements the `Runnable` interface. After the compiler receives the program's bytecode, it dynamically loads that bytecode as a *Java* class on the current (main) thread, causing the *Scandal* program to be executed.

2.3.1 The Linking Process

The main entry point to the compilation process is given by the `Compiler` class, whose constructor requires a path to a *.scandal* file. This class contains a `link` routine that is called before each compilation to resolve dependencies, and which is given in Listing 2.2 below. The `Compiler` class has a property named `imports`, which is an array of paths to other *.scandal* files upon which the program at hand depends. It also holds a `path` property, which was passed to its constructor, and which is used as an argument to `link`'s first call. A *Scandal* program may have at its outermost scope `import` statements, which take a single string as a parameter, which in turn represents a path to a *.scandal* file in the file system. Any code contained in the file may depend on this imported path's content. Similarly, the imported path's content may depend itself on other imports, and so on, provided there is no circularity, that is, nothing imports something that depends on itself. We may regard then the linking process as a directed graph, in which arrows point toward dependencies. Since we do not allow cycles, this is a directed acyclic graph. It may very well be the case that more than one import depend on a particular file, in which case we certainly do not want to import that code twice. In order to import each dependency exactly once in an order that will satisfy every node of the DAG that points to it, we need to somehow sort the array of imports. It is easy to see that this is no different than the problem of donning garments, in which one must have her socks on before putting her shoes, and where some items may call for no particular order, such as a watch [3, 612]. The solution for this problem is to topologically sort the array of imports. Since it is a DAG, however, that is very easily accomplished by a depth-first search of the graph, which is exactly what Listing 2.2 accomplishes recursively.

Listing 2.2. The linking process of a *Scandal* program.

```
1 private void link(String inPath) throws Exception {
2   if (imports.contains(inPath)) return;
3   Program program = getProgram(getCode(inPath));
4   for (Node node : program.nodes)
5     if (node instanceof ImportStatement)
6       link(((ImportStatement) node).expression.firstToken.text);
7   imports.add(inPath);
8 }
```

The if-statement in line 2 of the `link` routine deals with the base case of the recursion, namely the case in which we have already discovered that vertex. If we are seeing a vertex for the first time, line 3 converts the code into an AST, so we can check for any `import` statements therein. That is, in turn, accomplished by the for-loop in line 4, which checks each node in the AST's outermost scope for `import` statements. For each one it finds, line 6 recursively calls the `link` routine with the path extracted from that `import` statement. Since any code upon which we might depend needs to appear *before* our own, the first vertex that is finished needs to go in front of the list, and so on. To be precise, this is a *reverse* topological order. If the chain of imports given by the user contains a cycle, then no topological order exists, and the *Scandal* program will throw a runtime error. This is not ideal, and future versions of *Scandal* will throw a compilation error instead. In order to do so, however, more structure needs to be added to the compiler, so that we may check for backward edges in the linking process, although this feature remains unimplemented.

2.3.2 The Scanning Process

The design of the entire complier takes full advantage of *Java*'s object-oriented paradigm. In order to convert strings of characters from the input file into tokens, we first define a particular *type* of token for each individual construct in the DSL. This is accomplished by the `Token` class, which contains a static enumeration `Kind`, that in turn defines a type for each string of characters the DSL understands. The constructor of `Token` takes a `Token.Kind` as input, and each instance of `Token` contains, in addition, a `text` property, which holds the particular string of characters for that token's kind, as well as other properties that are convenient when throwing errors, namely that token's line number, position within the input array of characters, position within the line, and length. The `Token` class also contains methods for converting strings into numbers, as well as convenience methods for determining whether the kind of a particular instance of `Token` belongs to a particular *family* of tokens, i.e., whether a token is an arithmetic operator, or whether it is a comparison operator, and so on.

What the `Scanner` class accomplishes is the conversion of an array of characters into an array of instances of `Token`. The mechanism is conceptually very simple: we scan the input array from left to right and, whenever we see a string of characters that matches one of the DSL's constructs, we instantiate a new `Token` and add it to the array of tokens we hold, in order. In the process, we skip any white space found. These can be tab characters, space characters, new lines, hence *Scandal*, unlike *Python* or *Make*, makes no syntactical use of line breaks or indentation. The only role white spaces play in a *Scandal* program is that of improved readability. *Scandal* also supports two kinds of comments: single-line, which are preceded by two forward slashes, and multi-line, where a slash *immediately* followed by a star character initiates the comment, and a start immediately followed by a slash terminates it. Unlike *Java* or *Swift*, comments are not processed as documentation, and are thus completely discarded. Their only purpose is to document the *.scandal* file in which they are contained. String literals in *Scandal* are declared by enclosing the text between quotes, and single apostrophe are neither allowed, nor in the language's alphabet anywhere. Besides token kinds that bear syntactical relevance, there is an additional *end-of-file* kind that exists for convenience, and is placed at the end of the token array right before the `scan` method returns. Checking for illegal characters, or combinations thereof, such as a name that begins with a number, for example, is all the checking the Scanner class does. All syntactical checking is delegated to the parsing stage of compilation.

2.3.3 The Parsing Process

The main purpose of the parsing stage is to convert the concrete syntax of a *Scandal* program into an abstract syntax tree, where constructs are hierarchically embedded in one another. An instance of the Parser class is constructed by passing a reference to a Scanner object. The process is unraveled by invoking the parse method, which returns an instance of the Program class. A Program is a subclass of Node, an abstract class that provides basic structure for every node in the AST. In particular, Program is the node that lies at the root of the AST. For each construct specified by the concrete syntax of *Scandal*, there is a corresponding construct specified by its abstract syntax. More often than not, the abstract construct will be simpler, sometimes with many tokens removed. The job of the parser is to facilitate the process of inferring meaning from a given program, and it does so by going, from left to right, through the array of tokens passed by the scanner and, whenever it sees a sequence of tokens that matches one of the constructs in the concrete syntax, it consumes those tokens and creates a subclass of Node that corresponds to the construct at hand. It follows, for every acceptable construct in the DSL, there is a subclass of Node that defines it. Some nodes are nested hierarchically in others, and ultimately all nodes are nested in an instance of Program, hence why the parsing stage ultimately constructs a tree.

Structuring a program hierarchically is essential for inferring the meaning of complex expressions that have some sort of precedence relation among its sub-expressions. That is the case of arithmetic operations, in which, say, multiplication has precedence over addition, and exponentiation has precedence over multiplication. As an example, *Supercollider* evaluates $3 + 3 * 3$ to 18, since it parses the expression from left to right without regard for the precedence relations among arithmetic operators. This is counterintuitive, and does not correspond to how mathematical expressions are evaluated in general. We would like, instead, the expression $3 + 3 * 3$ to evaluate to 12, in which case we cannot take it from left to right. Rather, we must first evaluate $\mathrm{e}_2 = 3 * 3$, *then* evaluate $\mathrm{e}_1 = 3 + \mathrm{e}_2$. It is easy to see that, no matter how complex the expression might be, we can always represent it as a *binary* tree by taking the leftmost, highest-precedence operator and splitting the expression in half at that point. We then look at each sub-expression and do the same, until we reach a leaf. Note that the AST is not, in general, a binary tree. If two operators have the same precedence, we associate from left to right, that is, $1-2+3 = (1-2)+3 = 2$, which also corresponds to how mathematical expressions associate. Complex expressions are dealt in *Scandal* by the BinaryExpression class, and the fact that instances of BinaryExpression may contain other instances of BinaryExpression simply means we must construct them recursively. We shall discuss in detail each syntactical construct of *Scandal* in the sections that follow, along with their concrete and abstract syntax definitions, and parsing routines.

2.3.4 Decorating the AST

The idea of representing a program as a tree has many advantages, chief among them being the fact we can traverse the tree to infer its meaning. This is often non-trivial, and is necessary as many constructs are name-references to other constructs, and require that we look back to how they were originally declared if we are to make sense of them. In *Scandal*, every subclass of Node overrides the abstract method decorate, which in turn takes an instance of SymbolTable as an argument. The latter is a class that implements a LeBlanc-Cook symbol table [4]. Several nodes in the DSL define new naming scopes, Program being the node that holds the zeroth scope. These nodes are namely those that have Block, or its subclass LambdaBlock as members. IfStatement and WhileStatement both have Block as a child node, whereas LambdaLitBlock points to a LambdaBlock, who differs from Block in that it has a return statement. LambdaBlock only exist in the context of a lambda literal expression, however instances of Block, inside if or while-statements or on their own, may exits arbitrarily, always defining new naming scopes. Every time we enter a new scope in *Scandal*, we have access to variables that were declared in outer scopes, but the converse is not true. Also, every time we enter a new scope, we have the opportunity of re-declaring variables' names without the risk of clashing with names already declared in outer scopes. For each scope, we hold a hash table whose keys are the variables' names, and whose values are subclasses of the abstract type Declaration. In order to *remember* as we enter new scopes, and *forget* as we leave them, an instance of SymbolTable holds a Stack of name-declaration hash tables, since stacks are exactly the kind of data structure that gives us this last-in, first-out behavior. In order to trigger the whole process of decorating the AST, the Compiler class instantiates a SymbolTable, and passes that as an argument to the instance of Program that was returned by the parser. Listing 2.3 shows how this is done in the compile method inside Program. Since every node overrides the decorate method, this instance of SymbolTable is passed down along the entire tree. Nodes that introduce new naming scopes have the responsibility of pushing a new hash table onto the stack, then popping it before returning from the decorate method.

In addition to resolving names, the decoration process is crucial for type-checking expressions and statements in the DSL. Even though the *Java* bytecode instructions are explicitly typed, languages that compile to bytecode do not need to be. That is the case of *Scala* and *Groovy*, in which types can be inferred, or declared explicitly. Furthermore, there is a degree of latitude to which types can actually *change* in the bytecode implementation. The JVM only cares that, once a variable is stored in a certain slot number as, say, a float, that is, using the instruction FSTORE, that it be retrieved too as a float, that is, using the instruction FLOAD. It is perfectly possible to use the same slot number to, say, ISTORE an integer value. The only consistency the JVM requires is that, for as long as that slot holds an integer, the value can only be retrieved by an ILOAD instruction. This requirement naturally extends to method signatures, which are also explicitly typed in the JVM. Hence, like *JavaScript*, one can theoretically change the type of a variable attached to a name after it has been declared; unlike *JavaScript*, however, types have to be assigned to arguments when declaring a method, and that method signature is immutable. It is still possible to overload a method to accept multiple signatures, but overloaded names are still *different* methods, with altogether different bodies. The same applies to non-primitive types, that is, types that are instances of a class in the JVM. To store or retrieve non-primitive types, we use the ASTORE and ALOAD JVM instructions, respectively. Hence it is also theoretically possible to overwrite non-primitive types. However, method signatures that take non-primitives require a fully-qualified class name, hence are immutable as above. A fully-qualified name is the name of the class, preceded by the names of the packages in which it is contained, separated by forward slashes. For Compiler, for example, we have language/compiler/Compiler.

Listing 2.3. Triggering the compilation process of a *Scandal* program.

```
public void compile() throws Exception {
    imports.clear();
    code = "";
    link(path);
    for (String p : imports) code += getCode(p);
    symtab = new SymbolTable(className);
    program = getProgram(code);
    program.decorate(symtab);
    program.generate(null, symtab);
}
```

Scandal is, by design choice, strongly typed. There are many reasons for that. The main reason is that the only kind of method it supports is that of a lambda expression, even though *Scandal* is not a pure functional language. These lambda expressions define themselves their own parametrized sub-types, hence a lot of what the language *is* hinges on type safety. It is also a design choice to make *Scandal* accessible as an entry-level language, that is, directed toward an audience interested in learning audio signal processing in more depth, without the implementation hiding inherent to the unit-generator concept. Having types explicitly defined can help inexperienced programmers better debug their code, as well as help them understand the underlying implementation of the language. Type inference is, in essence, another way of hiding implementation, which has advantages, but also drawbacks. It is notoriously difficult to report errors and debug large projects in an IDE with languages that are not strongly typed. That is certainly the case with

JavaScript, of which *TypeScript* is a typed superset aimed exactly at facilitating development within an IDE. *Scandal* is fully integrate into its IDE, where reporting compilation errors to the programmer is a lot more informative, hence educational, than throwing runtime errors and aborting execution. For all these reasons, type-checking is one of the main jobs the decoration process accomplished. It can become rather involved, especially when it comes to composing partial applications of lambda expressions. We shall describe the intricacies of type checking alongside each of the DSL's constructs in the sections that follow.

2.3.5 Generating Bytecode

Similarly to the decoration process, bytecode generation is triggered from the root of the AST, that is, an instance of `Program` received from the parser, and which has been already decorated, and passed down to every node of the tree by a common abstract method each subclass of `Node` overrides. In this case, this common method is called `generate`, and it takes two arguments. The first is an instance of `org.objectweb.asm.MethodVisitor`, and the second is the the decorated instance of `SymbolTable`. `MethodVisitor` is part of the ASM library, which is a convenient set of tools aimed at facilitating the generation of *Java* bytecode. As the name suggests, it visits a method within the bytecode class and adds statements to it. As can be seen in line 9 of Listing 2.3, a null pointer is passed to the very first call to `generate`, since at that point we have not created any methods in the bytecode class yet. Every *Scandal* program compiles to a *Java* class, which in turn implements the `Runnable` interface. Inside the class, there are three methods: `init`, where we create the method bodies of lambda literal expressions, which are always fields in the *Java* class; `run`, which is a required override of the `Runnable` interface, and where we create all *Scandal* local variables and statements; and `main`, where we instantiate the class and call `run`. Inside `Program`, the `generate` method creates three instances of `MethodVisitor`, one for each aforementioned method.

If and only if a child node is an instance of `LambdaLitDeclaration`, a `Node` used to declare a name and assign to it a lambda literal expression, this child node is passed an instance of MethodVisitor that lives inside the init method. The immediate implication of this design choice is that lambda literal expressions are always global variables in a *Scandal* program, thus accessible everywhere. However, they must be declared at the outermost scope of the program, and will throw a compilation error if declared elsewhere. A similar design pattern applies to nodes that are instances of FieldDeclaration, a Node used to declare field variables in the *Java* class, which in turn correspond to global variables in the *Scandal* program. For both LambdaLitDeclaration and FieldDeclaration nodes, we need to add field declarations in the *Java* class, which is accomplished by instantiating, for each of these nodes, a org.objectweb.asm.FieldVisitor. This is only ever done inside Program hence, as a consequence, global variables in a *Scandal* program must always be declared at the outermost scope. Similarly to instances of LambdaLitDeclaration, instances of FieldDeclaration in inner scopes throw a compilation error. Every descendant of the root node that is *not* an instance of LambdaLitDeclaration receives as a parameter to its generate method an instance of MethodVisitor that lives inside the run method of the *Java* class. This includes instances of FieldDeclaration, which are only declared by a FieldVisitor, and whose assignment is done inside the run method, along with all other declarations and statements.

Unlike instances of FieldDeclaration, instances of LambdaLitDeclaration are marked as *final* in the *Java* class, hence cannot be reassigned. The reason is simple: once reassigning a variable that points to a method body, the latter may become inaccessible. In *Scandal*, one can create references to lambdas inside the run method, which are not instances of LambdaLitDeclaration, that is, which do not specify a method body. These references are rather instances of the superclass AssignmentDeclaration, and can be freely reassigned, even to lambdas that have different parameters, i.e., method signatures, that that of the original assignment. Reassigning references to lambdas come allow for great code re-usability. There is a third subclass of Node which can only be used at the outermost scope, namely ImportStatement. The reason is, besides clarity and organization of *Scandal* code, because the link routine inside Program only looks for import statements within the outermost scope of a program's AST. In all three such nodes, checking whether that particular instance lives in the outermost scope is a simple matter of asking the passed instance of SymbolTable whether the current scope number is zero.

2.3.6 Running a *Scandal* Program

Every Program node holds an array of bytes corresponding to a binary representation of the compiled *Scandal* program. This array is created right before the generate method returns. The Compliler class naturally holds a reference to an instance of Program, and utilizes the latter's bytecode property to dynamically instantiate the *Scandal* program as a *Java* class, that is, from an array of bytes stored in memory, rather than from a *.class* in the file system. Within the IDE, a path to a *Scandal* program is used to instantiate a Compiler. After calling the compile method, the resulting bytecode is used to define a subclass of java.lang.ClassLoader, namely DynamicClassLoader, which is capable of dynamically instantiating a byte array as a *Java* class, as opposed to the instance returned by the static method ClassLoader.getSystemClassLoader(), which can only load classes from the file system. Once defined, we construct and instantiate the program, finally casting the result to Runnable, as illustrated in Listing 2.4. The getInstance method is called from the IDE by the tab that currently holds the pogram's text editor, which is an instance of ScandalTab. After retrieving the instance of Runnable, the ScandalTab simply puts is on a new Thread. Starting the thread then causes the *Scandal* program to execute.

Listing 2.4. Obtaining an instance of a *Scandal* program.

```
public Runnable getInstance() throws Exception {
    ClassLoader context = ClassLoader.getSystemClassLoader();
    DynamicClassLoader loader = new DynamicClassLoader(context);
    return (Runnable) loader
            .define(className, program.bytecode)
            .getConstructor()
            .newInstance();
}
```

2.4 The Syntax of *Scandal*

In this section, we describe in detail every syntactical construct of *Scandal*. For each of them, we state their concrete and abstract syntax definitions, how one is converted into the other in the parser, as well as the particularities of type-checking and generating bytecode. We omit some constructs that, either have trivial implementations, or whose implementations are, *mutatis mutandis*, identical to other constructs, in which case we describe only a representative. In the discussion that follows, terminal symbols are in all-capital letters, productions in the concrete syntax begin with a lower-case letter, and their counterparts in the abstract syntax begins with an upper-case letter. We here present terminal symbols in the syntactical context in which they appear, and a complete list of terminal symbols can be found in Sec. **??**.

2.4.1 Top-Level Productions

At the topmost level of a *Scandal* program, there are basically only two kinds of constructs that are allowed, namely declarations and statements. The legal declarations at this level are further subdivided into three: assignment declarations, field declarations, and lambda literal declarations. In the productions that follow, the star symbol represents a *Kleene* star, and or-symbols and parenthesis are not tokens in the language. As a rule, terminal symbols will be given by their names, like `OR`, to avoid confusion with symbols in the language's grammar. Below are the production rules for program:

- type := `KW_INT` | `KW_FLOAT` | `KW_BOOL` | `KW_STRING` | `KW_ARRAY` | `KW_LAMBDA`
- declaration := assignmentDec | fieldDec | lambdaLitDec | paramDec
- program := (assignmentDec | fieldDec | lambdaLitDec | statement)*

In the AST, Declaration is an abstract class that has two subclasses: AssignmentDeclaration, and ParamDeclaration. The former has two subclasses, FieldDeclaration, and LambdaLitDeclaration. The primary difference between the two subclasses of Declaration is that the latter defines a type and a name without binding any value to that name at the time of declaration, while the former requires that some expression be given at the moment the variable is declared. It follows every variable declaration in *Scandal* must be initialized, except when they are parameters of a lambda literal, in which case they actually cannot be initialized. A program can contain any number of assignmentDec, fieldDec, or lambdaLitDec, in any order, while a paramDec only exist in the context of a lambda literal. As will be seen below, every declaration begins with a type token, or with a field flag, followed by a type token. The abstract syntax of Program is then:

- Declaration := AssignmentDeclaration | FieldDeclaration
- Declaration := LambdaLitDeclaration | ParamDeclaration
- Program := (AssignmentDeclaration | FieldDeclaration)*
- Program := (LambdaLitDeclaration | Statement)*

The parsing routine for program is very simple, and constructs an instance of Program by checking whether the next token in the array of tokens produced by the scanner is in the FIRST set of declaration. If it is, we attempt to construct an instance or subclass of AssignmentDeclaration, consuming in the process all the tokens therein. If not, we attempt to construct a subclass of the abstract type Statement. That is done much that same way, by looking at the set FIRST(statement). Listing 2.5 shows how a concrete program is converted into a Program node in the AST.

Listing 2.5. Parsing topmost-level constructs in *Scandal*.

```
public Program parse() throws Exception {
  Token firstToken = token;
  ArrayList<Node> nodes = new ArrayList<>();
  while (token.kind != EOF) {
    if (token.isDeclaration()) nodes.add(assignmentDeclaration());
    else nodes.add(statement());
  }
  matchEOF();
  return new Program(firstToken, nodes);
}
```

In Listing 2.5, we construct an instance of Program by first creating an array of nodes. These nodes, however, must be either a subclass of AssignmentDeclaration, or a subclass of the abstract class Statement. Line 5 checks whether the next unconsumed token is in the FIRST set of a declaration. If so, further parsing is delegated to the assignmentDeclaration routine. If not, the only other option is that the next token initiates a statement, and parsing thereof is delegated to the statement routine in line 6. Nodes are added in the exact order in which they appear in the *Scandal* program, regardless whether they are declarations or statements. An end-of-file token was included in the scanning process for convenience, and here we make use of it by checking the next available token against the `EOF` kind. As soon as we find it, we know we have reached the end of the token array, and can thus stop looking for declarations and statements. If we were expecting a particular token, but `EOF` appeared prematurely, we throw an error.

Inside an instance of Program, type-checking is completely delegated to each node in the node array. More precisely, inside the decorate routine, we iterate over the node array and, for each node, we call node.decorate, passing along the symbol table instantiated by the compiler. Generating bytecode, on the other hand, is a lot more complex, since we need to provide the overall structure for the entire *Java* class. That is accomplished inside the generate method by creating an instance of org.objectweb.asm.ClassWriter. The latter, which we call cw, manages the creation of the *Java* class itself, including the generation of the byte array used to instantiate and run the *Scandal* program. In particular, we set the JRE to version 1.8, make the access to the class public, and define it as a subclass of java/lang/Object that implements the java/lang/Runnable interface. We then create three instances of MethodVisitor by calling cw.visitMethod, one for each method in the *Java* class. The methods are namely <init>, run, and main. In <init>, we basically go through the node array and, if the particular node is an instance of LambdaLitDeclaration, we call node.generate, passing the appropriate instance of MethodVisitor and our symbol table as parameters. What the generate method does inside a LambdaLitDeclaration is somewhat complicated, and we defer its explanation to the moment we discuss the LambdaLitExpression class. Before visiting run, we go once again over all nodes in the node array and, if they are either an instance of LambdaLitDeclaration or an instance of FieldDeclaration, we call cw.visitField. This method creates fields in the Java class, which correspond to field variables in the *Scandal* program. Every field is marked as static, since we make no use of *Java*'s object-oriented paradigm. In addition, lambda fields are marked as final, as previously discussed, and we take the opportunity to pass cw along to the instances of LambdaLitExpression for which we are creating field declarations, and ask them to create a method body for the lambda literal expression. This is accomplished inside each lambda literal expression by an overloaded generate method, which takes, instead of a MethodWriter, the instance of ClassWriter, namely cw, and uses that to create its own MethodWriter, which will correspond to the lambda's method. The instances of LambdaLitExpression are accessed through the lambda property inside the LambdaLitDeclaration, and the particularities of creating method bodies for lambdas will be discussed momentarily. The next step is to add a body for the *Java* class' run method. To do so, we go yet once more over the array of nodes, and this time we generate any node that is *not* an instance of LambdaLitDeclaration, for obvious reasons. We do visit instances of FieldDeclaration, since cw.visitField only created the field, but never assigned any value to it. Since we only allow unassigned declarations in *Scandal* when declaring lambda parameters, we have something to assign to that field, and generate inside FieldDeclaration takes care of that.

Listing 2.6. Using the ASM framework to construct a main method.

```
private void addMain(ClassWriter cw, SymbolTable symtab) {
    MethodVisitor mv =
        cw.visitMethod(ACC_PUBLIC + ACC_STATIC, "main", "([Ljava/lang/String;)V", null, null);
   mv.visitTypeInsn(NEW, symtab.className);
   mv.visitInsn(DUP);
   mv.visitMethodInsn(INVOKESPECIAL, symtab.className, "<init>", "()V", false);
   mv.visitMethodInsn(INVOKEVIRTUAL, symtab.className, "run", "()V", false);
   mv.visitInsn(RETURN);
   mv.visitMaxs(0, 0);
}
```

Finally, we visit the main method in the *Java* class, which is shown in Listing 2.6. This is the standard main method in *Java*, which is always public and static, takes an array of strings, and returns nothing. Line 3 uses cw to create an instance of MethodVisitor, namely mv, with exactly these properties. Bytecode syntax for method signatures is given by a parenthesized list of argument types, followed by the return type. Hence a void method that takes a String[] in *Java* becomes ([Ljava/lang/String;)V, where the left bracket means we have an array of whatever type follows, and the colon separates argument types. Naturally, java/lang/String is a string, and V stands for the void type. The JVM is stack-based, so in line 4 we create a new instance of the *Java* class, whose name is stored in our symbol table, and leave it on top of the stack. In line 5 we duplicate whatever is on top of the stack, since we will need to use our newly created *Java* class twice, namely to call on it init , and then run. These two calls are made in lines 6 and 7, respectively. Notice both method signatures take no arguments and return nothing, hence are equivalent to ()V in bytecode. Finally, we add a return statement to the main method's body, which is omitted in void *Java* methods, but required in bytecode. A bytecode method requires that we compute the maximum number of elements the stack will have, as well as the total number of local variables in the method. ASM does that for us, and we asked it to do so by passing a ClassWriter.COMPUTE_FRAMES as an argument while constructing cw. The two arguments to mv.visitMaxs are the maximum stack size, and the total local variables. We pass zeros since we are not computing them, but the call must be made nonetheless.

2.4.2 Subclasses of Declaration

The class Declaration is an abstract type that extends Node by adding three instance variables, namely a Token to hold the name we are declaring, an integer to hold its slot number, and a boolean property to distinguish whether this is a field or not. Slot numbers are not necessary for fields, hence are only used in the context of the *Java* class' run method.

Declaration branches out into two non-abstract subclasses, ParamDeclaration and AssignmentDeclaration . The latter has itself two other subclasses, FieldDeclaration and LambdaLitDeclaration. As discussed above, the difference is that ParamDeclaration only occurs inside a LambdaLitDeclaration; FieldDeclaration and LambdaLitDeclaration only occur at the outermost scope; and AssignmentDeclaration occurs anywhere. Below are the production rules for the concrete syntax of declarations in *Scandal*.

- paramDeclaration := type `IDENT`
- assignmentDeclaration := type `IDENT ASSIGN` expression
- fieldDeclaration := `KW_FIELD` assignmentDeclaration
- lambdaAssignment := `KW_LAMBDA IDENT ASSIGN` (paramDeclaration)*
- lambdaLitDeclaration := lambdaAssignment lambdaLit
- lambdaLitDeclaration := lambdaAssignment lambdaBlock

Listing 2.7. Parsing Top-Level Declarations.

```java
public AssignmentDeclaration assignmentDeclaration() throws Exception {
  boolean isField = token.kind == KW_FIELD;
  if (isField) consume();
  Token firstToken = consume();
  Token identToken = match(IDENT);
  match(ASSIGN);
  Expression e = expression();
  if (e instanceof LambdaLitExpression)
    return new LambdaLitDeclaration(firstToken, identToken, (LambdaLitExpression) e);
  if (isField) return new FieldDeclaration(firstToken, identToken, e);
  return new AssignmentDeclaration(firstToken, identToken, e);
}
```

As shown in line 5 of Listing 2.5, we parse declarations by looking at the very first token at hand. In particular, we have FIRST(declaration) = type ∪ `KW_FIELD`. Observing that FieldDeclaration is the only subclass of Declaration that may make use of a field flag, we can begin parsing declarations by first checking whether the first token of a declaration is indeed a field flag, setting a local boolean property accordingly, and consuming the `KW_FIELD` token, as shown in line 2 of Listing 2.7. We then store the type and identifier tokens, consume the equals sign and delegate the expression rule to the expression routine. Based on which type of expression we receive, we create the corresponding subclass of AssignmentDeclaration. Even though lambda literal declarations are always fields in the *Java* class, the field flag is not necessary, but *can* be used without errors, since all that determines an instance of LambdaLitDeclaration is that the expression it contains is a subclass of LambdaLitExpression. Unassigned declarations, on the other hand, will fail the match(ASSIGN) call in line 6, and will cause a compilation error.

2.4.2.1 The ParamDeclaration Class

ParamDeclaration is basically an unchanged implementation of the abstract type Declaration. It adds no new properties, thus consisting of basically a type Token and an identifier Token. Since it is not abstract, it must override decorate and generate, the two abstract methods in Node that provide functionality to all nodes in the AST. Parsing a parameter declaration is absolutely straightforward, and done in the context of a LambdaLitExpression. We simply store and consume the type and identifier tokens, then use those to instantiate a ParameterDeclaration.

When a lambda literal expression is decorated, a new scope in the symbol table is introduced, so that parameter names do not clash with local variables in the *Java* class' run method. Thus inside an instance of ParamDeclaration, the decorate method checks only the symbol table at the top of the stack of symbol tables to see whether any two parameters have the same identifier, in which case it throws a compilation error. If not, it inserts the identifier into the topmost scope of the symbol table, associating to the identifier the instance of Declaration at hand. Since parameter declarations are local variables inside a lambda body, they need to have the slotNumber property set so they can be accessed. This is accomplished, however, by the lambda literal expression class before the decorate method is called on a parameter declaration, as we shall see momentarily. In the generate method, we do nothing, since there is no value we can bind to the declaration's identifier at the moment. Naturally, these values will exist in the context of a lambda application.

2.4.2.2 The `LambdaLitDeclaration` Class

The `LambdaLitDeclaration` class is a particular case of `AssignmentDeclaration` where the expression is of type `LambdaLitExpression`. By defining a new type, we are able to separate more easily instances of lambda literals from other nodes inside a `Program`, as previously seen. As we shall see, having a specific type for lambda declarations is also invaluable when the underlying implementation of a lambda is obscured by partial applications and compositions, in which case we need to unravel an entire chain of bindings until we find a name that is bound to an expression of type `LambdaLitDeclaration`. We construct a lambda literal declaration by taking a `LambdaLitExpression`, and passing it to the constructor of the superclass. It follows the superclass' `expression` property is just a reference to this lambda literal expression property, which we call `lambda`. Naturally, every `LambdaLiteralExpression` inherits from `Expression`. At the time we construct a lambda literal declaration, we immediately set the `isField` boolean property to true, as discussed above.

Lambda literal declarations have very different implementations of the `Node` abstract methods than those of `AssignmentDeclaration`, hence both `decorate` and `generate` are overridden. The bodies of these methods are substantially simpler than the superclass' implementation, given the restricted nature of this type. Inside `decorate`, we check the entire stack of symbol tables to see whether we are not being redeclared, in which case an error is thrown. Checking only the topmost scope symbol table would work exactly the same, since lambda literal declarations are only allowed at the outermost scope, hence the stack only contain a single symbol table when we call `decorate`. If we are being declared for the first time, then we insert the identifier into the symbol table, associating to it the instance of `LambdaLitDeclaration` we have. Unlike parameter declarations, we now have an expression to decorate, which we do by calling `lambda.decorate`, hence delegating decoration to the `LambdaLitExpression` instance. Similarly, the `generate` method calls `lambda.generate`, which causes a lambda literal expression to be left on top of the JVM stack. We then bind this expression to the identToken.text property and return.

2.4.2.3 The FieldDeclaration Class

Field declarations are possibly the simplest type of declaration. They mostly exist for convenience, in order not to clutter its superclass AssignmentDeclaration, which has a somewhat more involved implementation. We construct them by calling the superclass' constructor with exactly the same arguments, but in addition we set the isField boolean property to true. We also override both decorate and generate. In the former, and similarly to LambdaLitDeclaration, we check all symbol table scopes to see if we are not being redeclared. Naturally, there is only ever one scope to check. If all is fine, we insert ourselves into the symbol table with a key given by identToken.text and a value of this. We then call expression .decorate, after which the expression will be decorated with a non-null type, a property that is common to every node. Unlike LambdaLitDeclaration, in which the declaration and lambda always had the same type by construction, here we can have runtime errors if the program tries to store, say, a float into an integer slot. We then simply check whether the expression's type is the same as the declaration's. The latter never needed to be decorated, and was set when the constructor of Node was called, since it could be inferred from the declaration's first token alone. The overridden generate method is identical to that of LambdaLitDeclaration.

2.4.2.4 The AssignmentDeclaration Class

Assignment declarations are the most general an common type of declaration in *Scandal*. They correspond to all variable declarations that are not *special*, neither in the sense of declaring a method body, nor in the sense of being global to a *Scandal* program. In other words, they live inside the Java class' run method, as well as inside a lambda's body. Since the isField property is false by default, we construct a AssignmentDeclaration by passing a type token and an identifier token to the superclass, then storing our own expression property, the latter being what differentiates us from the abstract type Declaration.

The decoration process is similar to those of the two subclasses of AssignmentDeclaration, but a bit trickier. We start by checking the top of the stack of symbol tables to see if there is no name clash, then insert into the symbol table a key of identToken.text with value this. We then assign a slot number to this variable, which we do by maintaining a property slotCount inside SymbolTable. We assign our slot number to the current slot count, then increase the latter. We call expression.decorate, similarly to what we do in field and lambda literal declarations, to decorate the expression, which will cause it to have a non-null type in most cases, except when the expression is an instance of LambdaAppExpression, in which case we hit a small roadblock in the type-checking process. To understand the situation, we provide in Listing 2.8 a small snippet of *Scandal* code.

Listing 2.8. Type inference in *Scandal*.

```
1 lambda id = float x -> x
2 lambda higherOrder = float x -> lambda f -> {
3   float val = f(x)
4   return val
5 }
```

When a lambda expression in *Scandal* has a parameter of type lambda, we have no mechanism in the language to tell what parameter types pertain to said lambda. The corresponding construction in *Java* is an instance of the Function interface, which is a parameterized type. A lambda expression in *Java* that takes a float and returns a float has type Function<Float, Float>, for example. It has been a design choice so far in *Scandal* not to introduce parameterized types, and attempt instead at some yet crude type inference mechanism. It is a long-term goal to actually make *all* types inferred. In Listing 2.8, we have an instance of ParamDeclaration that defines a variable f of type lambda. Inside the block, the mechanism of choice to in fact *declare* what parameter types f has is through an assignment declaration. In line 3, we apply x to f and store the result in val. Since both x and val have type float, we are now at a position to determine with that f takes a single argument of type `float`, and returns also a float. Note that omitting line 3 and putting `return f(x)` instead would cause a compilation error, exactly because we cannot infer parameter types of a lambda expression inside a lambda literal if there is no application thereof.

Given the discussion above, whenever an assignment declaration calls `expression.decorate`, and this expression happens to be a lambda application inside a lambda literal, instead of expecting the call to `expression.decorate` to define a type for the expression, we actually decorate the expression ourselves. The process is very simple: after calling `expression.decorate`, we check if the expression is an instance of `LambdaAppExpression`. If so, we look for the declaration of that application's expression. If the declaration is an instance of `ParamDec`, we know our expression is an application of a lambda is a parameter of lambda literal expression, since parameter declarations only ever exist in this context. We then trust the programmer will make use of the lambda literal expression correctly, by applying to it a lambda expression that has the same parameter types as those inferred inside the block. If not, a runtime error will occur. This is obviously not a complete implementation and, as discussed previously, future versions of *Scandal* will throw a compilation error instead. Finally, the `expression` property will have to have a type, which we check against the declaration type. Naturally, in the special case we decorate the expression ourselves, this test never fails. If it does, we throw a compilation error. Overriding the `generate` method inside an assignment declaration is straightforward. We make a call to `expression.generate`, which causes the expression value to be left on top of the JVM stack, after which we switch over the expression type, using the appropriate JVM instruction to store the variable.

2.4.3 Subclasses of Statement

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BIOGRAPHICAL SKETCH

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