

Chapter 1

Handling exceptions

All applications have to deal with exceptional situations. Arithmetic errors may occur (such as division by zero), unexpected situations may arise (file not found), or resources may be exhausted (network down, disk full, etc.). The old-fashioned solution is to have operations that fail return a special *error code*; this means that client code must check the return value of each operation, and take special action to handle errors.

Modern programming languages, including Smalltalk, instead offer a dedicated exception-handling mechanism that greatly simplifies the way in which exceptional situations are signaled and handled. Before the development of the ANSI Smalltalk standard in 1996, several exception handling mechanisms existed, largely incompatible with each other. Pharo's exception handling follows the ANSI standard, with some embellishments; we present it in this chapter from a user perspective.

The basic idea behind exception handling is that client code does not clutter the main logic flow with checks for error codes, but specifies instead an *exception handler* to “catch” exceptions. When something goes wrong, instead of returning an error code, the method that detects the exceptional situation interrupts the main flow of execution by *signaling* an exception. This does two things: it captures essential information about the context in which the exception occurred, and transfers control to the exception handler, written by the client, which decides what to do about it. The “essential information about the context” is saved in an Exception object; various classes of Exception are specified to cover the varied exceptional situations that may arise.

Pharo's exception-handling mechanism is particularly expressive and flexible, covering a wide range of possibilities. Exception handlers can be used to *ensure* that certain actions take place even if something goes wrong, or to take action only if something goes wrong. Like everything in Smalltalk, exceptions are objects, and respond to a variety of messages. When an excep-

tion is caught by a handler, there are many possible responses: the handler can specify an alternative action to perform; it can ask the exception object to *resume* the interrupted operation; it can *retry* the operation; it can *pass* the exception to another handler; or it can *reraise* a completely different exception.

With the help of a series of examples, we shall explore all of these possibilities, and we shall also take a brief look into the internal mechanics of exceptions and exception handlers. However, before we do that, we need to stop and think for a moment about the consequence of adding exceptions into a language: *we can no longer be sure that a message send will give us an answer*. In other words, once we have exceptions, any message send has the potential not to return to the sender: it may fail. We thank Hernan Wilkinson and Christopher Oliver for their comments.

1.1 Ensuring execution

The `ensure:` message can be sent to a block to make sure that, even if the block fails (*e.g.*, raises an exception) the argument block will still be executed:

```
anyBlock ensure: ensuredBlock    "ensuredBlock will run even if anyBlock fails"
```

Consider the following example, which creates an image file from a screenshot taken by the user:

```
| writer |  
writer := GIFReadWrite on: (FileStream newFileNamed: 'Pharo.gif').  
[ writer nextPutImage: (Form fromUser) ]  
  ensure: [ writer close ]
```

This code ensures that the writer file handle will be closed, even if an error occurs in `Form fromUser` or while writing to the file.

Here is how it works in more detail. The `nextPutImage:` method of the class `GIFReadWrite` converts a form (*i.e.*, an instance of the class `Form`, representing a bitmap image) into a GIF image. This method writes into a stream which has been opened on a file. The `nextPutImage:` method does not close the stream it is writing to, therefore we should be sure to close the stream even if a problem arises while writing. This is achieved by sending the message `ensure:` to the block that does the writing. In case `nextPutImage:` fails, control will flow into the block passed to `ensure:`. If it does *not* fail, the ensured block will still be executed. So, in either case, we can be sure that writer is closed.

Here is another use of `ensure:`, in class `Cursor`:

```

Cursor»showWhile: aBlock
  "While evaluating the argument, aBlock,
  make the receiver be the cursor shape."
  | oldcursor |
  oldcursor := Sensor currentCursor.
  self show.
  ↑aBlock ensure: [ oldcursor show ]

```

The argument [oldcursor show] is evaluated whether or not aBlock signals an exception. Note that the result of ensure: is the value of the receiver, not that of the argument.

```
[ 1 ] ensure: [ 0 ]  →  1  "not 0"
```

1.2 Handling non-local returns


The message ifCurtailed: is typically used for “cleaning” actions. It is similar to ensure:, but instead of ensuring that its argument block is evaluated even if the receiver terminates abnormally, ifCurtailed: does so *only* if the receiver fails or returns.

In the following example, the receiver of ifCurtailed: performs an early return, so the following statement is never reached. In Smalltalk, this is referred to as a *non-local return*. Nevertheless the argument block will be executed.

```
[↑ 10] ifCurtailed: [Transcript show: 'We see this'].
Transcript show: 'But not this'.
```

In the following example, we can see clearly that the argument to ifCurtailed: is evaluated only when the receiver terminates abnormally.

```
[Error signal] ifCurtailed: [Transcript show: 'Abandoned'; cr].
Transcript show: 'Proceeded'; cr.
```

 Open a transcript and evaluate the code above in a workspace. When the pre-debugger windows opens, first try selecting `Proceed` and then `Abandon`. Note that the argument to ifCurtailed: is evaluated *only* when the receiver terminates abnormally. What happens when you select `Debug`?

Here are some examples of ifCurtailed: usage: the text of the Transcript show: describes the situation:

```
[↑ 10] ifCurtailed: [Transcript show: 'This is displayed'; cr]
```

```
[10] ifCurtailed: [Transcript show: 'This is not displayed'; cr]
```

```
[1 / 0] ifCurtailed: [Transcript show: 'This is displayed after selecting Abandon in the
  debugger'; cr]
```

Although in Pharo `ifCurtailed:` and `ensure:` are implemented using a marker primitive (described at the end of the chapter), in principle `ifCurtailed:` could be implemented using `ensure:` as follows:

```
ifCurtailed: curtailBlock
| result curtailed |
curtailed := true.
[ result := self value.
  curtailed := false ] ensure: [ curtailed ifTrue: [ curtailBlock value ] ].
↑ result
```

In a similar fashion, `ensure:` could be implemented using `ifCurtailed:` as follows:

```
ensure: ensureBlock
| result |
result := self ifCurtailed: ensureBlock.
"If we reach this point, then the receiver has not been curtailed,
  so ensureBlock still needs to be evaluated"
ensureBlock value.
↑ result
```

Both `ensure:` and `ifCurtailed:` are very useful for making sure that important “cleanup” code is executed, but are not by themselves sufficient for handling all exceptional situations. Now let’s look at a more general mechanism for handling exceptions.

1.3 Exception handlers

The general mechanism is provided by the message `on:do:.` It looks like this:

```
aBlock on: exceptionClass do: handlerAction
```

`aBlock` is the code that detects an abnormal situation and signals an exception; it is called the *protected block*. `handlerAction` is the block that is evaluated if an exception is signaled; it is called the *exception handler*. `exceptionClass` defines the class of exceptions that `handlerAction` will be asked to handle.

The beauty of this mechanism lies in the fact that the protected block can be written in a straightforward way, *without regard to any possible errors*. A single exception handler is responsible for taking care of anything that may go wrong.

Consider the following example, where we want to copy the contents of one file to another. Although several file-related things could go wrong, with exception handling we simply write a straight-line method, and define a single exception handler for the whole transaction:

```
source := 'log.txt'.
destination := 'log-backup.txt'.
[ fromStream := FileDirectory default oldFileNameed: source.
  [ toStream := FileDirectory default newFileNameed: destination.
    [ toStream nextPutAll: fromStream contents ]
      ensure: [ toStream close ] ]
    ensure: [ fromStream close ] ]
on: FileStreamException
do: [ :ex | UIManager default inform: 'Copy failed -- ', ex description ].
```

If any exception concerning `FileStreams` is raised, the handler block (the block after `do:`) is executed with the exception object as its argument. Our handler code alerts the user that the copy has failed, and delegates to the exception object `ex` the task of providing details about the error. Note the two nested uses of `ensure`: to make sure that the two file streams are closed, whether or not an exception occurs.

It is important to understand that the block that is the receiver of the message `on:do:` defines the scope of the exception handler. This handler will be used only if the receiver (*i.e.*, the protected block) has not completed. Once completed, the exception handler will not be used. Moreover, a handler is associated exclusively with the kind of exception specified as the first argument to `on:do:`. Thus, in the previous example, only a `FileStreamException` (or a more specific variant thereof) can be handled.

1.4 Error codes — don't do this!

Without exceptions, one (bad) way to handle a method that may fail to produce an expected result is to introduce explicit error codes as possible return values. In fact, in languages like C, code is littered with checks for such error codes, which often obscure the main application logic. Error codes are also fragile in the face of evolution: if new error codes are added, then all clients must be adapted to take the new codes into account. By using exceptions instead of error codes, the programmer is freed from the task of explicitly checking each return value, and the program logic stays uncluttered. Moreover, because exceptions are classes, as new exceptional situations are discovered, they can be subclassed; old clients will still work, although they may provide less-specific exception handling than newer clients.

If Smalltalk did not provide exception-handling support, then the tiny example we saw in the previous section would be written something like

this, using error codes:

"Pseudo-code -- luckily Smalltalk does not work like this. Without the benefit of exception handling we must check error codes for each operation."

```
source := 'log.txt'.
destination := 'log-backup.txt'.
success := 1. "define two constants, our error codes"
failure := 0.
fromStream := FileDirectory default oldFileName: source.
fromStream ifNil: [
    UIManager default inform: 'Copy failed -- could not open', source.
    ↑ failure "terminate this block with error code"].
toStream := FileDirectory default newFileName: destination.
toStream ifNil: [
    fromStream close.
    UIManager default inform: 'Copy failed -- could not open', destination.
    ↑ failure ].
contents := fromStream contents.
contents ifNil: [
    fromStream close.
    toStream close.
    UIManager default inform: 'Copy failed -- source file has no contents'.
    ↑ failure ].
result := toStream nextPutAll: contents.
result ifFalse: [
    fromStream close.
    toStream close.
    UIManager default inform: 'Copy failed -- could not write to ', destination.
    ↑ failure ].
fromStream close.
toStream close.
↑ success.
```

What a mess! Without exception handling, we must explicitly check the result of each operation before proceeding to the next. Not only must we check error codes at each point that something might go wrong, but we must also be prepared to cleanup any operations performed up to that point and abort the rest of the code.

1.5 Specifying which Exceptions will be Handled

In Smalltalk, exceptions are, of course, objects. In Pharo, an exception is an instance of an exception class which is part of a hierarchy of exception classes. For example, because the exceptions `FileDoesNotExistException`, `FileExistsException` and `CannotDeleteFileException` are special kinds of `FileStreamException`, they are represented as subclasses of

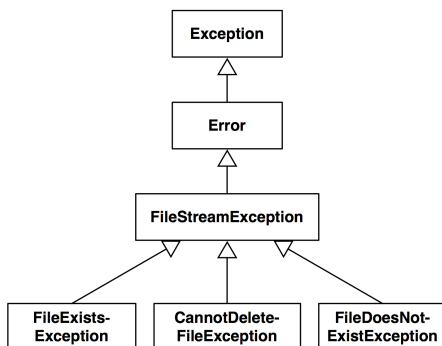


Figure 1.1: A small part of the Pharo exception hierarchy.

`FileStreamException`, as shown in Figure 1.1. This notion of “specialization” lets us associate an exception handler with a more or less general exceptional situation. So, we can write:

```
[ ... ] on: Error do: [ ... ]
[ ... ] on: FileStreamException do: [ ... ]
[ ... ] on: FileDoesNotExistException do: [ ... ]
```

The class `FileStreamException` adds information to class `Exception` to characterize the specific abnormal situation it describes. Specifically, `FileStreamException` defines the `fileName` instance variable, which contains the name of the file that signaled the exception. The root of the exception class hierarchy is `Exception`, which is a direct subclass of `Object`.

Two key messages are involved in exception handling: `on:do:`, which, as we have already seen, is sent to blocks to set an exception handler, and `signal`, which is sent to subclasses of `Exception` to signal that an exception has occurred.

1.6 Signaling an exception

To signal an exception¹, you only need to create an instance of the exception class, and to send it the message `signal`, or `signal:` with a textual description. The class `Exception` class provides a convenience method `signal`, which creates and signals an exception. So, here are two equivalent ways to signal a `ZeroDivide` exception:

¹Synonyms are to “raise” or to “throw” an exception. Since the vital message is called `signal`, we use that terminology exclusively in this chapter.

ZeroDivide new signal.

ZeroDivide signal. *"class-side convenience method does the same as above"*

You may wonder why it is necessary to create an instance of an exception in order to signal it, rather than having the exception class itself take on this responsibility. Creating an instance is important because it encapsulates information about the context in which the exception was signaled. We can therefore have many exception instances, each describing the context of a different exception.

When an exception is signaled, the exception handling mechanism searches in the execution stack for an exception handler associated with the class of the signaled exception. When a handler is encountered (*i.e.*, the message on:do: is on the stack), the implementation checks that the exceptionClass is a superclass of the signaled exception, and then executes the handlerAction with the exception as its sole argument. We will see shortly some of the ways in which the handler can use the exception object.

When signaling an exception, it is possible to provide information specific to the situation just encountered, as illustrated in the code below. For example, if the file to be opened does not exist, the name of the non-existent file can be recorded in the exception object:

StandardFileStream class»oldFileName: fileName

"Open an existing file with the given name for reading and writing. If the name has no directory part, then default directory will be assumed. If the file does not exist, an exception will be signaled. If the file exists, its prior contents may be modified or replaced, but the file will not be truncated on close."

| fullName |

fullName := self fullName: fileName.

↑(self isAFileNamed: fullName)

ifTrue: [self new open: fullName forWrite: true]

ifFalse: ["File does not exist..."]

(FileDoesNotExistException new fileName: fullName) signal]

The exception handler may make use of this information to recover from the abnormal situation. The argument ex in an exception handler [ex | ...] will be an instance of FileDoesNotExistException or of one of its subclasses. Here the exception is queried for the filename of the missing file by sending it the message fileName.

| result |

result := [(StandardFileStream oldFileName: 'error42.log') contentsOfEntireFile]

on: FileDoesNotExistException

do: [ex | ex fileName , ' not available'].

Transcript show: result; cr

Every exception has a default description that is used by the development tools to report exceptional situations in a clear and comprehensible manner. To make the description available, all exception objects respond to the message description. Moreover, the default description can be changed by sending the message `messageText: aDescription`, or by signaling the exception using `signal: aDescription`.

Another example of signaling occurs in the `doesNotUnderstand:` mechanism, a pillar of the reflective capabilities of Smalltalk. Whenever an object is sent a message that it does not understand, the VM will (eventually) send it the message `doesNotUnderstand:` with an argument representing the offending message. The default implementation of `doesNotUnderstand:`, defined in class `Object`, simply signals a `MessageNotUnderstood` exception, causing a debugger to be opened at that point in the execution.

The `doesNotUnderstand:` method illustrates the way in which exception-specific information, such as the receiver and the message that is not understood, can be stored in the exception, and thus made available to the debugger.

```
Object>doesNotUnderstand: aMessage
```

```
"Handle the fact that there was an attempt to send the given message to the receiver
but the receiver does not understand this message (typically sent from the machine
when a message is sent to the receiver and no method is defined for that selector)."
```

```
MessageNotUnderstood new
```

```
  message: aMessage;
```

```
  receiver: self;
```

```
  signal.
```

```
↑ aMessage sentTo: self.
```

That completes our description of how exceptions are used. The remainder of this chapter discusses how exceptions are implemented, and adds some details that are relevant only if you define your own exceptions.

1.7 Halt implementation

As we discussed in the Debugger chapter of *Pharo By Example*, the usual way of setting a breakpoint within a Smalltalk method is to insert the message `send self halt` into the code. The method `halt`, implemented in `Object`, uses exceptions to open a debugger at the location of the breakpoint; it is defined as follows:

Object»halt

"This is the typical message to use for inserting breakpoints during debugging. It behaves like halt:, but does not call on halt: in order to avoid putting this message on the stack. Halt is especially useful when the breakpoint message is an arbitrary one."

Halt signal

Halt is a direct subclass of Exception. A Halt exception is *resumable*, which means that it is possible to continue execution after a Halt is signaled.

Halt overrides the defaultAction method, which specifies the action to perform if the exception is not caught (*i.e.*, there is no exception handler for Halt anywhere on the execution stack):

Halt»defaultAction

"No one has handled this error, but now give them a chance to decide how to debug it. If no one handles this then open debugger (see UnhandledError–defaultAction)"

UnhandledError signalForException: self

This code signals a new exception, UnhandledError, that conveys the idea that no handler is present. The defaultAction of UnhandledError is to open a debugger:

UnhandledError»defaultAction

"The current computation is terminated. The cause of the error should be logged or reported to the user. If the program is operating in an interactive debugging environment the computation should be suspended and the debugger activated."

↑ ToolSet debugError: exception.

A few messages later, the debugger opens:

StandardToolSet»debug: aProcess context: aContext label: aString contents: contents
fullView: aBool

↑ Debugger openOn: aProcess context: aContext label: aString contents: contents
fullView: aBool

1.8 Finding handlers

We will now take a look at how exception handlers are found and fetched from the execution stack when an exception is signaled. However, before we do this, we need to understand how the control flow of a program is internally represented in the virtual machine.

At each point in the execution of a program, the execution stack of the program is represented as a list of activation contexts. Each activation context represents a method invocation and contains all the information needed

for its execution, namely its receiver, its arguments, and its local variables. It also contains a reference to the context that triggered its creation, *i.e.*, the activation context associated with the method execution that sent the message that created this context. In Pharo, the class `MethodContext` models this information. The references between activation contexts link them into a chain: this chain of activation contexts *is* Smalltalk's execution stack.

Actually, there are two kinds of activation context in Pharo: `methodContexts` and `blockContexts`: the latter are used to represent the execution of blocks. They have a common superclass `ContextPart`. We will ignore this detail for now.

Suppose that we attempt to open a `FileStream` on a non-existent file from a `dolt`. A `FileDoesNotExistException` will be signaled, and the execution stack will contain `MethodContexts` for `dolt`, `oldFileNamed:`, and `signal`, as shown in Figure 1.2.

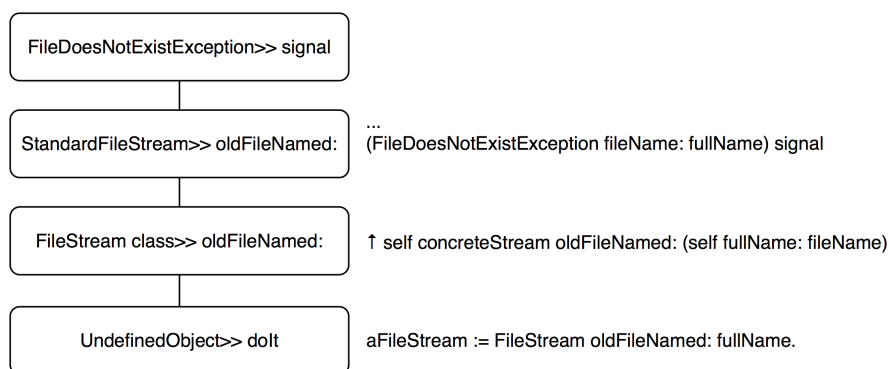


Figure 1.2: A Pharo execution stack.

Since everything is an object in Smalltalk, we would expect method contexts to be objects. However, some Smalltalk implementations use the native C execution stack of the virtual machine to avoid creating objects all the time. The current Pharo virtual machine does actually use full Smalltalk objects all the time; for speed, it recycles old method context objects rather than creating a new one for each message-send.

When we send `aBlock on: ExceptionClass do: actionHandler`, we intend to associate an exception handler (`actionHandler`) with a given class of exceptions (`ExceptionClass`) for the activation context of the protected block `aBlock`. This information is used to identify and execute `actionHandler` whenever an exception of an appropriate class is signaled; `actionHandler` can be found by traversing the stack starting from the top (the most recent message-send) and working down to the context that sent the `on:do:` message.

If there is no exception handler on the stack, the message `defaultAction` will

be sent either by `ContextPart»handleSignal:` or by `UndefinedObject»handleSignal:`. The latter is associated with the bottom of the stack, and is defined as follows:

```
UndefinedObject»handleSignal: exception
    "When no more handler (on:do:) context is left in the sender chain, this gets called.
    Return from signal with default action."
    ↑ exception resumeUnchecked: exception defaultAction
```

The message `handleSignal:` is sent by `Exception»signal`.

When an exception *E* is signaled, the system identifies and fetches the corresponding exception handler by searching down the stack as follows:

1. Look in the current activation context for a handler, and test if that handler `canHandleSignal: E`.
2. If no handler is found and the stack is not empty, go down the stack and return to step 1.
3. If no handler is found and the stack is empty, then send `defaultAction` to *E*. The default implementation in the `Error` class leads to the opening of a debugger.
4. If the handler is found, send it value: *E*.

Nested Exceptions. Exception handlers are outside of their own scope. This means that if an exception is signaled from within an exception handler—what we call a nested exception—a *separate* handler must be set to catch the nested exception.

Here is an example where one `on:do:` message is the receiver of another one; the second will catch errors signaled by the handler of the first:

```
result := [[ Error signal: 'error 1' ]
  on: Exception
  do: [ Error signal: 'error 2' ] ]
  on: Exception
  do: [:ex | ex description ].
result  → 'Error: error 2'
```

Without the second handler, the nested exception will not be caught, and the debugger will be invoked.

An alternative would be to specify the second handler within the first one:

```

result := [ Error signal: 'error 1' ]
  on: Exception
  do: [[ Error signal: 'error 2' ]
    on: Exception
    do: [:ex | ex description ]].
result  → 'Error: error 2'

```

1.9 Handling exceptions

When an exception is signaled, the handler has several choices about how to handle it. In particular, it may:

- (i) *abandon* the execution of the protected block, by simply specifying an alternative result;
- (ii) *return* an alternative result for the protected block, by sending `returnValue` to the exception object;
- (iii) *retry* the protected block, by sending `retry`, or try a different block by sending `retryUsing`;
- (iv) *resume* the protected block at the failure point, by sending `resume` or `resume`;
- (v) *pass* the caught exception to the enclosing handler, by sending `pass`; or
- (vi) *resignal* a different exception, by sending `resignalAs:` to the exception.

We will briefly look at the first three possibilities, and then we will take a closer look at the remaining ones.

Abandon the protected block

The first possibility is to abandon the execution of the protected block, as follows:

```

answer := [ |result|
  result := 6 * 7.
  Error signal.
  result "This part is never evaluated"]
  on: Error
  do: [:ex | 3 + 4 ].
answer  → 7

```

The handler takes over from the point where the error is signaled, and any code following in the original block is not evaluated.

Return a value with return:

A block returns the value of the last statement in the block, regardless of whether the block is protected or not. However, there are some situations where the result needs to be returned by the handler block. The message `return: aValue` sent to an exception has the effect of returning *aValue* as the value of the protected block:

```
result := [Error signal]
  on: Error
  do: [ :ex | ex return: 3 + 4 ].
result  → 7
```

The ANSI standard is not clear regarding the difference between using `do: [:ex | 100]` and `do: [:ex | ex return: 100]` to return a value. We suggest that you use `return:` since it is more intention-revealing, even if these two expressions are equivalent in Pharo.

A variant of `return:` is the message `return`, which returns `nil`.

Note that, in any case, control will *not* return to the protected block, but will be passed on up to the enclosing context.

```
6 * ([Error signal] on: Error do: [ :ex | ex return: 3 + 4 ])  → 42
```

Retry a computation with retry and retryUsing:

Sometimes we may want to change the circumstances that led to the exception and retry the protected block. This is done by sending `retry` or `retryUsing:` to the exception object. It is important to be sure that the conditions that caused the exception have been changed before retrying the protected block, or else an infinite loop will result:

```
[Error signal] on: Error do: [ :ex | ex retry]  "will loop endlessly"
```

Here is a better example. The protected block is re-evaluated within a modified environment where `theMeaningOfLife` is properly initialized:

```
result := [ theMeaningOfLife * 7 ]  "error -- theMeaningOfLife is nil"
  on: Error
  do: [ :ex | theMeaningOfLife := 6. ex retry ].
result  → 42
```

The message `retryUsing: aNewBlock` enables the protected block to be replaced by `aNewBlock`. This new block is executed and is protected with the same handler as the original block.

```

x := 0.
result := [ x/x ]   "fails for x=0"
  on: Error
  do: [:ex |
    x := x + 1.
    ex retryUsing: [1/((x-1)*(x-2))]   "fails for x=1 and x=2"
  ].
result  → (1/2)   "succeeds when x=3"

```

The following code loops endlessly:

```
[1 / 0] on: ArithmeticError do: [:ex | ex retryUsing: [ 1 / 0 ]]
```

whereas this will signal an Error:

```
[1 / 0] on: ArithmeticError do: [:ex | ex retryUsing: [ Error signal ]]
```

As another example, recall the file handling code we saw earlier, in which we printed a message to the Transcript when a file is not found. Instead, we could prompt for the file as follows:

```

[(StandardFileStream oldFileNamed: 'error42.log') contentsOfEntireFile]
  on: FileDoesNotExistException
  do: [:ex | ex retryUsing: [FileList modalFileSelector contentsOfEntireFile] ]

```

1.10 Resuming execution

A method that signals an exception that is `Resumable` can be resumed at the place immediately following the signal. An exception handler may therefore perform some action, and then resume the execution flow. This behavior is achieved by sending `resume:` to the exception in the handler. The argument is the value to be used in place of the expression that signaled the exception. In the following example we signal and catch `MyResumableTestError`, which is defined in the `Tests-Exceptions` category:

```

result := [ | log |
  log := OrderedCollection new.
  log addLast: 1.
  log addLast: MyResumableTestError signal.
  log addLast: 2.
  log addLast: MyResumableTestError signal.
  log addLast: 3.
  log ]
  on: MyResumableTestError
  do: [:ex | ex resume: 0 ].
result  → an OrderedCollection(1 0 2 0 3)

```

Here we can clearly see that the value of `MyResumableTestError` signal is the value of the argument to the `resume:` message.

The message `resume` is equivalent to `resume: nil`.

The usefulness of resuming an exception is illustrated by the class `Installer`, which implements an automatic package loading mechanism. When installing packages, warnings may be signaled. Warnings should not be considered fatal errors, so the installer should simply ignore the warning and continue installing.

```
Installer>installQuietly: packageNameCollectionOrDetectBlock
  self package: packageNameCollectionOrDetectBlock.
  [ self install ] on: Warning do: [ :ex | ex resume ].
```

Another situation where resumption is useful is when you want to ask the user what to do. For example, suppose that we were to define a class `ResumableLoader` with the following method:

```
ResumableLoader>readOptionsFrom: aStream
  | option |
  [aStream atEnd]
  whileFalse: [option := self parseOption: aStream.
    "nil if invalid"
    option isNil
    ifTrue: [InvalidOption signal]
    ifFalse: [self addOption: option]].
  aStream close
```

If an invalid option is encountered, we signal an `InvalidOption` exception. The context that sends `readOptionsFrom:` can set up a suitable handler:

```
ResumableLoader>readConfiguration
  | stream |
  stream := self optionStream.
  [self readOptionsFrom: stream]
  on: InvalidOption
  do: [:ex | (UIManager default confirm: 'Invalid option line. Continue loading?')
    ifTrue: [ex resume]
    ifFalse: [ex return]].
  stream close
```

Depending on user input, the handler in `readConfiguration` might return `nil`, or it might resume the exception, causing the signal message send in `readOptionsFrom:` to return and the parsing of the options stream to continue.

Note that `InvalidOption` must be resumable; it suffices to define it as a subclass of `Exception`.

Example: Deprecation

Deprecation offers a case study of a mechanism built using resumable exceptions. Deprecation is a software re-engineering pattern that allows us to mark a method as being “deprecated”, meaning that it may disappear in a future release and should not be used by new code. In Pharo, a method can be marked as deprecated as follows:

```
Utilities class>convertCRtoLF: fileName
```

```
"Convert the given file to LF line endings. Put the result in a file with the extension '.lf'"
```

```
self deprecated: 'Use "FileStream convertCRtoLF: fileName" instead.'
```

```
on: '10 July 2009' in: #Pharo1.0 .
```

```
FileStream convertCRtoLF: fileName
```

When the message `convertCRtoLF:` is sent, if the `raiseDeprecationWarnings` preference is true, then a pop-up window is displayed with a notification and the programmer may resume the application execution; this is shown in Figure 1.3.

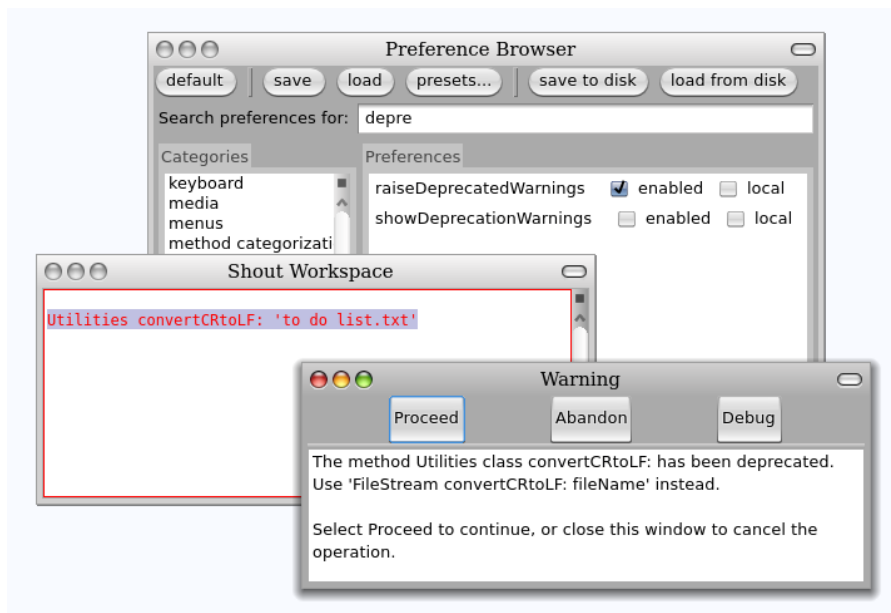


Figure 1.3: Sending a deprecated message.

Deprecation is implemented in Pharo in just a few steps. First, we define *Deprecation* as a subclass of *Warning*. It should have some instance variables to contain information about the deprecation: in Pharo these are `methodReference`, `explanationString`, `deprecationDate` and `versionString`; we therefore

need to define an instance-side initialization method for these variables, and a class-side instance creation method that sends the corresponding message.

When we define a new exception class, we should consider overriding `isResumable`, `description`, and `defaultAction`. In this case the inherited implementations of the first two methods are fine:

- `isResumable` is inherited from `Exception`, and answers `true`;
- `description` is inherited from `Exception`, and answers an adequate textual description.

However, it is necessary to override the implementation of `defaultAction`, because we want that to depend on some preferences. Here is Pharo's implementation:

```
Deprecation>>defaultAction
Log ifNotNil: [:log| log add: self].
Preferences showDeprecationWarnings ifTrue:
  [Transcript nextPutAll: explanationString; cr; flush].
Preferences raiseDeprecatedWarnings ifTrue:
  [super defaultAction]
```

The first preference simply causes a warning message to be written on the Transcript. The second preference asks for an exception to be signaled, which is accomplished by super-sending `defaultAction`.

We also need to implement some convenience methods in `Object`, like this one:

```
Object>>deprecated: anExplanationString on: date in: version
(Deprecation
  method: thisContext sender method
  explanation: anExplanationString
  on: date
  in: version) signal
```

1.11 Passing exceptions on

To illustrate the remaining possibilities for handling exceptions, we will look at how to implement a generalization of the `perform:` method. If we send `perform: aSymbol` to an object, this will cause the message named *aSymbol* to be sent to that object:

```
5 perform: #factorial → 120 "same as: 5 factorial"
```

Several variants of this method exist. For example:

```
1 perform: #+ withArguments: #(2)  →  3  "same as: 1 + 2"
```

These perform:-like methods are very useful for accessing an interface dynamically, since the messages to be sent can be determined at run-time.

One message that is missing is one that will send a cascade of unary messages to a given receiver. A simple and naive implementation is:

```
Object»performAll: selectorCollection
  selectorCollection do: [:each | self perform: each]  "aborts on first error"
```

This method could be used as follows:

```
Morph new performAll: #( #activate #beTransparent #beUnsticky)
```

However, there is a complication. There might be a selector in the collection that the object does not understand (such as #activate). We would like to ignore such selectors and continue sending the remaining messages. The following implementation seems to be reasonable:

```
Object»performAll: selectorCollection
  selectorCollection do: [:each |
    [self perform: each]
    on: MessageNotUnderstood
    do: [:ex | ex return]]  "also ignores internal errors"
```

On closer examination we notice another problem. This handler will not only catch and ignore messages not understood by the original receiver, but also any messages sent but not understood in methods for messages that *are* understood! This will hide programming errors in those methods, which is not our intent. To fix this, we need our handler to analyze the exception to see if it was indeed caused by the attempt to perform the current selector. Here is the correct implementation.

Method 1.1: *Object»performAll:*

```
Object»performAll: selectorCollection
  selectorCollection do: [:each |
    [self perform: each]
    on: MessageNotUnderstood
    do: [:ex | (ex receiver == self and: [ex message selector == each])
      ifTrue: [ex return]
      ifFalse: [ex pass]]]  "pass internal errors on"
```

This has the effect of passing on MessageNotUnderstood errors to the surrounding context when they are not part of the list of messages we are performing. The pass message will pass the exception on to the next applicable handler in the execution stack.

If there is no next handler on the stack, the `defaultAction` message is sent to the exception instance. The `pass` action does not modify the sender chain in any way—but the handler that control is passed to may do so. Like the other messages discussed in this section, `pass` is special—it never returns to the sender.

The goal of this section has been to demonstrate the power of exceptions. It should be clear that while you can do almost anything with exceptions, the code that results is not always easy to understand. There is often a simpler way to get the same effect without exceptions; see method 1.2 on page 28 for a better way to implement `performAll:`.

1.12 Resending exceptions

Now suppose that in our `performAll:` example we no longer want to ignore selectors not understood by the receiver, but instead we want to consider an occurrence of such a selector as an error. However, we want it to be signaled as an application-specific exception, let's say `InvalidAction`, rather than the generic `MessageNotUnderstood`. In other words, we want the ability to “resignal” a signaled exception as a different one.

It might seem that the solution would simply be to signal the new exception in the handler block. The handler block in our implementation of `performAll:` would be:

```
[ex | (ex receiver == self and: [ex message selector == each])
  ifTrue: [InvalidAction signal]    "signals from the wrong context"
  ifFalse: [ex pass]]
```

A closer look reveals a subtle problem with this solution, however. Our original intent was to replace the occurrence of `MessageNotUnderstood` with `InvalidAction`. This replacement should have the same effect as if `InvalidAction` were signaled at the same place in the program as the original `MessageNotUnderstood` exception. Our solution signals `InvalidAction` in a different location. The difference in locations may well lead to a difference in the applicable handlers.

To solve this problem, resignaling an exception is a special action handled by the system. For this purpose, the system provides the message `resignalAs:`. The correct implementation of a handler block in our `performAll:` example would be:

```
[ex | (ex receiver == self and: [ex message selector == each])
  ifTrue: [ex resignalAs: InvalidAction] "resignals from original context"
  ifFalse: [ex pass]]
```

1.13 Comparing outer with pass

The method `outer` is very similar to `pass`. Sending `outer` to an exception also evaluates the enclosing handler action. The only difference is that if the `outer` handler resumes the exception, then control will be returned to the point where `outer` was sent, not the original point where the exception was signaled:

```
passResume := [[ Warning signal . 1 ]   "resume to here"
  on: Warning
  do: [ :ex | ex pass . 2 ]]
  on: Warning
  do: [ :ex | ex resume ].
passResume  → 1  "resumes to original signal point"
```

```
outerResume := [[ Warning signal . 1 ]
  on: Warning
  do: [ :ex | ex outer . 2 ]]   "resume to here"
  on: Warning
  do: [ :ex | ex resume ].
outerResume  → 2  "resumes to where outer was sent"
```

1.14 Catching sets of exceptions

So far we have always used `on:do:` to catch just a single class of exception. The handler will only be invoked if the exception signaled is a sub-instance of the specified exception class. However, we can imagine situations where we might like to catch multiple classes of exceptions. This is easy to do:

```
result := [ Warning signal . 1/0 ]
  on: Warning, ZeroDivide
  do: [ :ex | ex resume: 1 ].
result  → 1
```

If you are wondering how this works, just have a look at the implementation of `Exception class», anotherException`,

```
Exception class», anotherException
  "Create an exception set."

  ↑ExceptionSet new
    add: self;
    add: anotherException;
    yourself
```

The rest of the magic occurs in the class `ExceptionSet`, which has a surprisingly trivial implementation.

```
Object subclass: #ExceptionSet
  instanceVariableNames: 'exceptions'
  classVariableNames: "
  poolDictionaries: "
  category: 'Exceptions-Kernel'

ExceptionSet»initialize
  super initialize.
  exceptions := OrderedCollection new

ExceptionSet», anException
  self add: anException.
  ↑self

ExceptionSet»add: anException
  exceptions add: anException

ExceptionSet»handles: anException
  exceptions do: [:ex | (ex handles: anException) ifTrue: [↑true]].
  ↑false
```

1.15 Exceptions implementation

Up to now, we have presented the use of exceptions without really explaining deeply how there are implemented at the Virtual Machine level. Note that since you do not need to know how exceptions are implemented to use them, you can simply skip this section in a first reading. Now if you are curious and really want to know how this is implemented at the Virtual Machine level, this section is for you. The mechanism is quite simple, making it worth to know how it operates.

So let's have a look at how exceptions are implemented at the Virtual Machine level.

Storing Handlers. First we need to understand how the exception class and its associated handler are stored and how this information is found at run-time. Let's look at the definition of the central method `on:do:` defined on the class `BlockClosure`.

```
BlockClosure»on: exception do: handlerAction
  "Evaluate the receiver in the scope of an exception handler."
  | handlerActive |
  <primitive: 199>
  handlerActive := true.
  ↑self value
```

This code tells us two things: First, this method is implemented as a primitive, which means that a primitive operation of the virtual machine is executed when this method is invoked. VM primitives don't normally return: successful execution of a primitive terminates the method that contains the `<primitive: n>` instruction, answering the result of the primitive. So, the Smalltalk code that follows the primitive serves two purposes: it documents what the primitive does, and is available to be executed if the primitive should fail. Here we see that `on:do:` simply sets the temporary variable `handlerActive` to true, and then evaluates the receiver (which is, of course, a block).

This is surprisingly simple, but somewhat puzzling. Where are the arguments of the `on:do:` method stored? Let's look at the definition of the class `MethodContext`, whose instances make up the execution stack:

```
ContextPart variableSubclass: #MethodContext
  instanceVariableNames: 'method closureOrNil receiver'
  classVariableNames: "
  poolDictionaries: "
  category: 'Kernel-Methods'
```

There is no instance variable here to store the exception class or the handler, nor is there any place in the superclass to store them. However, note that `MethodContext` is defined as a `variableSubclass`. This means that in addition to the named instance variables, objects of this class have some numbered slots. In fact, every `MethodContext` has a numbered slot for each argument of the method whose invocation it represents. There are also additional numbered slots for the temporary variables of the method.

To verify this, you can evaluate the following piece of code:

```
| exception handler |
[exception := thisContext sender at: 1.
 handler := thisContext sender at: 2.
 1 / 0]
on: Error
do: [:ex| ].
{ exception . handler } explore
```

The last line explores a 2-element array that contains the exception class and the exception handler.

Note that you can also execute the following code you obtain an explorer and that you can see that the exception class and the handler are stored in the first and second variable instance variables of the method context object (a method context represents an execution stack element).

```
[thisContext sender explore] on: Error do: [:ex].
```

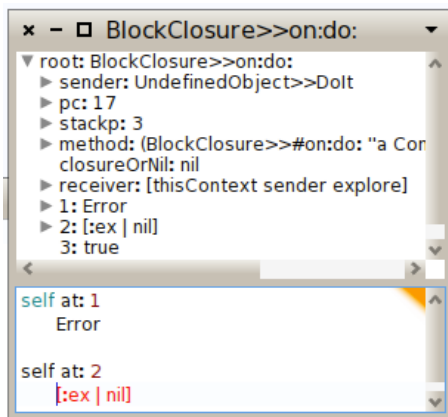


Figure 1.4: Explore a method context to find the exception class and the handler.

Finding Handlers. Now that we know where the information is stored, let's have a look at how it is found at runtime.

We might think that the primitive 199 is complex to write. But it too is trivial, because primitive 199 *always* fails! Because the primitive always fails, the Smalltalk body of `on:do:` is always executed. However, the presence of the `<primitive: 199>` bytecode marks the executing context in a unique way.

The source code of the primitive is found in `Interpreter»primitiveMarkHandlerMethod` in the *VMMaker SqueakSource* project:

```
primitiveMarkHandlerMethod
```

"Primitive. Mark the method for exception handling. The primitive must fail after marking the context so that the regular code is run."

```
self inline: false.
```

```
↑self primitiveFail
```

So now we know that when the method `on:do:` is executed, the `MethodContext` that makes up the stack frame is tagged and the handler and exception class are stored there.

Now, if an exception is signaled further up the stack, the method `signal` can search the stack to find the appropriate handler:

Exception»`signal`

*"Ask ContextHandlers in the sender chain to handle this signal.
The default is to execute and return my defaultAction."*

```
signalContext := thisContext contextTag.  
↑ thisContext nextHandlerContext handleSignal: self
```

ContextPart»`nextHandlerContext`

```
↑ self sender findNextHandlerContextStarting
```

The method `findNextHandlerContextStarting` is implemented as a primitive (number 197); its body describes what it does. It looks to see if the stack frame is a context created by the execution of the method `on:do:` (it just looks to see if the primitive number is 199). If this is the case it answers with that context.

ContextPart»`findNextHandlerContextStarting`

"Return the next handler marked context, returning nil if there is none. Search starts with self and proceeds up to nil."

```
| ctx |  
<primitive: 197>  
ctx := self.  
[ ctx isHandlerContext ifTrue: [↑ctx].  
  (ctx := ctx sender) == nil ] whileFalse.  
↑nil
```

MethodContext»`isHandlerContext`

"is this context for method that is marked?"

```
↑method primitive = 199
```

Since the method context supplied by `findNextHandlerContextStarting` contains all the exception-handling information, it can be examined to see if the exception class is suitable for handling the current exception. If so, the associated handler can be executed; if not, the look-up can continue further. This is all implemented in the `handleSignal:` method.

ContextPart»`handleSignal:` exception

"Sent to handler (on:do:) contexts only. If my exception class (first arg) handles exception then execute my handle block (second arg), otherwise forward this message to the next handler context. If none left, execute exception's defaultAction (see nil>>handleSignal:)."

```
| val |  
(((self tempAt: 1) handles: exception) and: [self tempAt: 3]) ifFalse: [
```

```

↑ self nextHandlerContext handleSignal: exception].

exception privHandlerContext: self contextTag.
self tempAt: 3 put: false. "disable self while executing handle block"
val := [(self tempAt: 2) valueWithPossibleArgs: {exception}]
  ensure: [self tempAt: 3 put: true].
self return: val. "return from self if not otherwise directed in handle block"

```

Notice how this method uses tempAt: 1 to access the exception class, and ask if it handles the exception. What about tempAt: 3? That is the temporary variable handlerActive of the on:do: method. Checking that handlerActive is true and then setting it to false ensures that a handler will not be asked to handle an exception that it signals itself. The return: message sent as the final action of handleSignal is responsible for “unwinding” the execution stack by removing the stack frames above self.

The full story is only slightly more complicated because there are actually two classes of objects that make up the stack, MethodContexts, which we have already discussed, and BlockContexts, which represent the execution of blocks. ContextPart is their common superclass.

So, to summarize, the signal method, with minimal assistance from the virtual machine, finds the context that correspond to an on:do: message with an appropriate exception class. Because the execution stack is made up of Context objects that may be manipulated just like any other object, the stack can be shortened at any time. This is a superb example of flexibility of Smalltalk.

1.16 Other kinds of Exception

The class Exception in Pharo has ten direct subclasses, as shown in Figure 1.5. The first thing that we notice from this figure is that the Exception hierarchy is a bit of a mess; you can expect to see some of the details change as Pharo is improved.

The second thing that we notice is that there are two large sub-hierarchies: Error and Notification. Errors tell us that the program has fallen into some kind of abnormal situation. In contrast, Notifications tell us that an event has occurred, but without the assumption that it is abnormal. So, if a Notification is not handled, the program will continue to execute. An important subclass of Notification is Warning; warnings are used to notify other parts of the system, or the user, of abnormal but non-lethal behavior.

The property of being resumable is largely orthogonal to the location of an exception in the hierarchy. In general, Errors are not resumable, but 10 of its subclasses *are* resumable. For example, MessageNotUnderstood is a subclass of Error, but it is resumable. TestFailures are not resumable, but, as you would

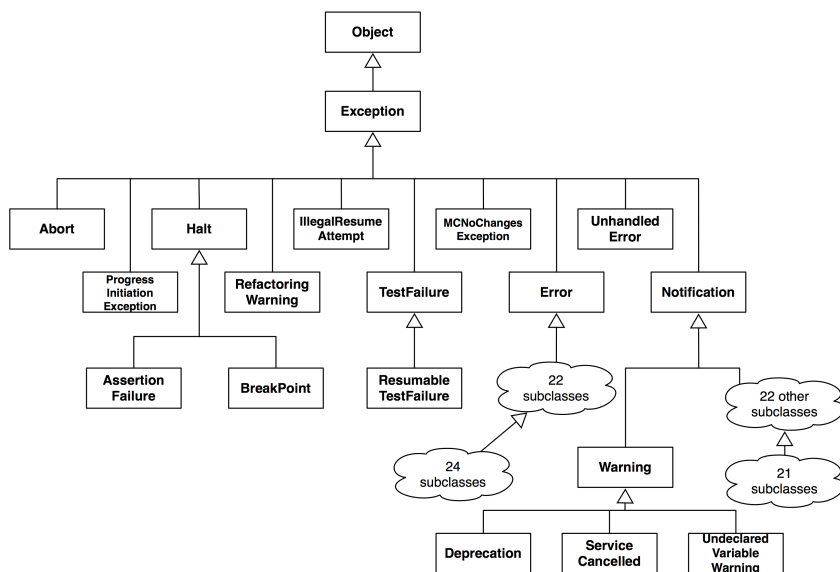


Figure 1.5: The whole Pharo exception hierarchy.

expect, `ResumableTestFailures` are.

Resumability is controlled by the private `Exception` method `isResumable`. For example:

```

Exception new isResumable  → true
Error new isResumable    → false
Notification new isResumable → true
Halt new isResumable     → true
MessageNotUnderstood new isResumable → true
  
```

As it turns out, roughly 2/3 of all exceptions are resumable:

```

Exception allSubclasses size  → 103
(Exception allSubclasses select: [:each | each new isResumable]) size → 66
  
```

If you declare a new subclass of exceptions, you should look in its protocol for the `isResumable` method, and override it as appropriate to the semantics of your exception.

In some situations, it will never makes sense to resume an exception. In such a case you should signal a non-resumable subclass — either an existing one or one of your own creation. In other situations, it will always be OK to resume an exception, without the handler having to do anything. In fact, this gives us another way of characterizing a notification: a `Notification` is a resumable `Exception` that can be safely resumed without first modifying the

state of the system. More often, it will be safe to resume an exception only if the state of the system is first modified in some way. So, if you signal a resumable exception, you should be very clear about what you expect an exception handler to do before it resumes the exception.

1.17 When not to use Exceptions

Just because Pharo has exception handling, you should not conclude that it is always appropriate to use it. Recall that in the introduction to this chapter, we said that exception handling is for *exceptional* situations. So, the first rule for using exceptions is *not* to use them for situations that *can reasonably be expected to occur* in a normal execution.

Of course, if you are writing a library, what is normal depends on the context in which your library is used. To make this concrete, let's look at Dictionary as an example: *aDictionary* at: *aKey* will signal an Error if *aKey* is not present. But you should not write a handler for this error! If the logic of your application is such that there is some possibility that the key will not be in the dictionary, then you should instead use at: *aKey* ifAbsent: [*remedial action*]. In fact, Dictionary»at: is implemented using Dictionary»at:ifAbsent:. *aCollection* detect: *aPredicateBlock* is similar: if there is any possibility that the predicate might not be satisfied, you should use *aCollection* detect: *aPredicateBlock* ifNone: [*remedial action*].

When you write methods that signal exceptions, you should consider whether you should also provide an alternative method that takes a remedial block as an additional argument, and evaluates it if the normal action cannot be completed. Although this technique can be used in any programming language that support closures, because Smalltalk uses closures for *all* its control structures, it is a particularly natural one to use in Smalltalk.

Another way of avoiding exception handling is to test the precondition of the exception before sending the message that may signal it. For example, in method 1.1, we sent a message to an object using perform:, and handled the MessageNotUnderstood error that might ensue. A much simpler alternative is to check to see if the message is understood before executing the perform:

Method 1.2: Object»performAll: revisited

```
performAll: selectorCollection
  selectorCollection
    do: [:each | (self respondsTo: each)
              ifTrue: [self perform: each]]
```

The primary objection to method 1.2 is efficiency. The implementation of respondsTo: s has to lookup s in the target's method dictionary to find out if s will be understood. If the answer is yes, then perform: will look it up again.

Moreover, the first lookup is implemented in Smalltalk, not in the virtual machine. If this code is in a performance-critical loop, this might be an issue. However, if the collection of messages comes from a user interaction, the speed of `performAll:` will not be a problem.

1.18 Chapter Summary

In this chapter we saw how to use exceptions to signal and handle abnormal situations arising in our code.

- Don't use exceptions as a control-flow mechanism. Reserve them for notifications and for *abnormal* situations. Consider providing methods that take blocks as arguments as an alternative to signaling exceptions.
- Use `protectedBlock ensure: actionBlock` to ensure that `actionBlock` will be performed even if `protectedBlock` terminates abnormally.
- Use `protectedBlock ifCurtailed: actionBlock` to ensure that `actionBlock` will be performed *only* if `protectedBlock` terminates abnormally.
- Exceptions are objects. Exception classes form a hierarchy with the class `Exception` at the root of the hierarchy.
- Use `protectedBlock on: ExceptionClass do: handlerBlock` to catch exceptions that are instances of `ExceptionClass` (or any of its subclasses). The `handlerBlock` should take an exception instance as its sole argument.
- Exceptions are signaled by sending one of the messages `signal` or `signal:`. `signal:` takes a descriptive string as its argument. The description of an exception can be obtained by sending it the message `description`.
- You can set a breakpoint in your code by inserting the message `send self halt`. This signals a resumable `Halt` exception, which, by default, will open a debugger at the point where the breakpoint occurs.
- When an exception is signaled, the runtime system will search up the execution stack, looking for a handler for that specific class of exception. If none is found, the `defaultAction` for that exception will be performed (*i.e.*, in most cases the debugger will be opened).
- An exception handler may terminate the protected block by sending `return:` to the signaled exception; the value of the protected block will be the argument supplied to `return:`.
- An exception handler may retry a protected block by sending `retry` to the signaled exception. The handler remains in effect.

- An exception handler may specify a new block to try by sending `retryUsing:` to the signaled exception, with the new block as its argument. Here, too, the handler remains in effect.
- Notifications are subclass of Exception with the property that they can be safely resumed without the handler having to take any specific action.

Acknowledgments. We gratefully acknowledge Vassili Bykov for the raw material he provided. We also thank Paolo Bonzini, the main developer of GNU Smalltalk, for the Smalltalk implementations of `ensure:` and `ifCurtailed:`.