Katana: An ELF/DWARF Manipulation Tool with Hotpatching Capabilities

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08 May 2011

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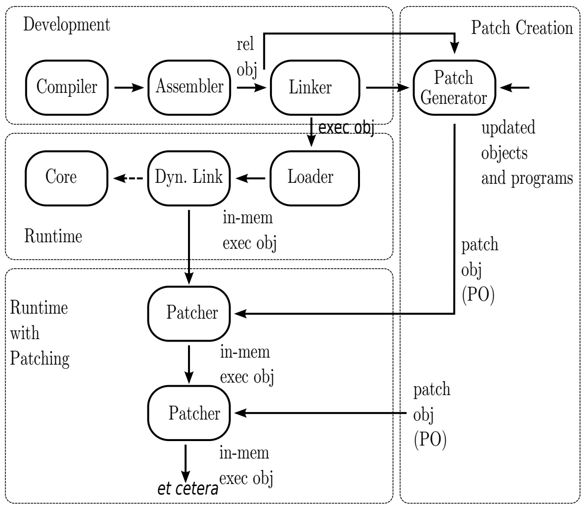
1 Introduction

Katana is a research system for ELF/DWARF manipulation. It was originally developed for research into hotpatching. It was later revised for research into security implication of gcc/C++ exception handling, which is implemented primarily using DWARF call frame information. Therefore, if you are interested in vulnerabilities related to exceptiong handling/DWARF you may probably ignore the parts of this manual which discuss hotpatching. If you are instead interested in hotpatching, you may probably ignore the parts of this manual that deal with manipulating exception handling structures.

Katana aims to provide a hot-patching system for userland. Further it aims to work with existing toolchains and formats so as to be easy to use and to hopefully pave the way for incorporating patching as a standard part of the toolchain. Because of this aim, Katana operates at the object level rather than requiring any access to the source code itself. This has the added bonus of making it, in theory, language agnostic (although no work has been done to test it with anything besides programs written in C). A diagram of software lifecycle with hotpatching is shown below (unless you are reading this in plain text)

This document is intended to provide a users guide to Katana, insight into its inner workings, and discussion of its flaws and plans for the future. As the software is not complete, making use of Katana without understanding the inner workings and technical shortcomings is not recommended. Nevertheless, the only sections of this document necessary for "Users' Guide" purposes are "What Katana Does", "What Katana Does Not Do (Yet)", and most importantly "How to Use Katana For Hotpatching".



This document is a work in progress. It is not a polished guide yet.

2 General Usage Information

2.1 Shell

If Katana is not passed an argument indicating one of the hot-patching commands (described later in *How to Use Katana For Hotpatching), then it is assumed to be operating as a shell. If it is provided an argument, that argument is taken as the name of a file to read shell commands from. Otherwise commands are read from stdin using the readline library.

2.1.1 Syntax and Data Model

The Katana shell syntax is very simple. There are no control flow structures, only commands and variables. A line is terminated by a semicolon (;) or a newline character. Each line may be either blank, contain exactly one COMMAND, or contain an ASSIGNMENT.

A COMMAND is of the form $\text{COMMAND}_{\text{IDENTIFIER}}$ PARAM PARAM PARAM …., where tokens are seperated by spaces and the number of PARAMs depends on the command.

An ASSIGNMENT is currently of the form VARIABLE=COMMAND although in the future it may be possible to write other sorts of assignments.

A VARIABLE reference consists of a dollar-sign ($) followed by a letter or underscore followed by any number of letters, underscores, or digits.

A COMMAND$_{\text{IDENTIFIER}}$ is one or more words which identify a COMMAND. In many cases a command is identified by only one word, but sometimes similar commands are grouped by sharing the first word in their identifier.

A PARAM is a VARIABLE reference, STRING, or NUMBER

A STRING is any literal beginning and ending with the character “.

A NUMBER is a decimal, hex, or float literal.

- Data Types

  The following types of variables exist

  - string
  - ELF
  - ELF section
  - raw data
  - array

2.1.2 Available Commands

- load

  Usage: `load FILENAME`
  Params: FILENAME must a string literal or variable that can be interpreted as a string.
  Function: Loads the data in the given file as an ELF object if possible. If not, loads it as raw data.

- save

  Usage: `save VAR FILENAME`
  Params: VAR must be a variable that can be interpreted as an ELF object or that can be interpreted as raw data. FILENAME must be a literal or variable that can be interpreted as a string.
  Function: Saves VAR to FILENAME.

- dwarfscript

- dwarfscript emit

  Usage: `dwarfscript emit [SECTION] ELF OUTFILE`
  Params: SECTION must be the name (string) of the section to write as Dwarfscript. If not specified it defaults to ".eh_{frame}". ELF must be an ELF object. OUTFILE must be a string with the name of a file to write the resulting Dwarfscript to.
  Function: Writes the Dwarfscript representation of the given SECTION from the given ELF to OUTFILE.

- dwarfscript compile

  Usage: `dwarfscript compile INFILE`
  Params: INFILE must be a string containing the name of a file.
  Function: Interprets the contents of the file named by INFILE as Dwarfscript and compiles the Dwarfscript into beinary form. Returns an array with 3 items 0: raw data for .eh_{frame} 1: raw data for .$\text{eh}_{\text{framehdr}}$ 2: raw data for .$\text{gcc}_{\text{excepttable}}$.

* extract

  - extract section

    Usage: `extract section ELF SECTION_NAME` *Params*: ELF must be an ELF object. $\text{SECTION}_{\text{NAME}}$ must be a string. *Function*: Returns the data and header information for the specified section

  - extract $\text{section}_{\text{data}}$

    Usage: `extract section ELF SECTION_NAME` *Params*: ELF must be an ELF object. $\text{SECTION}_{\text{NAME}}$ must be a string. *Function*: Like extract section except extracts only the raw data stored in the section and not any header information.

* replace

  - replace section

    Usage: `replace section ELF SECTION_NAME NEW_SECTION` *Params*: ELF must be an ELF object. $\text{SECTION}_{\text{NAME}}$ must be a string.

$\text{NEW}_{\text{SECTION}}$ must be either an ELF section or raw data. *Function*: Replaces the section with the name $\text{SECTION}_{\text{NAME}}$ in the oject ELF with the data from $\text{NEW}_{\text{SECTION}}$. Section headers are replaced if $\text{NEW}_{\text{SECTION}}$ is able to provide them, but not if it is only raw data.

  - replace raw

    Usage: `replace raw ELF OFFSET NEW_DATA` *Params*: ELF must be an ELF object. ADDRESS must be an integer. NEW_{DATA} must be raw data. *Function*: Replaces the raw data at OFFSET in the ELF object with NEW_{DATA}. OFFSET must refer to a location in an existing section.

- info

  - info eh

    Usage: `info eh ELF [OUTFILE]` *Params*: ELF must be an ELF object. OUTFILE, if present, must be the name of a writable file (which may or may not exist yet). *Function*: Prints out information about the exception-handling structures in ELF. If OUTFILE is present, this information is written to it.

- hash

  - hash elf

    Usage: `hash elf STR` *Params*: STR must be a string. *Function*: Prints the result of running elf_{hash} (from libelf) on the string.

- patch

  - gen

    Usage: `patch gen OLD_OBJECTS_DIR NEW_OBJECTS_DIR EXECUTABLE` *Params*: All three params are strings. The first two are the old and new object file directories respectively. The last is the name of the executable that can be found in both directories. *Function*: Generates (and returns) a patch object ELF.

  - apply

    Usage: `patch apply PO PID` *Params*: The PO parameter should be an ELF patch object. PID should be the (integer) pid of the process that PO is to be applied to. *Function*: Applies the patch object PO to the running process described by PID.

- ! (shell command)

  The rest of the line following by ! is executed in a shell.

2.1.3 History

Command history is saved using libreadline in `$HOME/.katana_history`.

3 Hotpatching

3.1 Other Systems

There are other hotpatching systems in existence. The curious are invited to explore Ginseng and Polus. Both of these systems parse the source code, which adds significant complexity to them and results in significant programmer annotation of the code to give hints to the systems. Ginseng uses complicated type-wrappers when patching variables which does not fit cleanly with existing executables and has some impact on the performance of the software. Ginseng is considerably more mature than Katana, however. Neither system is production ready, but Ginseng is probably closer than Katana at the moment.

The system most like Katana in many ways is KSplice, and the curious reader is definitely invited to investigate. KSplice patches the kernel and not userland, does not attempt to patch variables, and creates patches as kernel modules rather than working towards a general ELF-based patch format.

3.2 What Katana Does

- Runs on x86 and x86-64
- Generates patches for simple programs

- Applies simple patches

3.3 What Katana Does Not Do (Yet)

- Patch any major programs: it has not yet been demonstrated on anything more than toy examples
- Provide any method to handle opaque data it cannot patch (void*, situations where which action a user would prefer is unclear, etc)
- Patch previously patched processes
- Provide robust operation
- Run on any architectures other than x86 and x86-64
- Tested on any operating system besides GNU/Linux
- Allow for calls in patched code to previously unused functions
- Work for programs which actually make use of some of the large code model features of the x86-64 ABI.
- And much more

See Roadmap for more things which are not complete

3.4 What Katana May Never Do

- Work on any binary formats besides ELF

3.5 How to Use Katana For Hotpatching

Katana is intended to be used in two stages. The first stage generates a patch object from two different versions of an treee. By an object tree, we mean the set of object files (.o files) and the executable binary they comprise. Katana works completely at the object level, so the source code itself is not strictly required, although all objects must be compiled with debugging information. This step may be done by the software vendor. In the second stage, the patch is applied to a running process. The original source trees are not necessary during patch application, as the patch object contains all information necessary to patch the in-memory process at the object level. It is also possible to view the contents of a patch object in a human-readable way for the purposes of sanity-checking, determining what changes the patch makes, etc.

3.5.1 Preparing a Package for Patching Support

Katana aims to be much less invasive than other hot-patching system and require minimal work to be used with any project. It does, however, have some requirements.

3.5.2 Source Code Practices

Katana does not look at the source code, therefore unlike several other hot-patching systems, it does not require any annotation in the source code. There are, however, some best practices to follow.

- Avoid the use of `void*` at least for global variables (since Katana does not currently patch local variables, preferring to wait until any functions using changed variables are no longer on the stack). Since it is typeless and opaque, it is very hard to analyze and patch.
- Avoid unnamed types. i.e., instead of `typedef struct {...} Foo;` use `typedef struct Foo_ {...} Foo;`.
- Avoid accessing structure members by offsets instead of by the member names. As long as you keep all the code where you do this up to date, it should not be a problem, but katana cannot detect when you do this.

3.5.3 Compilation/Linking

Required CFLAGS:

- -g

Recommended CFLAGS:

- -ffunction-sections
- -fdata-sections

Recommended LDFLAGS:

- –emit-relocs

3.5.4 To Generate a Patch

Let the location of your project be /project. You must have two versions of your software available: the version identical to the running software which must be hotpatched, call it v0, and the version to which you wish to hotpatch the running software, call it v1. Let foo be the name of your program. Then /project/v0/foo must exist and /project/v0 must also contain (possibly in subdirectories) all of the object files which contributed to /project/v0/foo. The source code itself is immaterial, as Katana does not parse it. Similarly, /project/v1/foo must exist and /project/v1 contain all of the object files contributing to /project/v1/foo. Katana is then invoked as

`katana [OPTIONS] -g [-o OUTPUT_FILE] /project/v0 /project/v1 foo`

or more formally

`katana [OPTIONS] -g [-o OUTUT_FILE] OLD_OBJECTS_DIR NEW_OBJECTS_DIR EXECUTABLE_NAME`

If `-o OUTPUT_FILE` is not specified, the output file will be `OLD_OBJECTS_DIR/EXECUTABLE_NAME.po`

3.5.5 To Apply a Patch

The process to be patched is running with a pid of PID. It can be patched from its current version to a more recent version by the Patch Object (PO) file PATCH. Katana is then invoked as

`katana [OPTIONS] -p [-s] PATCH PID`

If all goes well, the patcher will run, print out some status messages, and leave your program in better state than it found it. The optional -s flag tells Katana to stop the target program after patching it and detaching from it. This is mostly of use for debugging Katana.

3.5.6 To View a Patch

One of the goals of Katana and its Patch Object (PO) format is to increase the transparency of patches: a user about to apply a patch should know what it will do. This goal is not yet fully realized, but it is possible to view some information about a patch with

`katana [OPTIONS] -l PATCH`

3.5.7 Options

The following options may be passed to katana regardless of whether one is generating, applying, or viewing a patch:

- -c CONFIG where CONFIG is the name of a configuration file to load

3.5.8 Configuration Files

Note that this feature is a work in progress. There isn't much you can do with configuration files right now and the information here may be out of date. Please do not rely on it.

Katana loads configuration files as follows. Configuration files loaded later in the sequence may overwrite settings from files earlier in the sequence.

- *etc/katana +* ~.katana
- ~/.config/katana
- ./katana
- any file specified with -c

Configuration files are written in JSON. The JSON requirement that strings be quoted is relaxed (i.e. anything is assumed to be a string unless it can be interpreted otherwise). The following properties are recognized:

- maxWaitForPatching <INTEGER> This value specifies the maximum number of seconds to wait for the target to enter a safe state.
- flags <OBJECT> The value of flags should be an object which may contain the following properties, all of which should be bool-valued:
  - checkPtraceWrites Whenever something is written into the target memory, read the value back out and verify that it was written correctly. This has a performance penalty, but does provide some more robust error checking, although it should not be necessary.

3.5.9 See Also

- The katana manpage (although the information in this document is considerably more extensive than in the manpage)
- S. Bratus, J. Oakley, A. Ramaswamy, S. Smith, M. Locasto. *Katana: Towards Patching as a Runtime part of the Compiler-Linker-Loader Toolchain.* International Journal of Secure Software Engineering (IJSEE). 1, 3 (2010).

3.6 Patch Object Format

We have developed a patch object (PO) format which we hope will eventually pave the way for a standardized vendor-neutral patch format for hotpatching. We are not advancing our format as such, but it embodies some of the principles which we think are important. Why should patching not be a part of the ABI and of the standard toolchain?

- A PO is a valid ELF file.
- A PO utilizes DWARF information to describe types, variables, and functions requiring patching.
- A PO allows type transformations to be specified using a language based on the DWARF standard.

Through the use of existing standards and well-structured ELF files utilizing a simple expression language for data patching, we aim to create patches that are easily examined (or modified) with existing tools. Relocatable objects containing new code and data which may be inserted at runtime are nothing new. This is the entire premise of the dynamic library. User-written functions which may have this code injection (in the case of patching data where the desired actions cannot be determined automatically) already exist as the .init and .fini sections. It is our view, however, that it is important to have a seperate patch format as opposed to patches merely being dynamic libraries which contain both the patch data and the logic to perform the patching (as is done by some other hotpatching systems). We view this as an unnecessary mixing of data and logic. The code to apply patches should live in one place on any given system, as most other executable content does.

As an ELF object, our PO files contain the following non-standard sections.

- .text.new Contains new/modified functions
- .rodata.new, .data.new new data
- .unsafe$_{\text{functions}}$ Contains a simple listing (of symbol indices) of the functions in the binary to be patched which should not have activation records on the stack when patching is taking place.
- .debug$_{\text{info}}$ Contains listings of the variables and functions which need to be patched using the DWARF data format. This section is standard and is used here with validly formatted data, but is used for patching

instead of debugging. The use of the the .debug_ name is preserved for compatibility with libdwarf and tools such as readelf, objdump, dwarfdump capable of listing DWARF information. It can be, however, confusing and the name will likely change in the future.

- .debug$_{\text{frame}}$ Like .debug$_{\text{info}}$ a standard section used in a nonstandard way, see notes above about the naming. Contains an extended version of DWARF Call Frame Information which describes how various data structures are to be patched. The details are not properly documented at the moment, please email the Authors for more details if you would like further information.

3.7 Patch Generation Process

This section of the document is still under construction, but we hope that the information that is provided will be of some use.

3.8 Configuration

Note that this feature is a work in progress. There isn't much you can do with configuration files right now.

Katana reads configuration files from (in order, with later configuration files overriding options found in earlier ones) from `/etc/katana`, `~/.katana`, `~/.config/katana`, and `./.katana`.

3.9 Initializing the patch object

Katana sets up a patch object ELF file with the necessary sections, see Patch Object Format

3.10 Comparing source trees

High level view:

- Katana compare the old and new source trees, looking at the object (.o) files.
- For object files which exist only in the new tree, their contents are added to the patch object being created.
- For object files which exist only in the old tree, a warning about their removal is issued and nothing further is done.

- For object files which exist in both trees, type diffing and function diffing are performed and the differences are written tot he patch object being created.

A more detailed (although still very rough) algorithm:

```
Walk the old and new object trees in parallel
  For each pair of objects (corresponding old and new objects)
    If the new object does not exist
      Issue a warning and continue
    If the old object does not exist
      Add all functions and vars to patch
      Continue
    If the two objects are the same
      Continue
    If the two objects differ
      For every global variable in the old object
        Compare with matching variable in the new object
        If the two are a different type or the type struct changes
          Generate a type transformation for the patch
        If the variable initializers changed
          If the variable is const
            Add new data to the patch
          Else
            Generate a warning (can't determine automatically if
                the change should be applied)
        If anything related to the variable changed
          Find all functions using the variable
          Add them to the unsafe functions list
      For every global variable only in the new object
        Add it to the patch
      For every function in the old object
        Compare with matching function in the new object
          If the functions differ
            Add the new text to the patch
            Add the function to the unsafe functions list.
      For ever function only in the new object
        Add the function to the patch
Write out the patch ELF!
```

3.11 Type Diffing

The general idea is that structures are examined for for added members, moved members, and changed members. If you need more detail than this, please contact the Authors.

3.12 Function Diffing

Functions are compared in an unsophisticated manner. The comparison is essentially byte-by-byte (i.e. no parsing of the machine instruction set is done). If bytes differ between the compiled version of the old function and the new function, then the function is assumed to need patching. The one exception to this is that relocations are accounted for. If bytes differ at an address that is fixed up by relocations, the relocations are examined to make sure that they are for the same symbol. If in fact they are, then the function is deemed not to have changed. If the symbol referred to corresponds to a variable that has changed then it may need to be moved to be patched. In that event the function may in fact have to be modified, but it will be modified only to apply the relocations rather than as a patch to the function per se and thus the function diffing stage does not concern itself with whether referenced symbols have changed.

3.13 Patch Application Process

This section of the document is not yet written. It will provide a description of the internal process that Katana uses to apply a patch. Understanding it is not necessary for using Katana.

The basic process is as follows

```
Read the patch file
Calculate versioning. This is currently not implemented.
Find malloc in the target, as we may need it
Calculate a safe state for the target (based on the unsafe functions list)
Wait for the target to reach a safe state
Map in necessary sections from the patch
Copy PLT and GOT to new locations as we may need to expand them
For each variable listed in the patch
  Apply the variable patch
For each function listed in the patch
 Apply the function patch
Apply necessary relocations
```

3.14 Roadmap

This section is highly incomplete. Future goals include

- Better interaction with the heap and dynamically allocated variables
- Better interaction with void*
- More efficient use of .rodata
- Patching already patched processes
- Patch composition
- Patch safety checking: make sure a patch actually corresponds to the process it's being applied to
- Storing warnings from generation inside a patch

4 DWARF Manipulation

For information on how katana can be used specifically for DWARF manipulation, please see Dartmouth College Tech Report TR2011-680.

5 Credits and Licensing

Katana is being written by James Oakley and was designed by Sergey Bratus, James Oakley, Ashwin Ramaswamy, Michael Locasto, and Sean Smith.