PADRONE: a Platform for Online Profiling, Analysis, and Optimization

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PADRONE is new platform for dynamic binary analysis and optimization. It provides an API to help clients design and develop analysis and optimization tools for binary executables. PADRONE attaches to running applications, only needing the executable binary in memory. No source code or debug information is needed. No application restart is needed either. This is specially interesting for legacy or commercial applications, but also in the context of cloud deployment, where actual hardware is unknown, and other applications competing for hardware resources can vary. We describe the infrastructure of PADRONE, and show that its profiling overhead is minimal. We illustrate its use through two examples. In the first one, we show how we measure the performance of the hotpot of benchmark. In the second one, we replace the hotspot of a function by an optimized version, while the program runs. We believe PADRONE fits an empty design point in the ecosystem of dynamic binary tools.

1. INTRODUCTION

Most of the studies on automatic code optimization have focused on source-to-source transformation tools. Sophisticated techniques have been developed for some classes of programs, and rapid progress is made in the field. However, there is a persistent hiatus between software vendors having to distribute generic programs, and end-users running them on a variety of hardware platforms, with varying levels of optimization opportunities. The next decade may well see an increasing variety of hardware, as it has already started to appear particularly in the embedded systems market. At the same time, one can expect more and more architecture-specific automatic optimization techniques.

Moreover, many "old" executables are still being used although they have been originally compiled for now outdated processor chips. Although most current processors are ensuring backward compatibility, these codes are obviously not taking advantage of new computing resources that appeared in recent processor chips.

All this argues for binary-to-binary optimizing transformations enabling to take advantage of current computing resources when re-compiling source codes cannot be considered. Such transformations can be applied either statically, *i.e.*, before executing the target code, or dynamically, *i.e.*, while the target code is running.

Dynamic optimization is mostly addressing adaptability to various architectures and execution environments. When deploying an application in the cloud, the executable file may be handled by various processor architectures providing varying levels of optimization opportunities. Anticipating numerous different adapted binary versions cannot be a general solution. Another point is related to interactions between applications sharing common hardware, where adaptation may be required to adapt to the varying availability of the resources. Finally, most code optimizations have a basic cost that has to be overcome by the gain they provide. Depending on the input data processed by the target code, an optimizing transformation may be or not profitable. One may argue about the use of programming language virtual machines as an alternative answer to these issues. However, this would enforce the re-writing of every program, while execution time performance is generally more difficult to address with virtual machines, compared to native binary code.

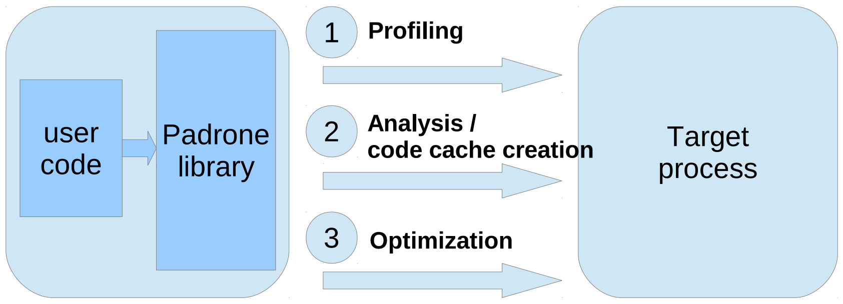


Fig. 1. Analysis and Optimization with PADRONE

In this paper, we show some recent progresses in profiling and analyzing running executable codes using our software framework that can be attached to any running process, in order to collect relevant information or to switch the control flow to some optimized code version. The analysis is run as a separated process, thus minimizing the instrumentation overhead. As an optimization example, we use our tools to automatically substitute binary code which has been originally vectorized for SSE processor units with AVX code. Since the main difference is related to the size of the vector registers (from 128 bits in SSE to 256 bits in AVX), such a code transformation potentially doubles the speed-up due to vectorization.

2. INFRASTRUCTURE

2.1. General Presentation

PADRONE is a library that provides an API. Clients developed with PADRONE are, in spirit, similar to *gdb*. A user can attach to an already running process, set breakpoints, define callbacks. After the process has been operated upon, PADRONE can detach and let the process run at full speed. The advantage of such an operating mode is the ability to leave the bulk of the analysis (or optimization) work to a different process. On a multicore system, the target process and PADRONE-initiated processes are likely to be scheduled by the operating system on distinct cores.

PADRONE is designed to work in a production environment, i.e., it makes absolutely no assumption about the running program: no debug information is needed, the running program can be stripped (and have no symbol table). Of course, no source code is needed, since PADRONE must be able to handle legacy applications in whatever shape they are available. The PADRONE framework assumes access only to the application binary file and memory space of the process.

PADRONE works on Gnu/Linux systems, and thus takes advantage of existing Linux mechanisms, including the *perf event* subsystem, the `ptrace` system call, the virtual `/proc` file system, or the ELF executable format, as detailed in the following sections. Currently PADRONE aims at optimizing x86 applications, although in the future the framework may evolve and work on other types of processors.

As Figure 1 shows, a typical PADRONE application proceeds in three steps. The first step is *profiling*. The idea is to observe the running process to see for instance where it spends most of its CPU time, or where some statistics of interest (e.g., IPC, cache misses, etc.) have unexpected values. The second step is the *analysis*. From the data collected during step one, critical functions and loops can be identified. If needed, a code cache is also created during this step. The code cache is created in the target process address space, and lets PADRONE inject additional or optimized code. The third and last step, the *optimization*, is usually external to the PADRONE core library, and implemented as separate user code, or even as a separate process (for instance by invoking a compiler). Typically, this step creates an optimized version of some code of the application (e.g., hot spots identified during the profiling step). This new code is then injected into the code cache in the target process address space, to be run there and complement or replace the process' own code. Note that a PADRONE client can repeat the profiling-analysis-optimization cycle as many times as necessary.

PADRONE is actually a toolbox to perform dynamic code modifications. It provides an API which can be used by third party applications to perform specific optimizations. The platform integrates three steps that are usually performed separately, typically with different tools. Sections 3.2 and 3.3 give several examples of PADRONE clients for on-line profiling and optimization tasks. The rest of this section describes the major components of PADRONE.

2.2. Profiling (Linux perf event subsystem)

PADRONE provides a profiling functionality, which is the usual first step if no information is available on the running process. It could happen that a user already knows what are the hotspots of a program, in which case that step can be skipped.

The profiling step is useful to measure where the program spends most of its CPU time. Indeed, one of the major goals of PADRONE is to identify the process hotspots, rather than trying to blindly optimize the complete running process. A statistical profiling is obtained by sampling the state of the running process, typically by probing the program counter of the running process at regular intervals. Each probe provides a sample, and each sample includes the IP (instruction pointer) and a call-chain. The handling of that list of samples is left to the analysis step, for instance to figure out the functions to which these IPs belong, and select the critical functions.

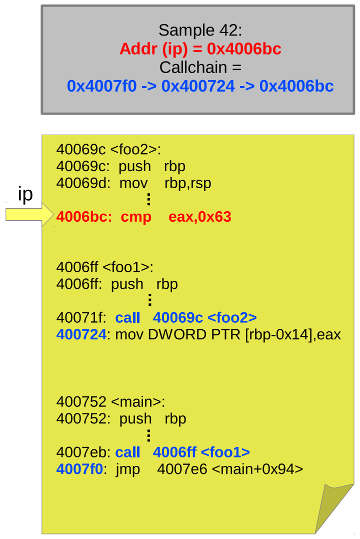
To perform the profiling, PADRONE uses the *Linux perf event* subsystem kernel interface which appeared in Linux version 2.6.31. That kernel interface has been initially created for the *perf* profiling tool, which is shipped with the kernel sources. The interface is based on performance counters: any modern processor now includes a PMU (Performance Monitoring Unit) which can be configured via dedicated registers to monitor specific hardware events. The actual values are read in other dedicated registers. Those registers (performance counters) can be used to measure for instance the number of executed instructions, number of cycles, number of cache misses, number of branch mispredictions, etc. The kernel interface manages the configuration and reading of the registers, and provides a system call called `sys_perf_event_open` to actually initialize a performance counter. The system call takes as parameter a data structure that indicates what kind of events we want to monitor, for which process (PID),[1] and whether we want to monitor the whole system or only a specific CPU (in that case a CPU id is passed).

Another important piece of information is the profiling mode, which can be either a *counting* mode or a *sampling* mode, as discussed later.[2] The call returns a file descriptor from which the client can directly read requested values (e.g. the number of branch mispredictions for a specific process on CPU0). This is the basic mode, or the counting mode. In this mode, it is up to the programmer to decide when to read the values, either on a regular basis or only when the client needs the information.

PADRONE uses the sampling mode in most cases. This mode is dynamic: the interface is configured to receive an interrupt every x occurrences of the event we are interested in. The consequence is that there is something to read on the associated

[1]Permission rights apply: if PADRONE is launched as non-privileged user, only their processes can be monitored.

[2]An example is available with the manual page of the system call, available at `http://www.man7.org/linux/man-pages/man2/perf_event_open.2.html`



```
Sample 42:
Addr (ip) = 0x4006bc
Callchain =
0x4007f0 -> 0x400724 -> 0x4006bc
```

```
40069c <foo2>:
40069c:  push   rbp
40069d:  mov    rbp,rsp
              ⋮
4006bc:  cmp    eax,0x63

4006ff <foo1>:
4006ff:  push   rbp
              ⋮
40071f:  call   40069c <foo2>
400724: mov DWORD PTR [rbp-0x14],eax

400752 <main>:
400752:  push   rbp
              ⋮
4007eb: call   4006ff <foo1>
4007f0:  jmp    4007e6 <main+0x94>
```

Fig. 2. Profiling sample including a call-chain

file descriptor: that mode can be then easily managed using a `poll`, or a `select`. Each time an interruption is raised, a sample is produced including the instruction pointer and call chain at the time the event occurred. Typically, PADRONE's profiling step uses a `PERF_COUNT_HW_CPU_CYCLE` type performance counter, in sampling mode: it is therefore informed of the state of the target process every x cycles. Another option of the sampling mode lets one give a frequency, for instance requesting to get at most 1000 samples per second (instead of a sample every x cycles). In this sampling mode, samples are stored by the kernel in a circular buffer. The client gets access to it by mapping (with `mmap`) the performance counter related file descriptor returned by `sys_perf_event_open`.

As mentioned, a sample contains the call chain related to the included instruction pointer. Consider the example of Figure 2. The last address of the call chain is the address (ip) of the sample (0x4006bc), and the address just before (0x400724) is the address of the call (the call chain actually provides the return address). The call targets function *foo2* where the ip of the sample is. This is how PADRONE retrieves the address of function *foo2* (0x40069c), which will be very important for the analysis step.

Section 3.1 gives a detailed account of the overhead incurred during the profiling phase, for various values of profiling duration and event frequency.

2.3. Analysis (Finding Critical Functions)

Once the profiling phase is done, PADRONE has a list of instructions pointers available for further analysis. The relative frequencies of occurrence of the addresses give an indication of where the "hottest regions" of the code are. Individual instruction pointers are moderately useful however, most optimization opportunities targeting coarser-grain structures, like functions and loops. PADRONE provides support for both. This sections illustrates function-level analysis.

Indeed functions are often the most convenient abstractions, since they are delimited pieces of code activated by a special instruction (*call* instruction on x86). Consequently, it is easy enough to substitute a function by another one. A basic feature of the PADRONE framework is to substitute a critical function with an optimized one, and make sure the optimized version is called instead of the original one. Given an

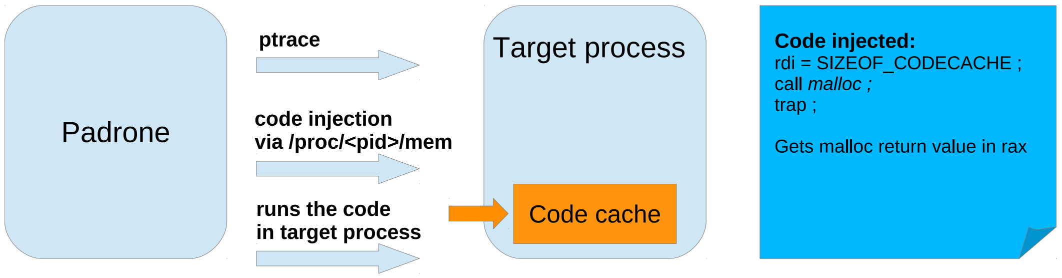

Padrone
ptrace
code injection via /proc/<pid>/mem
runs the code in target process
Target process
Code cache
Code injected:
rdi = SIZEOF_CODECACHE ;
call *malloc* ;
trap ;
Gets malloc return value in rax

Fig. 3. Code cache creation in target process

instruction pointer, PADRONE is able to detect the containing function. Given profile data, a typical pre-processing step consists in replacing individual instruction pointers with function addresses. This often removes unneeded details, providing data at the right level of abstraction.

However, figuring out the limits of a function is not as easy as it seems. PADRONE can only rely on the binary code of the process (read directly from process address space using `/proc/<pid>/mem`), with no symbol table or debug information. Even though the entry point of the function is found in the call chain associated with every sample, finding the "bottom end" is much more complicated. Function calls end with `ret` instructions on x86, but these can appear anywhere, once or more times, inside the function body.[3]A naive linear scanning of the code is clearly insufficient.

Control Flow Graph (CFG). A solution to that function's limit issue is to build a Control Flow Graph (CFG). The assembly code is used as an intermediate representation of the binary code and the CFG has to be built from this code only. Starting from the address of the first instruction of the function, binary code is disassembled and basic blocks are built along the way. PADRONE follows all possible control flow paths until reaching a `ret` instruction.[4] Building the CFG is part of PADRONE's API, and opens the way to detailed analysis actions. PADRONE goes further, by building a loop forest from the CFG. Control flow and loop iterations are central to many performance studies, and PADRONE makes this available to any client.

2.4. Code Cache

The PADRONE API allows the creation of a code cache in the target process memory space. That special memory area is typically used to host optimized versions of process's critical functions. It might happen that some functions optimizations are done in place, for instance when an instruction is replaced by another instruction of the same size or smaller (padding instructions would have to be added in that last case). But in most of the cases, functions must be significantly modified, and it would then be very hazardous to do all the modifications in place. The main reason is that one can never be certain that the overwritten code is not the target of a jump elsewhere in the program. Also, a client would be lucky if the modified version of the function is exactly the same size as the original one, leading to all sorts of problems linked to relative offsets in the code. The code cache is the solution to these issues.

PADRONE needs to allocate a buffer in the target process memory heap and manage that buffer, for instance to copy optimized functions into it. Since PADRONE and the target process do not share the same address space, some code must be injected into

[3]Tail call elimination also complicates the matter.
[4]Indirect jumps are currently handled in an unsatisfactory way, and optimized tail calls are considered part of the callee.

the target process code segment. This (small) piece of code needs to perform dynamic memory allocation as depicted on Figure 3. The `ptrace` system call is used to stop the process, read/write its registers or memory, resume it back in a new state, and write to `/proc/<pid>/mem` (the process memory space). At the time `ptrace` is called, the target process is stopped at a random address. PADRONE copies the injected code at that address, saving existing code and current state (registers) before the actual copy (PADRONE also has an option to indicate the address where you want the injected code to be copied into). To recover control after the injected the code is executed, this fragment ends with a `trap` instruction, which will stop the target process, and let PADRONE retrieve program state, restore original code, and resume execution.

The details of the code cache creation are the following:

(1) PADRONE stops the target process, obtaining the current instruction pointer IP;
(2) PADRONE saves the few bytes of code starting at IP, and replaces them with shell code;
(3) PADRONE relinquishes the process, and calls `wait`;
(4) execution of the target process resumes, allocating memory for the code cache, and eventually reaching a `trap` that suspends the process and send a `SIGCHILD` signal to PADRONE;
(5) PADRONE retrieves relevant registers (typically, `rax` contains the address returned by `malloc`), restores the original code and IP, and let the process continue normal execution.

The actual code is only slightly more complicated, for technical reasons. Because the code cache is placed in the target process address space and because it must be executable, `mprotect` has to set the appropriate properties on the memory area, and this in turn has alignment requirements, which are ensured with the help of `posix_memalign`.

Section 3.3 describes an experiments where the code cache is used to hold an optimized version of a function of the original program.

3. USING PADRONE

3.1. Measuring Profiling Overhead

Profiling has a cost, but the mechanism just described can make the overhead minimal. To quantify the impact of PADRONE's attaching, instrumenting, and detaching, we have run several experiments on SPEC CPU-2006 benchmark programs. Run time has been measured when varying two basic quantities:

— the duration of profiling d, in seconds: this is the time during which the Linux kernel *perf event* subsystem is leveraged to obtain performance data about the target process;
— the sampling frequency f, in units per seconds: this is the rate at which performance data is obtained by the client tool.

Our experiments have used durations of 1, 10, and 30 seconds, and sampling frequencies of 1 000, 10 000, and 100 000 samples per second. We believe this covers most of the use cases.

The run times and slowdown appear in the table of Figure 4. For each pair of parameters, the table shows the execution time, and the slowdown incurred by PADRONE's profiling. This slowdown is computed relative to a reference execution time, obtained by running the program standalone. As numbers show, the overhead is very small for short durations and reasonably low for reasonable frequencies. It is for instance perfectly possible to obtain a 10 seconds profile with a frequency of 10000 samples per second.

Program	Ref. time (s)	$d = 1$ s						$d = 10$ s						$d = 30$ s					
		f =1K/s		10K/s		100K/s		f =1K/s		10K/s		100K/s		f =1K/s		10K/s		100K/s	
`400.perlbench`	84	84	0%	84	0%	85	1%	83	0%	87	3%	93	10%	85	1%	117	39%	118	40%
`401.bzip2`	63	63	0%	63	0%	64	2%	63	0%	64	1%	68	8%	64	1%	75	20%	91	45%
`403.gcc`	12	12	1%	13	6%	13	4%	13	3%	15	22%	15	22%	22	76%	22	74%	22	76%
`410.bwaves`	470	472	0%	474	0%	477	1%	474	0%	476	1%	481	2%	472	0%	486	3%	512	8%
`416.gamess`	378	381	0%	378	0%	383	1%	381	0%	383	1%	391	3%	383	1%	404	7%	475	25%
`429.mcf`	281	273	-2%	270	-3%	271	-3%	272	-3%	281	0%	286	1%	273	-2%	281	0%	309	9%
`433.milc`	324	323	0%	320	-1%	325	0%	323	0%	325	0%	330	1%	325	0%	333	3%	351	8%
`434.zeusmp`	325	328	0%	329	1%	330	1%	329	1%	332	1%	335	2%	329	1%	356	9%	450	38%
`435.gromacs`	328	334	1%	331	1%	336	2%	334	1%	337	2%	342	4%	333	1%	354	7%	416	26%
`436.cactusADM`	598	600	0%	615	2%	619	3%	615	2%	612	2%	610	1%	612	2%	626	4%	651	8%
`437.leslie3d`	278	279	0%	283	1%	281	1%	281	0%	281	1%	288	3%	280	0%	297	6%	349	25%
`444.namd`	340	343	1%	343	0%	341	0%	348	2%	346	1%	350	3%	344	1%	356	4%	392	15%
`445.gobmk`	76	76	0%	77	1%	78	3%	76	0%	79	4%	89	17%	82	8%	147	94%	142	86%
`450.soplex`	82	83	1%	83	1%	84	2%	83	0%	85	3%	89	8%	84	1%	94	13%	122	47%
`453.povray`	141	141	0%	141	0%	141	0%	141	0%	146	3%	152	7%	142	0%	165	16%	205	44%
`454.calculix`	652	647	0%	653	0%	654	0%	647	0%	655	0%	656	0%	654	0%	670	2%	737	13%
`456.hmmer`	265	265	0%	265	0%	266	0%	265	0%	266	0%	270	1%	266	0%	277	4%	306	15%
`458.sjeng`	450	451	0%	452	0%	451	0%	448	0%	453	0%	459	1%	453	0%	475	5%	537	19%
`459.GemsFDTD`	293	293	0%	291	0%	294	0%	293	0%	295	0%	304	3%	294	0%	308	5%	374	27%
`462.libquantum`	292	296	1%	300	2%	299	2%	295	0%	304	4%	302	3%	296	1%	315	7%	330	12%
`464.h264ref`	381	393	3%	382	0%	386	1%	384	0%	389	2%	393	3%	385	1%	459	20%	570	49%
`465.tonto`	360	361	0%	363	0%	364	1%	362	0%	368	2%	370	2%	362	0%	402	11%	496	37%
`470.lbm`	246	249	1%	249	1%	250	1%	249	1%	250	1%	254	3%	249	1%	259	5%	279	13%
`471.omnetpp`	306	310	1%	289	-5%	316	3%	313	2%	316	3%	326	6%	314	2%	340	11%	412	34%
`473.astar`	212	213	0%	214	1%	216	1%	217	2%	214	0%	217	2%	216	1%	220	3%	242	14%
`481.wrf`	430	435	1%	437	1%	437	1%	436	1%	438	1%	437	1%	436	1%	474	10%	575	33%

Fig. 4. Profiling overhead on SPEC CPU-2006 programs: for every combination of d (duration) and f (sampling frequency), both run time and overhead (as a fraction of reference execution time) are shown. All quantities are rounded to the nearest integer.

```
if (padrone_init(&padrone, pid) < 0)
        return EXIT_FAILURE;

err = padrone_profile(&padrone, duration, frequency, &prof_result);
if (err < 0) goto failure;

mfs = padrone_profile_get_mfs(&prof_result);

err = padrone_fun_fetch_address_from_sample(&padrone, &fun_info, mfs);
if (err < 0) goto failure;

padrone_cfg_init(&cfg, &fun_info);
err = padrone_cfg_build(&cfg);
if (err < 0) goto failure;

padrone_fun_ipc_measure(&fun_info, 10);

padrone_profile_destroy(&prof_result);
padrone_cfg_destroy(&cfg);

failure:
        padrone_leave(&padrone);
        return err;
```

Fig. 5. Performance measurement (IPC) using the PADRONE API

3.2. Performance Analysis

PADRONE can be used for different purposes. One of the examples we give here is the capability to measure the performance (as IPC, or instructions per cycle) of a hot function. As depicted on Figure 6, we monitored the SPEC2006 LBM benchmark, and used PADRONE to detect a critical function and measure that function's IPC for 10 successive calls. The code of this client is shown on Figure 5: the call to `padrone_fun_ipc_measure` is the PADRONE API to capture performance counter values. You can notice in that same code that after having profiled the process and fetched the address of the critical function, we build the CFG of that hot function (`padrone_cfg_build`). The reason for that is explained in 2.4, i.e., we need to build the CFG to detect the function limit. With that function limit we are able to measure the function's IPC. The idea is to "trap" the beginning of the function execution, as well as all its possible return instructions. The first instruction of the function is replaced with a `trap` (after saving original instructions, to be restored before restarting the process), and we do the same with all the different `ret` instructions. Since PADRONE is "ptrace-attached" to the monitored process, it is informed of any `trap` execution. At the first `trap` PADRONE polls two hardware counters (previously configured as explained in 2.2) to get actual values of the number of cycles and number of retired instructions. The process is restarted, and the next `trap` signals the end of the function, at which time PADRONE can read again those same hardware counters, in order to compute the IPC.

3.3. Optimization by Function replacement

This section describes another possible usage of PADRONE, namely the replacement, at run time, of a given function by a custom, optimized version. To illustrate this task, we use a small program where the bulk of the work is made of a series of vector additions. The main function is called `redstep`, it performs N calls to `vecadd`, which adds two vectors and puts the result in a third vector. Vectors are ultimately stored in raw

```
% ps -ef | grep lbm
UID        PID  PPID  C STIME TTY          TIME CMD
padrone  29073 24509 99 17:53 pts/1    00:00:03 ./lbm_base.none [...]

% ./padrone 29073
[PADRONE_DEBUG] padrone_init: kernel version = 3.6.8-2.fc17.x86_64
[PADRONE] Total number of ip samples: 1049
[PADRONE] printing samples with a frequency > 10% (FREQ_THRESHOLD)
[PADRONE] main: most frequent ip = 0x401103
[PADRONE] padrone_fun_fetch_address_from_sample:
          -> function address = 0x400e70 (LBM_performStreamCollide)
[PADRONE] padrone_fun_ipc_measure: 0x400e70 (LBM_performStreamCollide)
[PADRONE] padrone_fun_ipc_measure: ipc = 1.341582
[PADRONE] padrone_fun_ipc_measure: 0x400e70 (LBM_performStreamCollide)
[PADRONE] padrone_fun_ipc_measure: ipc = 1.345427
[PADRONE] padrone_fun_ipc_measure: 0x400e70 (LBM_performStreamCollide)
[PADRONE] padrone_fun_ipc_measure: ipc = 1.350911
[PADRONE] padrone_fun_ipc_measure: 0x400e70 (LBM_performStreamCollide)
[PADRONE] padrone_fun_ipc_measure: ipc = 1.346134
...
[PADRONE] padrone_fun_ipc_measure: 0x400e70 (LBM_performStreamCollide)
[PADRONE] padrone_fun_ipc_measure: ipc = 1.340859
[PADRONE] padrone_fun_ipc_measure: 0x400e70 (LBM_performStreamCollide)
[PADRONE] padrone_fun_ipc_measure: ipc = 1.343773
[PADRONE] padrone_fun_ipc_measure: 0x400e70 (LBM_performStreamCollide)
[PADRONE] padrone_fun_ipc_measure: ipc = 1.351644
[PADRONE] padrone_fun_ipc_measure: 0x400e70 (LBM_performStreamCollide)
[PADRONE] padrone_fun_ipc_measure: ipc = 1.349698
[PADRONE] padrone_leave: padrone exiting
```

Fig. 6. Performance measurements (IPC) of SPEC2006 lbm hot function using PADRONE

arrays of double precision floating point numbers. We have modified the program to print the time taken by a call to `redstep`, i.e., the time taken by N calls to `vecadd` ($N = 1000$ in our experiments).

In this scenario, the original program is legacy. It has been compiled on a machine where SSE vector instructions are available, and the vector addition has been vectorized accordingly. We then run the same executable on a machine where AVX instructions are available, leading to a sub-optimal use of resources. The goal of our experiment is to show that, provided an AVX-enabled version of the `vecadd` function, PADRONE is able to replace a function on the fly.

The corresponding PADRONE client is sketched on Figure 7. The first step (profiling) is similar to the previous example, an detects the program's critical function (`vecadd` in our example). The tool then proceeds to replace the function with an optimized version (making full use of AVX hardware). The way the AVX binary version of the function is obtained is out of the scope of this paper which focuses on describing the infrastructure, i.e., we assume the binary code is basically provided by the user (via an array represented by the `assembly_64_hw` array in Figure 7).

PADRONE's API provides a function called `padrone_cc_insert` to insert a binary code into the code cache. It returns the address of this binary code, which is in our case the address of the optimized version of the critical function. Then `padrone_cc_fun_call_replace` is used to replace calls to the original function with calls to the optimized version. To achieve this, `padrone_cc_fun_call_replace` replaces the first instruction of the original function with a `trap` instruction. Each time the

```
if (padrone_init(&padrone, pid) < 0)
   return EXIT_FAILURE;
err = padrone_profile(&padrone, duration, frequency, &prof_result);
if (err < 0) goto failure;
mfs = padrone_profile_get_mfs(&prof_result);
err = padrone_fun_fetch_address_from_sample(&padrone, &fun_info, mfs);
if (err < 0) goto failure;

padrone_debug("hot fun address = %#lx", fun_info.ip_start);

uint8_t assembly_64_hw [] = ...;
padrone_cc_create(&padrone, &codecache, CC_ALLOC, fun_info.ip_start,
                  sizeof(assembly_64_hw) + 10);

fun_info.cc_fun_addr = padrone_cc_insert(&codecache, assembly_64_hw,
                                         sizeof(assembly_64_hw));

padrone_cc_fun_call_replace(&fun_info, FALSE);

padrone_profile_destroy(&prof_result);
padrone_cc_finish(&codecache);
failure:
        padrone_leave(&padrone);
        return err;
```

Fig. 7. vecadd replacement code using PADRONE API

```
% ./vecadd-sse
...
redstep:  62   166.92 ms    166.92 ns per iter
redstep:  63   165.58 ms    165.58 ns per iter
redstep:  64   165.51 ms    165.51 ns per iter
redstep:  65   113.10 ms    113.10 ns per iter
redstep:  66    89.32 ms     89.32 ns per iter
redstep:  67    89.37 ms     89.37 ns per iter
redstep:  68    89.78 ms     89.78 ns per iter
redstep:  69    89.59 ms     89.59 ns per iter
...
```

Fig. 8. vecadd replacement

process is stopped in the `trap`, PADRONE fetches the function's return address from the stack, to find out the address of the call site, and replace it with a call to the new function in the code cache. This is the quickest way to redirect flow of execution from original function to the optimized one.[5]

A run of the `vecadd-sse` program is depicted on Figure 8 (the PADRONE tool invocation is not shown). Every line in the output shows the time taken by a call to `redstep` (and the average time of calls to `vecadd`, of which there are one hundred). What appears on this figure is the fact that, after a certain numbers of calls, the `vecadd` function is replaced, leading to a large reduction of execution time for `redstep`. The 65th call to `redstep` is the phase-transition call: a few first calls to `vecadd` have used the original version, the next ones have used the new one.

[5]PADRONE's API also provides a way to install a code trampoline in original function. This basically replaces original function's first instruction with a `jmp` instruction to optimized binary code in the code cache.

4. RELATED WORK

This section reviews a number of works in the ecosystem of profiling and dynamic binary tools.

4.1. Profiling Tools

Pin [Luk et al. 2005] is a dynamic binary instrumentation framework developed and supported by Intel. Thanks to a flexible API, the community has developed a rich set of *pintools* for architecture exploration, emulation, security. Pin always executes from the code cache, and never executes the original code. Instead, we try to minimize the amount of code we modify, executing as much as possible from untouched original code. Pin is also more oriented toward instrumentation and analysis than optimization.

Tiptop [Rohou 2011] is a tool that displays events collected from the hardware performance monitoring unit. It is similar to the UNIX utility top and refreshes values at regular time intervals. However, the values are read and displayed at the granularity of the thread, without knowledge of the function or loop, and for rather large intervals (at least tenths of seconds). PADRONE focuses on much finer 3grain intervals, and takes into account the structure of the application (functions and loops). A number of tools that read performance counters have been proposed, including Rabbit[6], OProfile[7], libpfm, perfmon2[8], perf [Carvalho de Melo 2009], or vtune [Intel 2003]. LiMiT [Demme and Sethumadhavan 2011] is a very recent proposal to reduce the overhead of reading counters, by directly reading machine registers and avoiding the system call.

4.2. Dynamic Binary to Binary Optimizers

ADORE [Chen et al. 2004] also uses hardware counters to identify hotspots and phases. It then optimizes the application for the data cache, and generates helper threads. Dynamo [Bala et al. 2000] and DynamoRIO [Bruening 2004] insist on the need for transparency. We address it by keeping all the client and toolbox in a separate address space, and by modifying as little as necessary of the original code. DynamoRIO (and Pin) always execute code only from the code cache, while we dedicate it to newly generated code. We also incur marginal overhead by using the support of the PMU, which is independent of the size and complexity of the monitored code, while those tools rely on instrumentation. Qemu [Bellard 2005] is a fast machine emulator based on dynamic translation, and performing code generation. Valgrind [Nethercote and Seward 2007] also builds its on intermediate representation. We chose to only modify the minimum possible and let original code run.

4.3. Auto-vectorization

Several techniques have been proposed to dynamically generate SIMD instructions at run-time. Yardımcı and Franz [Yardımcı and Franz 2008] dynamically vectorize (and parallelize) loops based on a static analysis of the executables. Our approach is purely dynamic. El-Shobaky et al. [El-Shobaky et al. 2009] added automatic vectorization based on tree pattern matching to a JIT compiler. Nie et al. [Nie et al. 2010] also added auto-vectorization to a Java virtual machine. Nuzman et al. [Nuzman et al. 2011] perform speculative vectorization at the level of the bytecode in the context of split-compilation. The statically generated bytecode is speculatively vectorized in an abstract target-independent form and a JIT compiler materializes the actual parameters, such as vector length, alignment constraints, and other existing idioms. Clark et al. [Clark et al. 2007] propose to convey SIMD opportunities within standard scalar

[6]`http://www.scl.ameslab.gov/Projects/Rabbit`
[7]`http://oprofile.sourceforge.net`
[8]`http://perfmon2.sourceforge.net`

assembly code, relying on a dynamic translation mechanism to recognize instruction patterns that can be vectorized (in hardware).

5. CONCLUSION

This paper introduces a new infrastructure, called PADRONE, for dynamic binary optimization. It operates by profiling a target program with minimal overhead, analyzing profiling results, and acting on the running executable code. We argue that it fills an empty design point, and we show its potential for analysis and optimization of binary executable programs. We have shown that PADRONE's profiling overhead is reasonable, and illustrated the use of the platform in two applications: extracting performance data for compute intensive functions, and replacing a time-consuming function with an optimized version.

PADRONE is still in an early stage of development, and we plan to extend it along several dimensions. Our next research target is to integrate various forms of dynamic optimization right in the platform (rather than using pre-packaged variants, as in Section 3.3), by leveraging abstract program structures, like functions and loops. PADRONE is already able to recognize these structures, and we think that reasoning at that level of abstraction opens up a whole new range of potential dynamic optimizations. We plan to use PADRONE to explore this space.

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