APAC Korea 2016

Linux Kernel Instrumentation in Python

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Agenda

I. eBPF & BCC
- eBPF
- BCC

II. In-Kernel Virtual Machine
- KPlugs
- Application

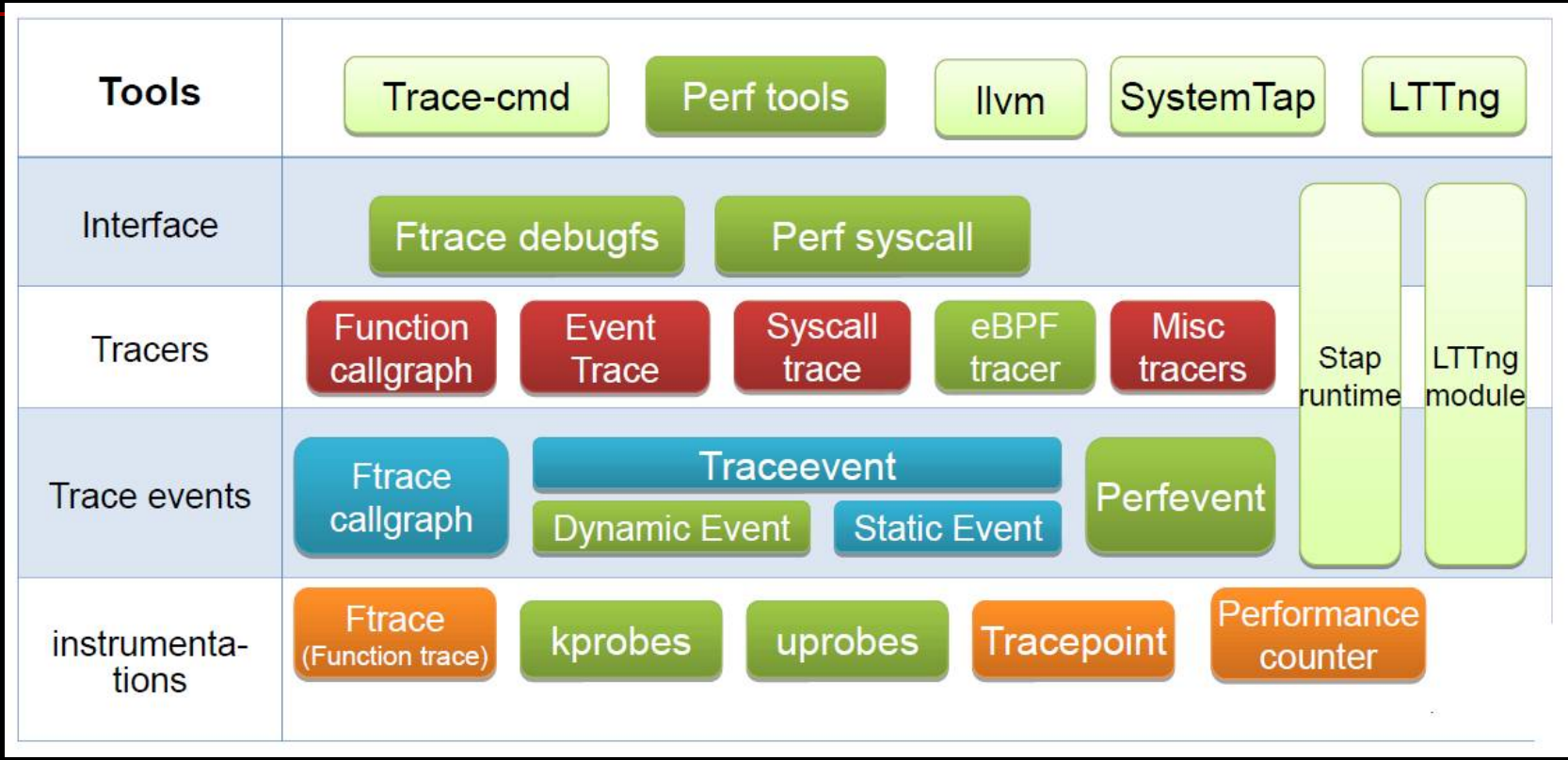
III. Python-assisted Data Center Dev
- HPC
- Software-Defined Everything

IV. Summary

I. eBPF & BCC

Background

- The Tracing Landscape



Source: http://tracingsummit.org/w/images/8/8c/TracingSummit2015-DynamicProbes.pdf

1) eBPF

- https://en.wikipedia.org/wiki/Berkeley_Packet_Filter
- http://lwn.net/

BPF (Berkeley Packet Filter, aka cBPF)

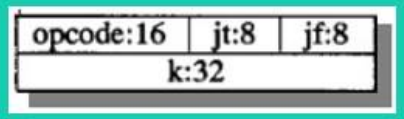
- Introduced in kernel 2.1.75 (1997)
- Originally designed for packet filtering (tcpdump…)
- Apply for seccomp filters, traffic control…

eBPF (extended BPF)

- Since Linux Kernel v3.15 and ongoing
- Aims at being a universal in-kernel virtual machine, it changes the old ways for Kernel instrumentation
- https://lwn.net/Articles/655544/

> BPF for tracing is currently a hot area, Starovoitov said. It is a better alternative to SystemTap and runs two to three times faster than Oracle's DTrace. Part of that speed comes from LLVM's optimizations plus the kernel's internal just-in-time compiler for BPF bytecode.

Comparison

	cBPF	eBPF
Register	**Two 32 bit registers:** A: accumulator X: indexing	**Eleven 64 bit registers:** R0: return value/exit value R1-R5: arguments R6-R9: callee saved registers R10: read-only frame pointer
Instruction	~30 	~90 
JIT	Support	Support (better mapping with newer architectures for JITing)
Toolchain	GCC, tools/net	LLVM eBPF backend
Platform	x86_64, ARM, ARM64, SPARC, PowerPC, MIPS and s390	x86-64, aarch64, s390x

System Call		`#include <linux/bpf.h>`
		`int bpf(int cmd, union bpf_attr *attr, unsigned int size);`
		(CALL, MAP, LOAD...)

Dev

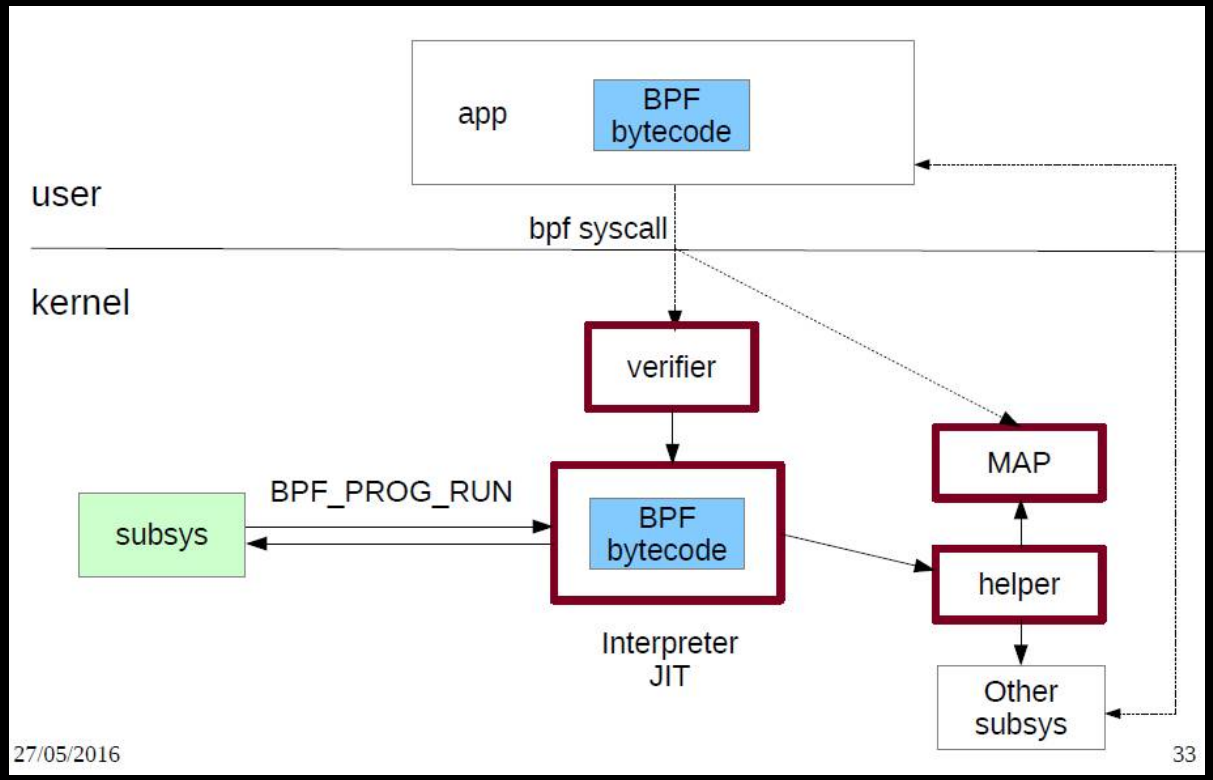
- **Dev Methods**

  1) write directly using eBPF assembly

  2) Write it using C, and compile with LLVM

  3) BCC

  …



Source: http://www.slideshare.net/vh21/meet-cutebetweenebpfandtracing

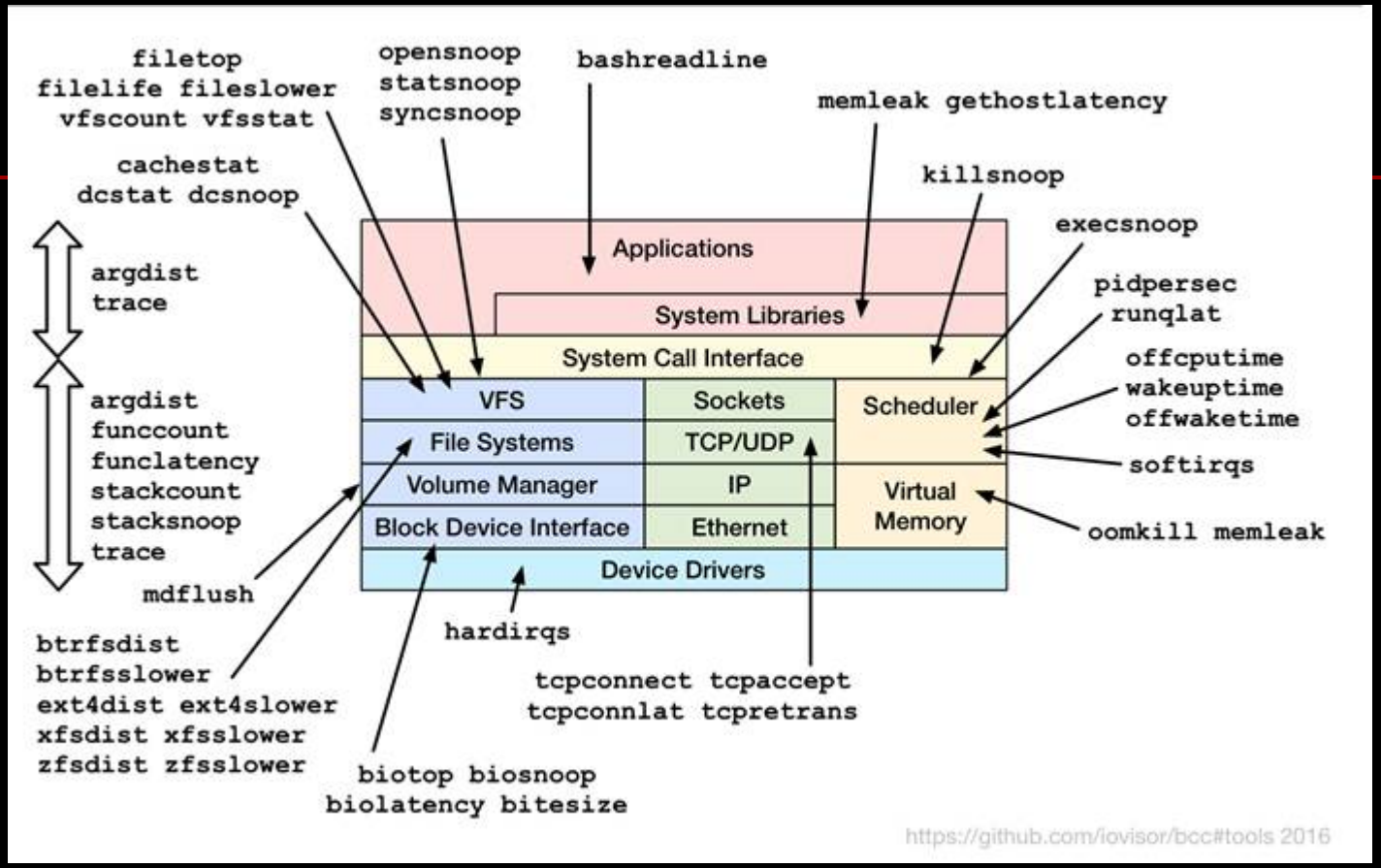
2) BCC (BPF Compiler Collection)

- https://iovisor.github.io/bcc/
- https://github.com/iovisor/bcc.git

A toolkit with Python/Lua frontend for compiling, loading, and executing BPF programs, which allows user-defined instrumentation on a live kernel image:

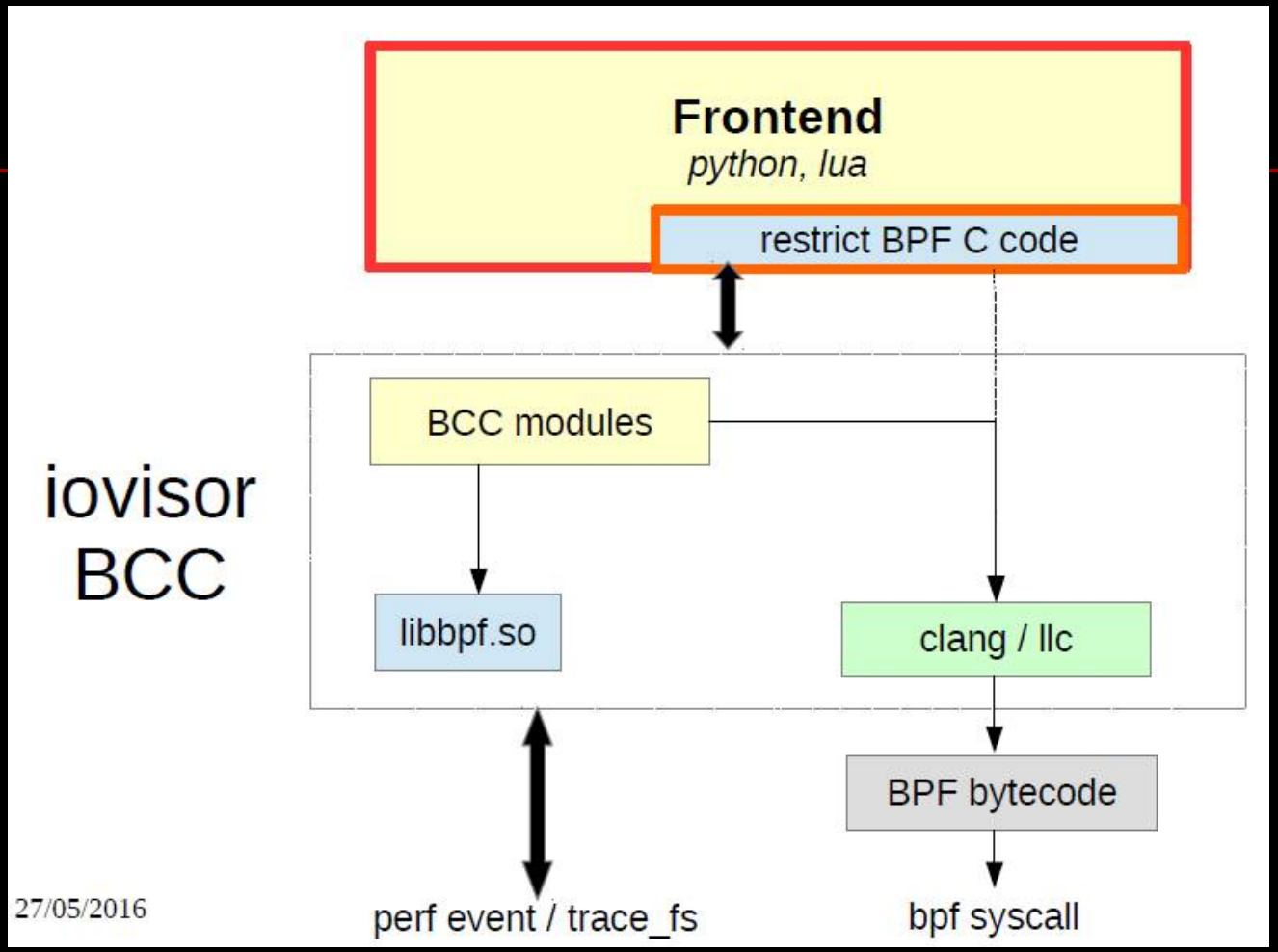
- Compile BPF program from C source
- Attach BPF program to kprobe/uprobe/tracepoint/USDT/socket
- Poll data from BPF program
- Framework for building new tools or one-off scripts
- …

- **BCC tools**



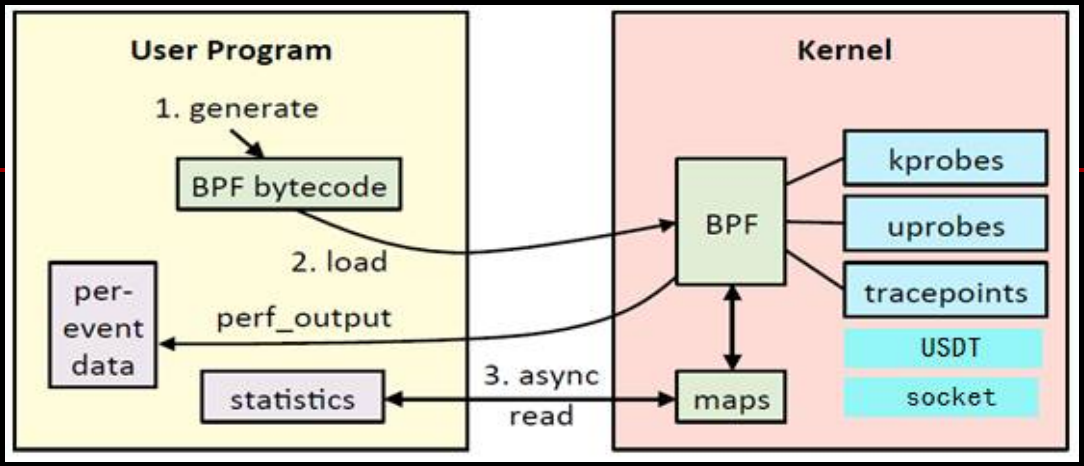
- **Python is given the fullest support**

Arch



Source: http://www.slideshare.net/vh21/meet-cutebetweenebpfandtracing

For Tracing



Source: http://www.slideshare.net/brendangregg/linux-bpf-superpowers

Sample

- bcc/examples/tracing/urandomread*.*

```
root@ubuntu:/opt/MyWorkSpace/MyProjs/Open-Source/OS/In-Kernel-VM/eBPF/BCC/bcc/examples/tracing# ./urandomread.py
TIME(s)            COMM             PID    GOTBITS
3031.665037000     dd               6604   8192
3031.665365000     dd               6604   8192
3031.665642000     dd               6604   8192
3031.665924000     dd               6604   8192
3031.666202000     dd               6604   8192
3095.286445000     systemd          1      128
3095.286518000     systemd          1      128
3095.286582000     systemd          1      128
3095.286671000     systemd          1      128
```

```
mydev@ubuntu:/opt/Tmp$ dd if=/dev/urandom of=/dev/null bs=1k count=5
5+0 records in
5+0 records out
5120 bytes (5.1 kB, 5.0 KiB) copied, 0.00182226 s, 2.8 MB/s
```

urandomread-explicit.py

```
#!/usr/bin/python
#
# urandomread-explicit  Example of instrumenting a kernel tracepoint.
#                       For Linux, uses BCC, BPF. Embedded C.
#
# This is an older example of instrumenting a tracepoint, which defines
# the argument struct and makes an explicit call to attach_tracepoint().
# See urandomread for a newer version that uses TRACEPOINT_PROBE().
#
# REQUIRES: Linux 4.7+ (BPF_PROG_TYPE_TRACEPOINT support).
#
# Test by running this, then in another shell, run:
#     dd if=/dev/urandom of=/dev/null bs=1k count=5
#
# Copyright 2016 Netflix, Inc.
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from __future__ import print_function
from bcc import BPF

# define BPF program
bpf_text = """
#include <uapi/linux/ptrace.h>

struct urandom_read_args {
    // from /sys/kernel/debug/tracing/events/random/urandom_read/format
    u64 __unused__;
    u32 got_bits;
    u32 pool_left;
    u32 input_left;
};

int printarg(struct urandom_read_args *args) {
    bpf_trace_printk("%d\\n", args->got_bits);
    return 0;
};
"""

# load BPF program
b = BPF(text=bpf_text)
b.attach_tracepoint("random:urandom_read", "printarg")

# header
print("%-18s %-16s %-6s %s" % ("TIME(s)", "COMM", "PID", "GOTBITS"))

# format output
while 1:
    try:
        (task, pid, cpu, flags, ts, msg) = b.trace_fields()
    except ValueError:
        continue
    print("%-18.9f %-16s %-6d %s" % (ts, task, pid, msg))
```
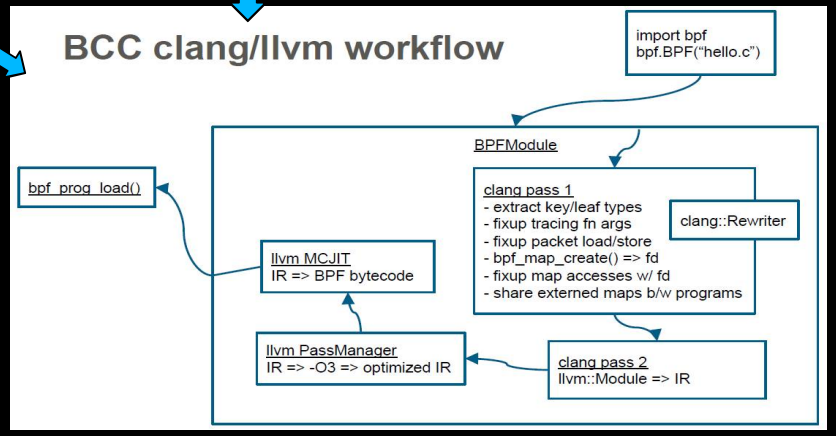

urandomread.py

```
#!/usr/bin/python
#
# urandomread  Example of instrumenting a kernel tracepoint.
#              For Linux, uses BCC, BPF. Embedded C.
#
# REQUIRES: Linux 4.7+ (BPF_PROG_TYPE_TRACEPOINT support).
#
# Test by running this, then in another shell, run:
#     dd if=/dev/urandom of=/dev/null bs=1k count=5
#
# Copyright 2016 Netflix, Inc.
# Licensed under the Apache License, Version 2.0 (the "License")

from __future__ import print_function
from bcc import BPF

# load BPF program
b = BPF(text="""
TRACEPOINT_PROBE(random, urandom_read) {
    // args is from /sys/kernel/debug/tracing/events/random/urandom_read/format
    bpf_trace_printk("%d\\n", args->got_bits);
    return 0;
};
""")

# header
print("%-18s %-16s %-6s %s" % ("TIME(s)", "COMM", "PID", "GOTBITS"))

# format output
while 1:
    try:
        (task, pid, cpu, flags, ts, msg) = b.trace_fields()
    except ValueError:
        continue
    print("%-18.9f %-16s %-6d %s" % (ts, task, pid, msg))
```

include/trace/events/random.h

```
290 TRACE_EVENT(urandom_read,
291         TP_PROTO(int got_bits, int pool_left, int input_left),
292
293         TP_ARGS(got_bits, pool_left, input_left),
294
295         TP_STRUCT__entry(
296                 __field(        int,  got_bits                  )
297                 __field(        int,  pool_left                 )
298                 __field(        int,  input_left                )
299         ),
300
301         TP_fast_assign(
302                 __entry->got_bits       = got_bits;
303                 __entry->pool_left      = pool_left;
304                 __entry->input_left     = input_left;
305         ),
306
307         TP_printk("got_bits %d nonblocking_pool_entropy_left %d "
308                   "input_entropy_left %d", __entry->got_bits,
309                   __entry->pool_left, __entry->input_left)
310 );
```

/sys/kernel/debug/tracing/trace_pipe

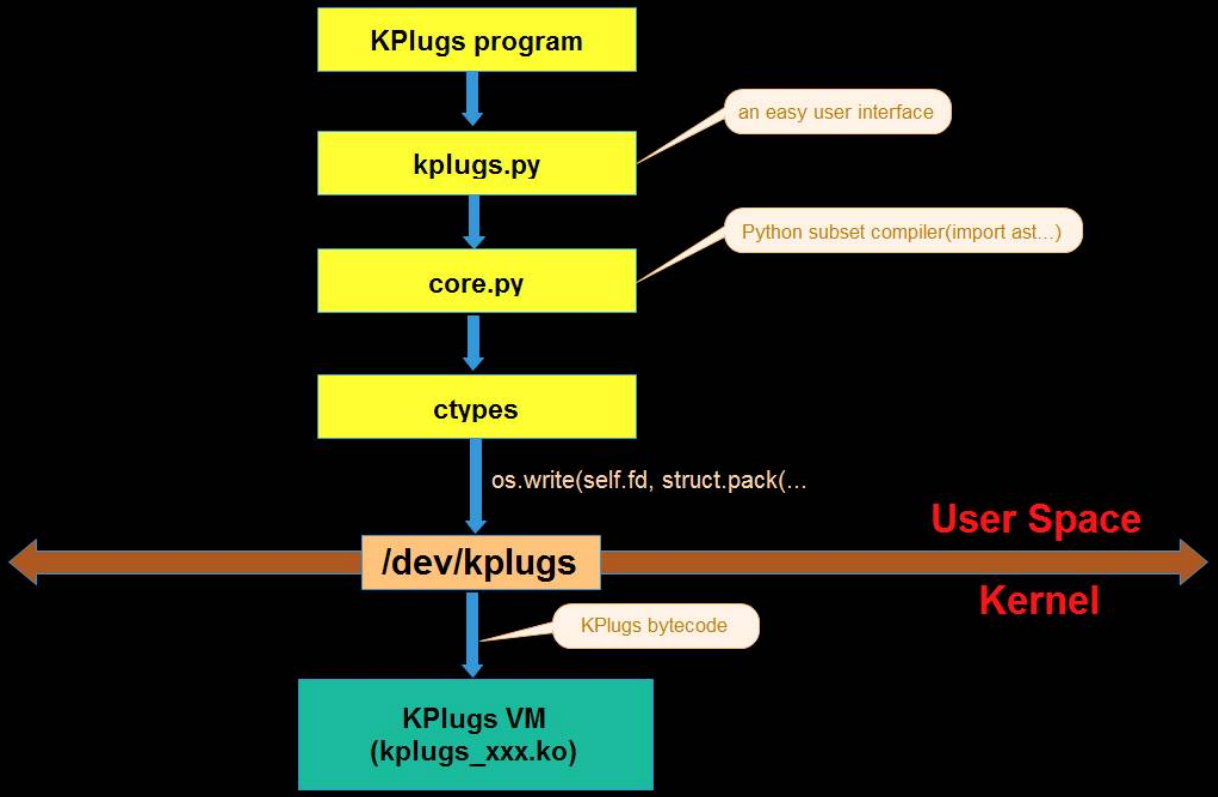


Source: http://linuxplumbersconf.org/2015/ocw//system/presentations/3249/original/bpf_llvm_2015aug19.pdf

II. In-Kernel Virtual Machine

1) KPlugs

- https://www.kplugs.org
- https://github.com/avielw/kplugs
- Arch



Hook sample

- kplugs.Mem - access all of the computer's memory of the computer (kernel and all processes' user space)
- kplugs.Symbol - resolve kernel symbols
- kplugs.Hook - hook kernel functions with a KPlugs function
- kplugs.Caller - call an exported kernel function

```python
#!/usr/bin/env python

import kplugs
import time

try:
    plug = kplugs.Plug()
    hook = kplugs.Hook()

    kernel_func = r'''

def my_hook(kp, regs):
    print "The registers are stored in %p" % regs
    return 0
'''
    my_hook = plug.compile(kernel_func)[0]
    hook.hook("sys_clone", my_hook)
    time.sleep(10)
    hook.unhook(my_hook)

finally:
    kplugs.release_kplugs()
```

```
root@ubuntu:/opt/MyWorkSpace/MyProjs/Open-Source/OS/In-Kernel-VM/Python/kplugs/samples# lsmod |grep kplugs
root@ubuntu:/opt/MyWorkSpace/MyProjs/Open-Source/OS/In-Kernel-VM/Python/kplugs/samples# modprobe kplugs_release
root@ubuntu:/opt/MyWorkSpace/MyProjs/Open-Source/OS/In-Kernel-VM/Python/kplugs/samples# lsmod |grep kplugs
kplugs_release         53248  0
root@ubuntu:/opt/MyWorkSpace/MyProjs/Open-Source/OS/In-Kernel-VM/Python/kplugs/samples# dmesg -C
root@ubuntu:/opt/MyWorkSpace/MyProjs/Open-Source/OS/In-Kernel-VM/Python/kplugs/samples# dmesg
root@ubuntu:/opt/MyWorkSpace/MyProjs/Open-Source/OS/In-Kernel-VM/Python/kplugs/samples#
root@ubuntu:/opt/MyWorkSpace/MyProjs/Open-Source/OS/In-Kernel-VM/Python/kplugs/samples# ./kplugs_hook.py
root@ubuntu:/opt/MyWorkSpace/MyProjs/Open-Source/OS/In-Kernel-VM/Python/kplugs/samples# dmesg
[ 6316.625909] The registers are stored in ffff8800978ffe50
[ 6317.644612] The registers are stored in ffff8800928a3e50
[ 6318.675235] The registers are stored in ffff8800928a3e50
[ 6319.694774] The registers are stored in ffff8800928a3e50
[ 6320.744613] The registers are stored in ffff8800928a3e50
[ 6321.763556] The registers are stored in ffff8800928a3e50
root@ubuntu:/opt/MyWorkSpace/MyProjs/Open-Source/OS/In-Kernel-VM/Python/kplugs/samples#
```

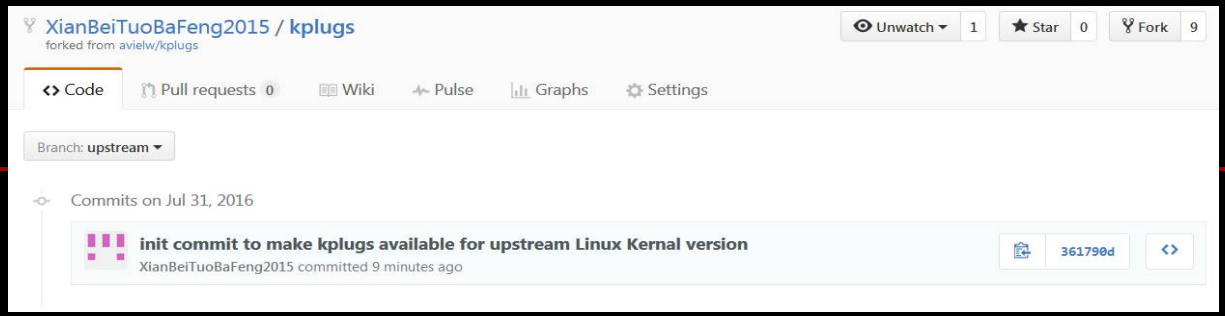
```
mydev@ubuntu:/opt/MyWorkSpace/Test/Linux/Thread$ ./multithread
```

```c
#include <pthread.h>
#include <stdio.h>
#include <unistd.h>

#define THREAD_NUM 5

void *thread_func(void *argu) {
    printf("Thread %d starting...\n", (int)argu);

    return NULL;
}

int main() {
    int i;
    pthread_t thread_ids[THREAD_NUM];

    for (i = 0;i < THREAD_NUM;i++) {
        sleep(1);
        pthread_create(&thread_ids[i], NULL, &thread_func, (void *)i);
    }

    for (i = 0;i < THREAD_NUM;i++) {
        pthread_join(thread_ids[i], NULL);
    }
    printf("--end of The program.--\n");

    return 0;
}
```

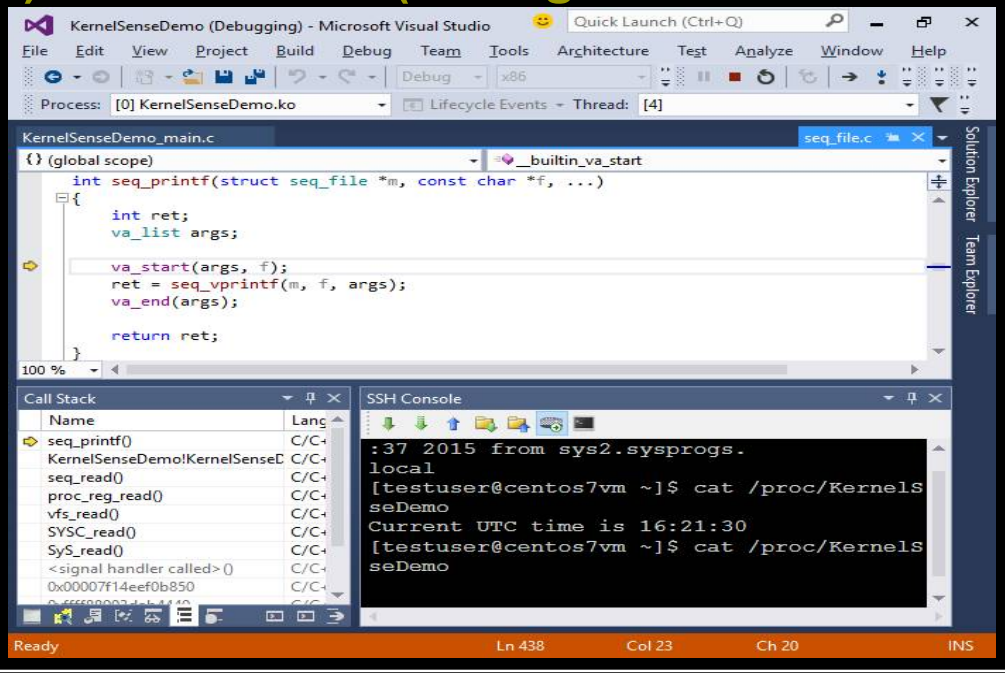
```
struct kprobe {
        struct hlist_node hlist;
        struct lit_head list;
        unsigned long nmissed;
        kprobe_opcode_t *addr;
        const char *symbol_name;
        unsigned int offset;
        kprobe_pre_handler_t pre_handler;
        kprobe_post_handler_t post_handler;
        kprobe_fault_handler_t fault_handler;
        kprobe_break_handler_t break_handler;
        kprobe_opcode_t opcode;
        struct arch_specific_insn ainsn;
        u32 flags;
}
```

```
def hook(self, where, func):
    if self._hooks.has_key(func.addr):
        raise Exception("This function is already a callback of this class")

    # create a kprobe struct
    kp = self._mem.alloc(KPROBE_STRUCT_MAXSIZE)
    if isinstance(where, str):
        sym = self._mem.alloc(len(where) + 1)
        self._mem[sym] = where + '\0'
        self._mem[kp + KPROBE_STRUCT_SYMBOL : kp + KPROBE_STRUCT_SYMBOL + WORD_SIZE] = sym
    else:
        self._mem[kp + KPROBE_STRUCT_ADDR : kp + KPROBE_STRUCT_ADDR + WORD_SIZE] = where
    self._mem[kp + KPROBE_STRUCT_HANDLER : kp + KPROBE_STRUCT_HANDLER + WORD_SIZE] = func.addr

    # register the kprobe hook
    err = self._caller["register_kprobe"](kp)
    if err:
        raise Exception("register_kprobe failed")
    self._hooks[func.addr] = kp
```

- **My Fork**
  https://github.com/XianBeiTuoBaFeng2015/kplugs



- **Debugging**
  1) python -m trace --trace ./kplugs_hello.py
  2) VisualKernel (Debug Linux Kernel with Visual Studio)

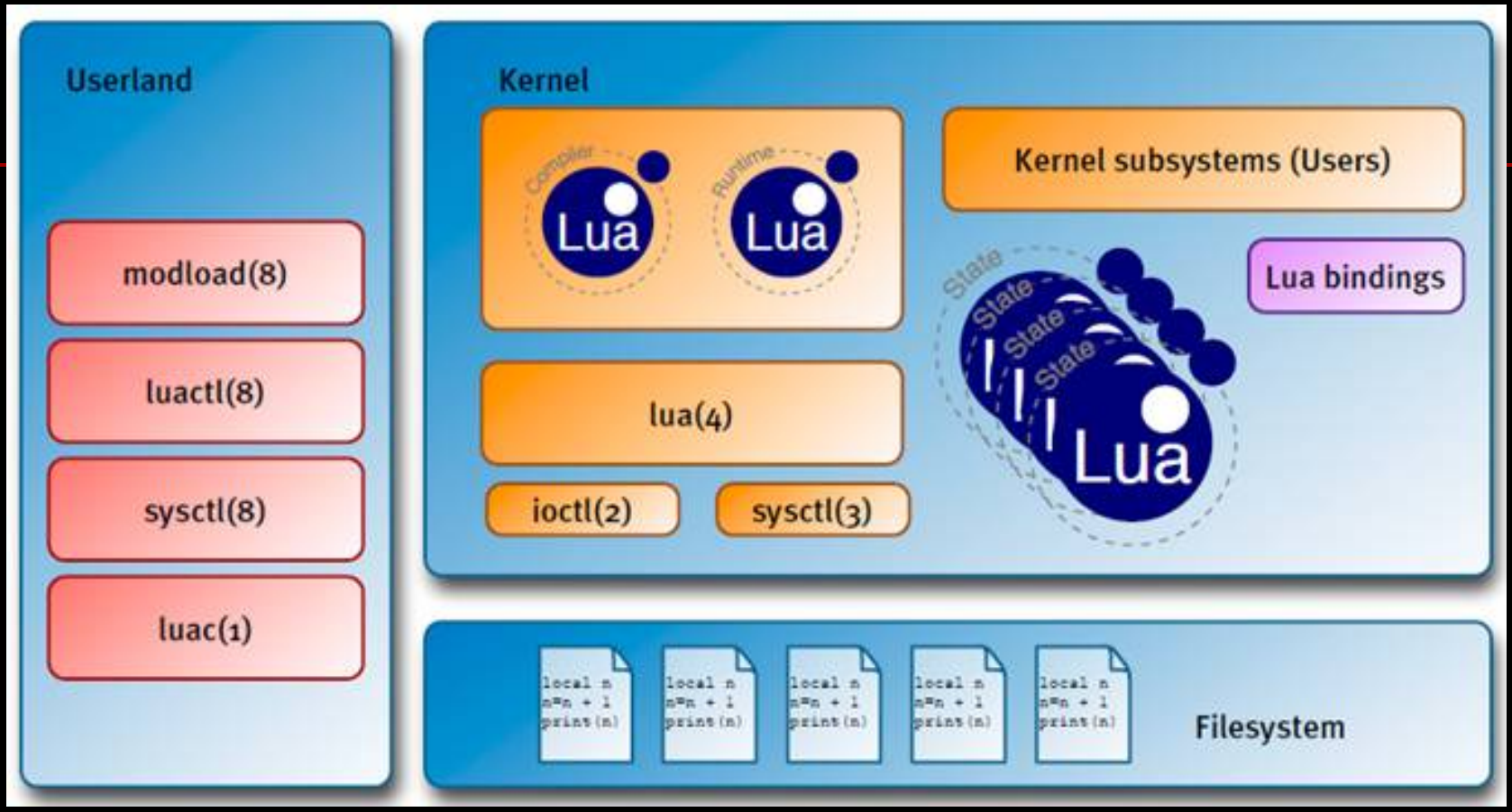


2) Application

- http://www.netbsd.org
- http://www.lua.org
- NetBSD Kernel scripting with Lua

- be part of NetBSD 6 (Userland)
- be part of NetBSD 7 (Kernel)

- The Big Picture



Source: https://archive.fosdem.org/2013/schedule/event/lua_in_the_netbsd_kernel/

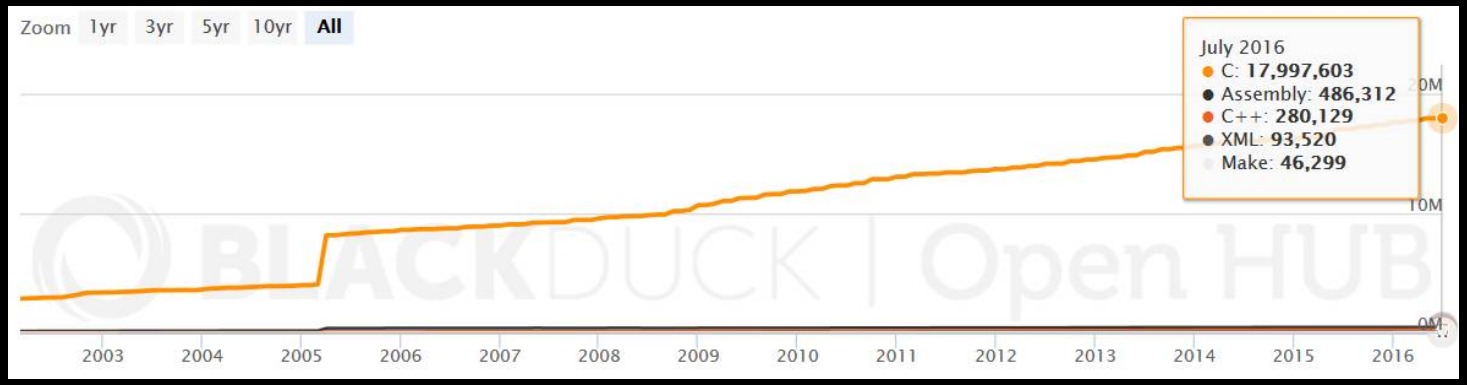
- still lack of JIT(Just-in-Time) support, but available on Linux

- **Why not Python?**
  - Huge library
  - Memory consumption
  - Difficult object mapping

VM size at megabytes level, but the key idea behind KPlugs is…

Conclusions

Reduce the size of Kernel source code



Source: https://www.openhub.net/p/linux/analyses/latest/languages_summary

Deliver a higher-level programming environment to the Kernel

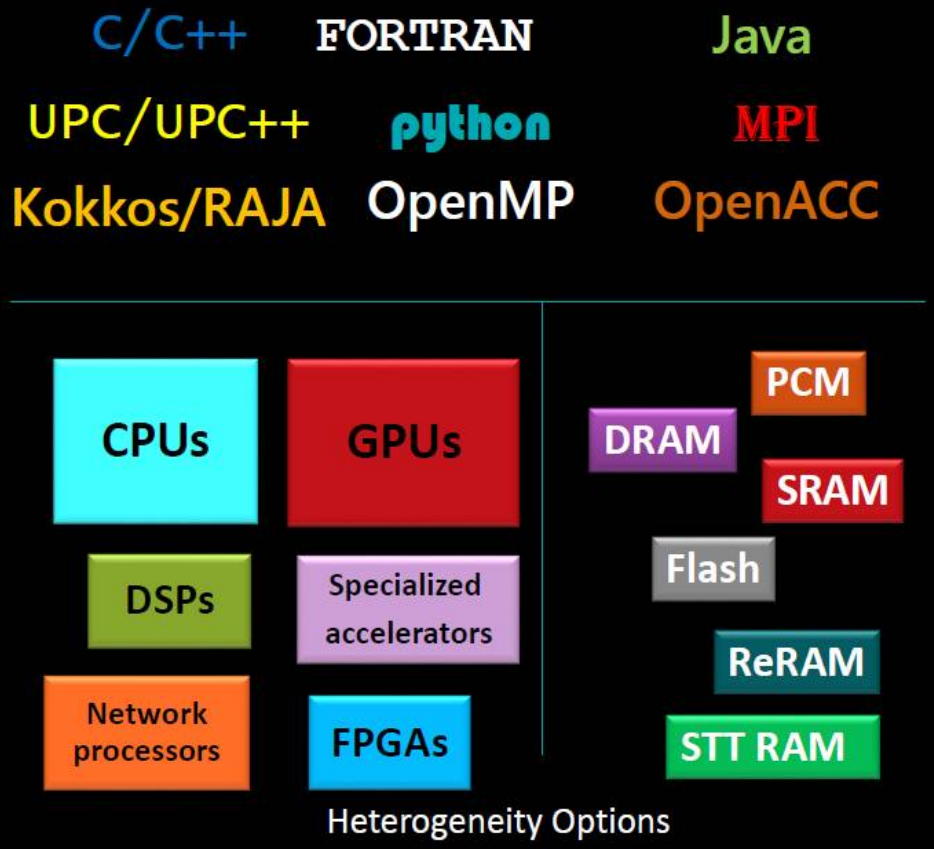
Let users explore the system in an easy way

Great innovation in OS development!

III. Python-assisted Data Center Dev

1) HPC

- High Performance Computing or Heterogeneous Parallel Computing



Anaconda

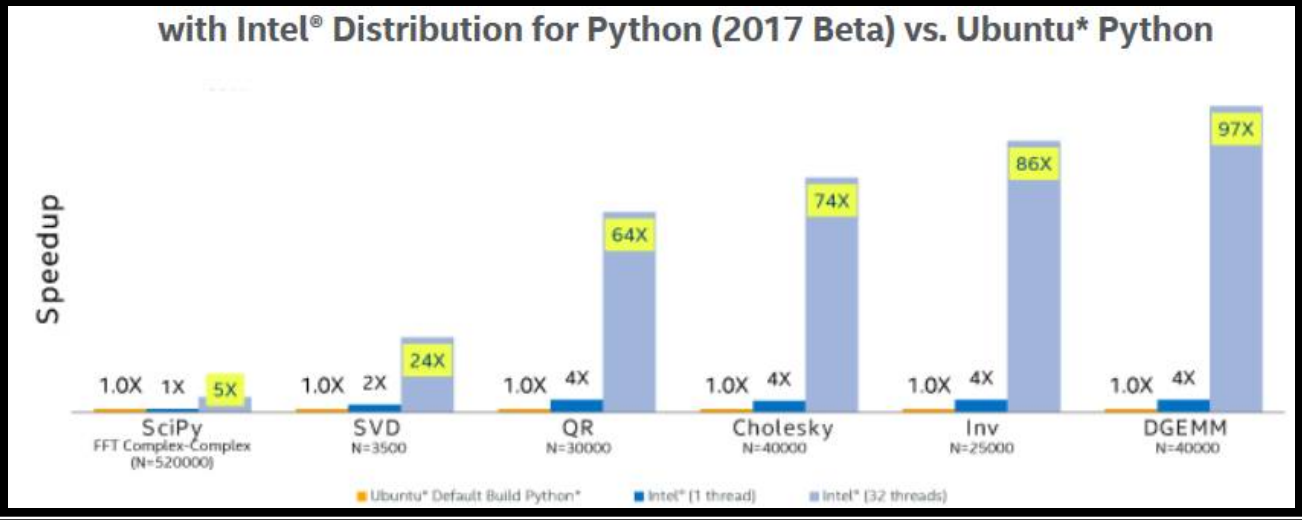
- https://www.continuum.io/
- Open Source Modern Analytics Platform Powered by Python
- Swissknife for Big Data, AI, HPC, Cloud/Web, Exploration & Viz

Intel

- **Intel Distribution for Python**
- **https://software.intel.com/en-us/python-distribution**
- **accelerated with MKL, MPI, TBB, DAAL**
- **support of Xeon Phi**
- **packages:**

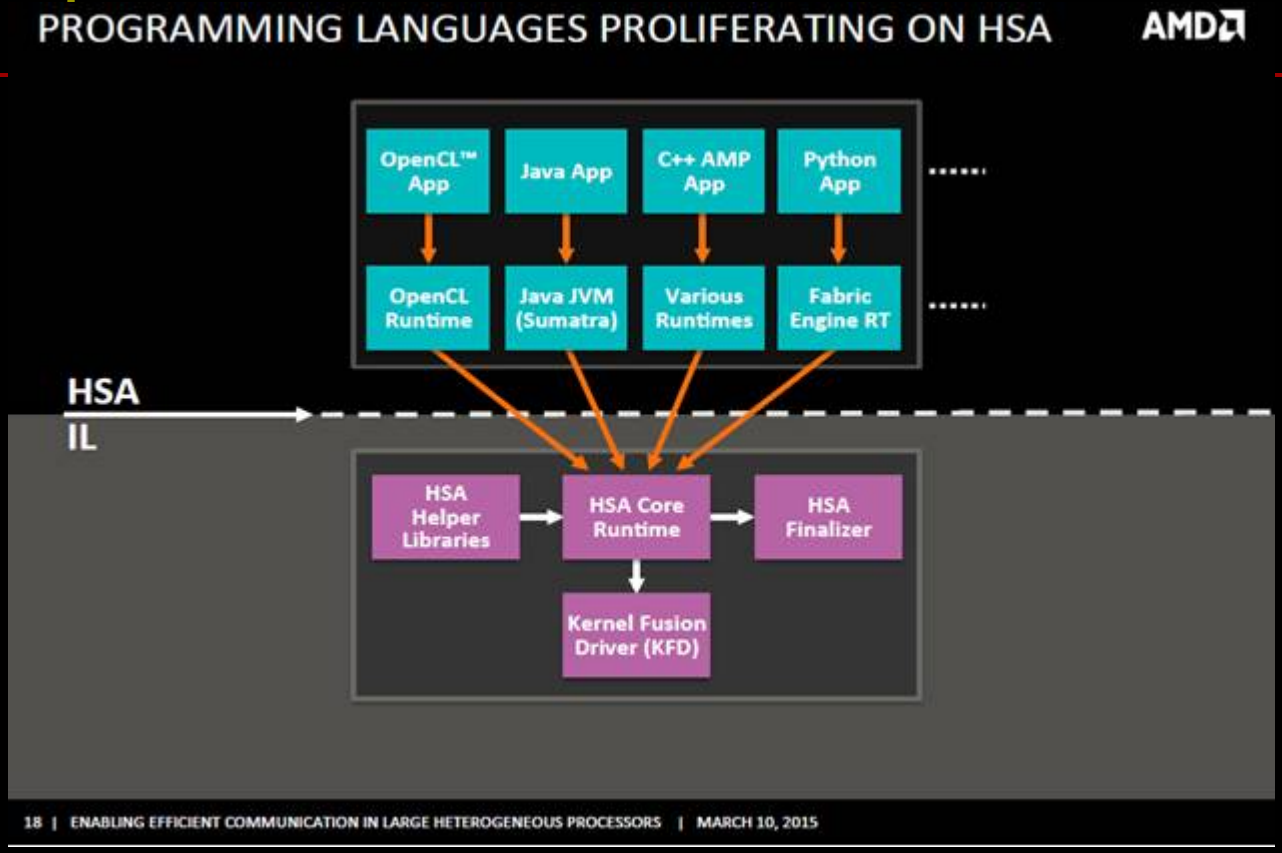
  - Included Python* packages: NumPy*, SciPy*, Pandas*, Matplotlib*, IPython*, Sympy*, NumExpr*, Scikit-learn* (Linux*, Microsoft Windows*, and OS X* operating systems), mpi4py* (Linux*), DistArray* (Linux*), PyTables (Linux* and Windows*), Numba* (Linux*, Windows*, and OS X*), Conda* package management tool
  - pyDAAL: Python package for the Intel Data Analytics Acceleration Library

- **Performance Boost on Select Numerical Functions**



AMD

- Heterogeneous System Architecture
- http://www.hsafoundation.com/



- https://github.com/ContinuumIO/Numba-HSA-Webinar/

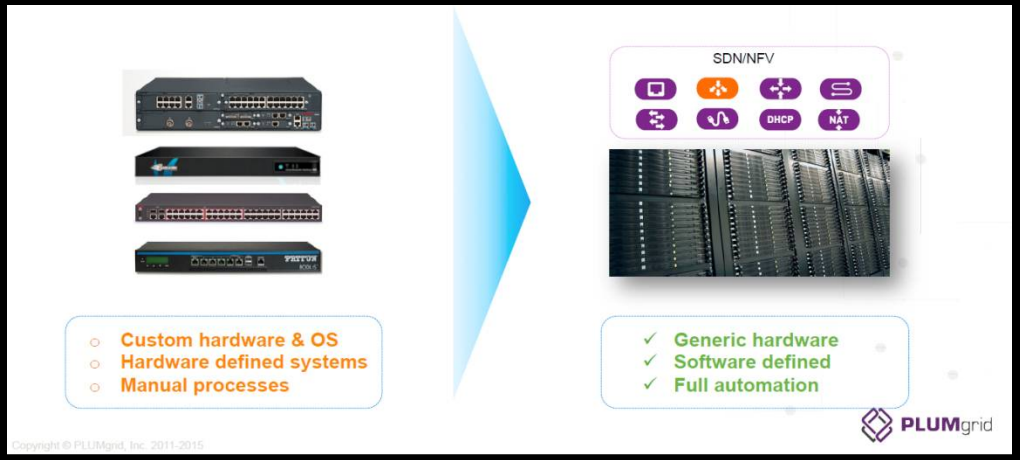
2) Software-Defined Everything (SDE)

- Software Defined Data Center (SDDC)
- Software-Defined Networking (SDN)
- Software-Defined Storage (SDS)
- https://en.wikipedia.org/wiki/Software-defined_data_center

The software-defined data center encompasses a variety of concepts and data center infrastructure components, and each component can be provisioned, operated, and managed through an application programming interface (API).[4] The core architectural components that comprise the software-defined data center[5] include the following:

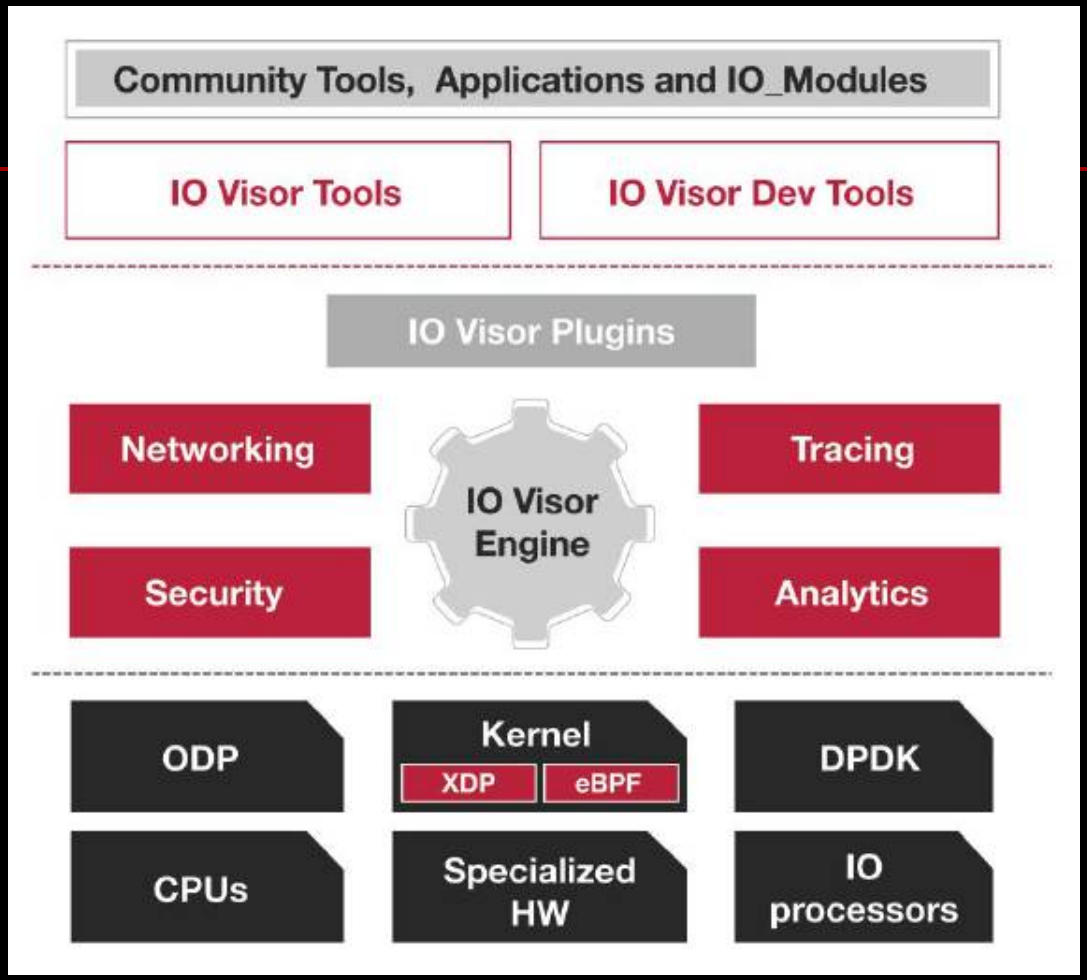
- Computer virtualization,[6] which is a software implementation of a computer.
- Software-defined networking (SDN), which includes network virtualization, is the process of merging hardware and software resources and networking functionality into a software-based virtual network.[5]
- Software-defined storage (SDS), which includes storage virtualization, suggests a service interface to provision capacity and SLAs (Service Level Agreements) for storage, including performance and durability.
- Management and automation software, enabling an administrator to provision, control, and manage all software-defined data center components.[7]

- Traditional to Software Defined Systems



KL3 Koo Li, 2016/5/28

- https://www.iovisor.org/



- https://github.com/iovisor/bcc/tree/master/src/cc/frontends/p4/compiler

IV. Summary

- User space/Kernel space Repartition & Unifying
  - write your function in user space, while run it in kernel
  - user space drivers
  - scripting your OS
- Compilation technologies are rapidly evolving
  - compiler infrastructure like LLVM
  - source-to-source, bytecode-to-bytecode, and bytecode to native code compiler
- Python-based Domain Specific Languages & language subset

- Python is sure to play an important role in next generation Software Defined Systems!

Q & A

Thanks!

Reference

Slides/materials from many and varied sources:

- http://en.wikipedia.org/wiki/
- http://www.slideshare.net/

- https://www.kernel.org/doc/Documentation/
- http://man7.org/linux/man-pages/man2/bpf.2.html
- http://tracingsummit.org
- http://www.brendangregg.com/blog/
- https://www.python.org
- http://llvm.org
- https://en.wikipedia.org/wiki/Just-in-time_compilation
- http://sysprogs.com/VisualKernel/
- https://www.netbsd.org/gallery/presentations/
- https://en.wikipedia.org/wiki/Anaconda_(Python_distribution)
- https://www.opennetworking.org/
- https://www.opnfv.org/
- http://pypy.org
- https://en.wikipedia.org/wiki/Runtime_system
- https://en.wikipedia.org/wiki/Intermediate_representation
- …