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北京开源芯片研究院
BEIJING INSTITUTE OF OPEN SOURCE CHIP

香山处理器 Tutorial

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2023.08.24

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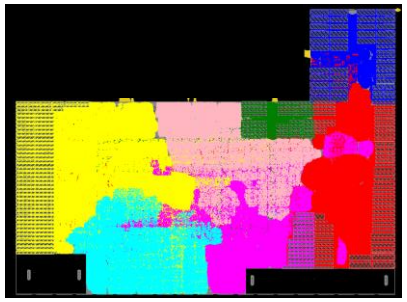
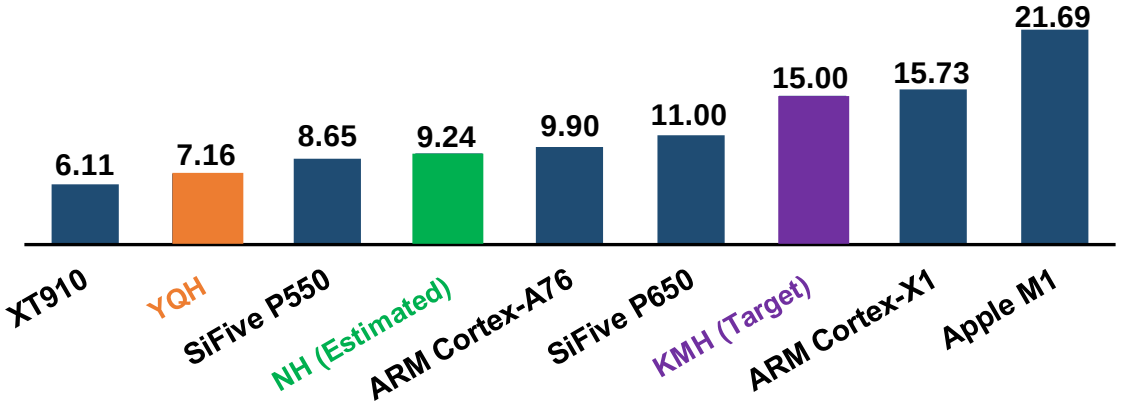
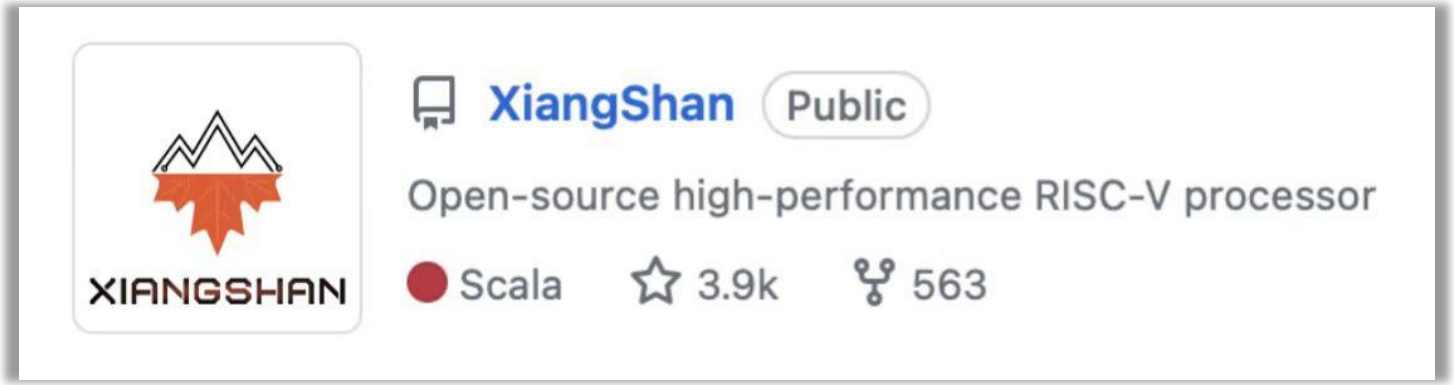
  - **28nm，1.3GHz，2021年7月**
  - **SPEC CPU2006 7.01@1GHz**
- **第二代：南湖 架构**
  - RV64GCBK，双核，超标量乱序执行
  - **14nm，2GHz，2023年中投片**
  - **预估 SPEC 2006 20@2GHz**
- **第三代：昆明湖 架构**
  - RV64GCBKHV，四核，超标量乱序执行
  - 与工业界企业伙伴紧密协作





香山：开源高性能 RISC-V 处理器

- 使用Chisel硬件设计语言实现
- 包含差分测试框架（DiffTest）、仿真快照、检查点等开发工具
- 建立了包含设计、实现、验证在内的全开源工具敏捷开发流程

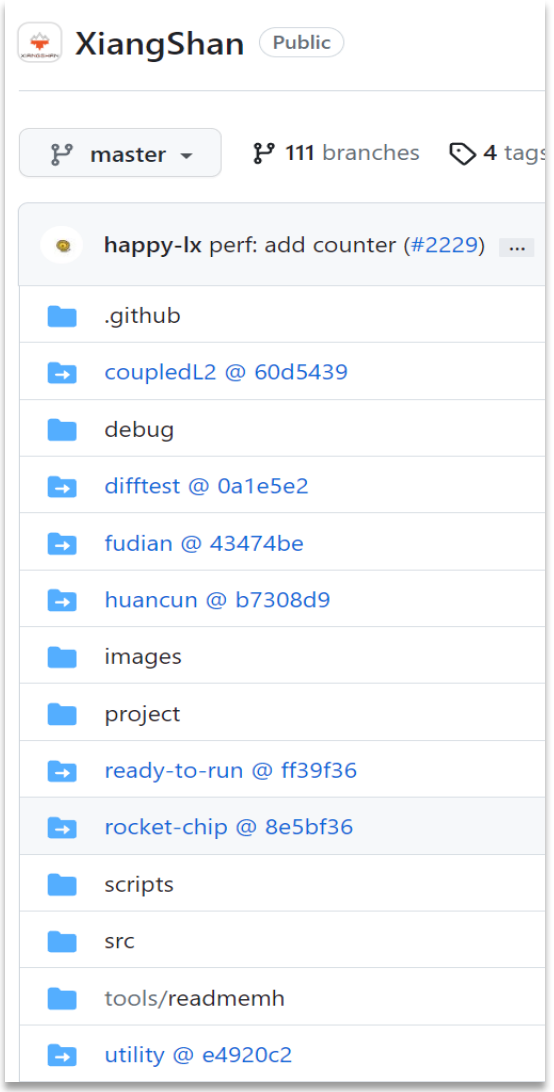


主仓库在全球最大开源项目托管平台 GitHub
已获得超过 3900 个星标，形成超过 500 分支
https://github.com/OpenXiangShan/XiangShan

微信公众号

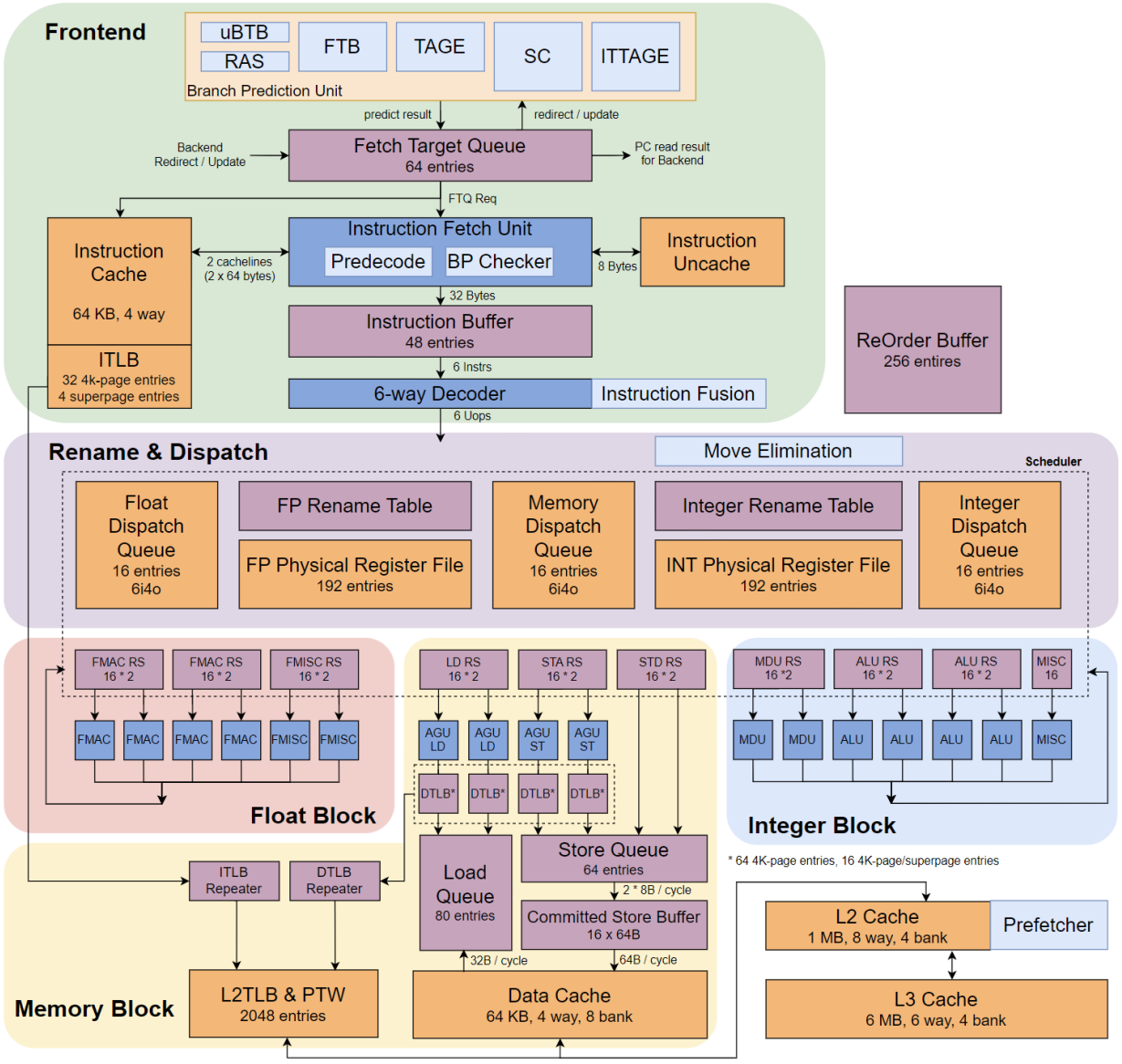
项目结构

```
.
├── scripts               # 生成 Verilog 及仿真使用的一些脚本
├── src                   # 结构设计与验证代码
│   └── main                # 结构设计代码
│       └── scala
│           ├── device          # 仿真用的一些外设
│           ├── system          # SoC 的描述
│           ├── top             # 顶层文件
│           ├── utils           # 一些基础硬件工具库
│           ├── xiangshan       # 香山 CPU 部分的设计代码
│           └── xstransforms    # 一些 FIRRTL Transforms
├── fudian                # 香山浮点子模块
├── huancun               # 香山 L2/L3 缓存子模块
├── difftest              # 香山协同仿真框架
├── ready-to-run          # 预先编译好的 nemu 动态链接库，和一些负载
└── rocket-chip           # 用来获取 Diplomacy 框架（等待上游拆分）
```

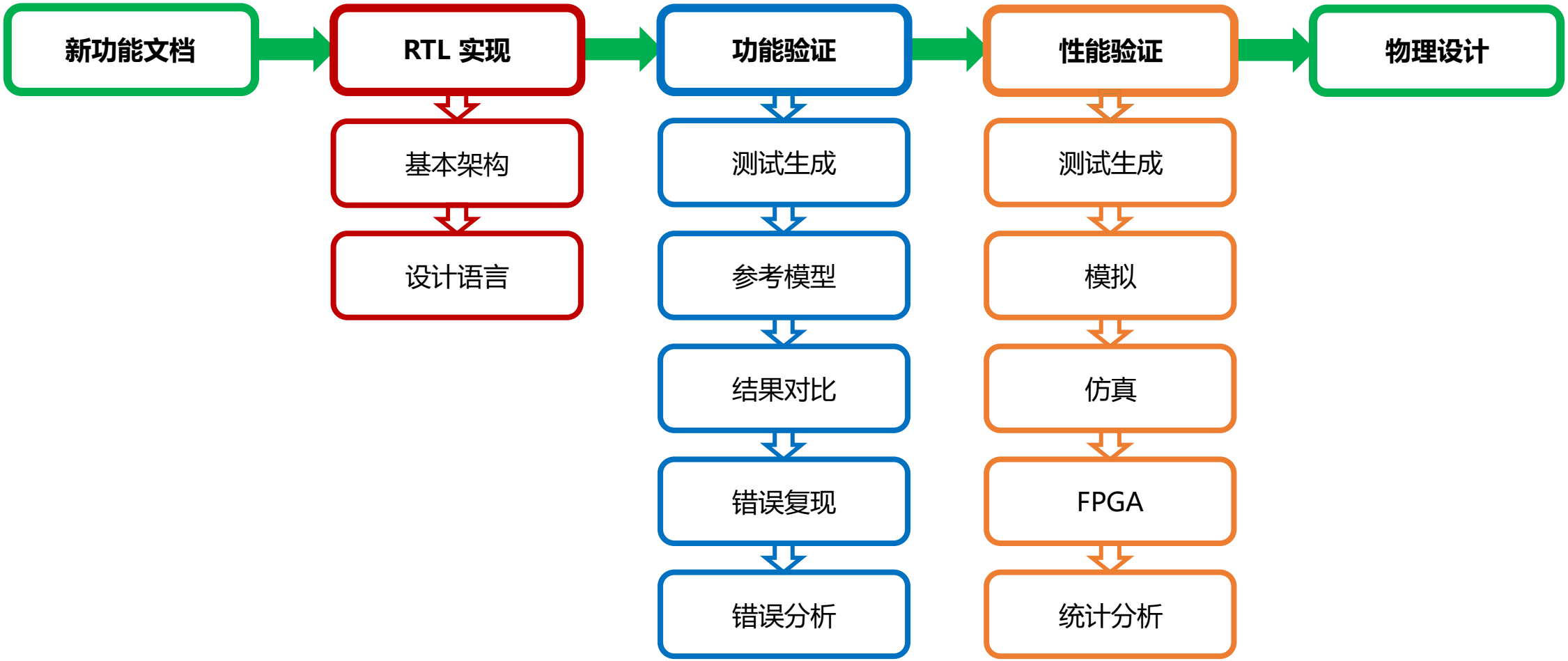


逻辑结构

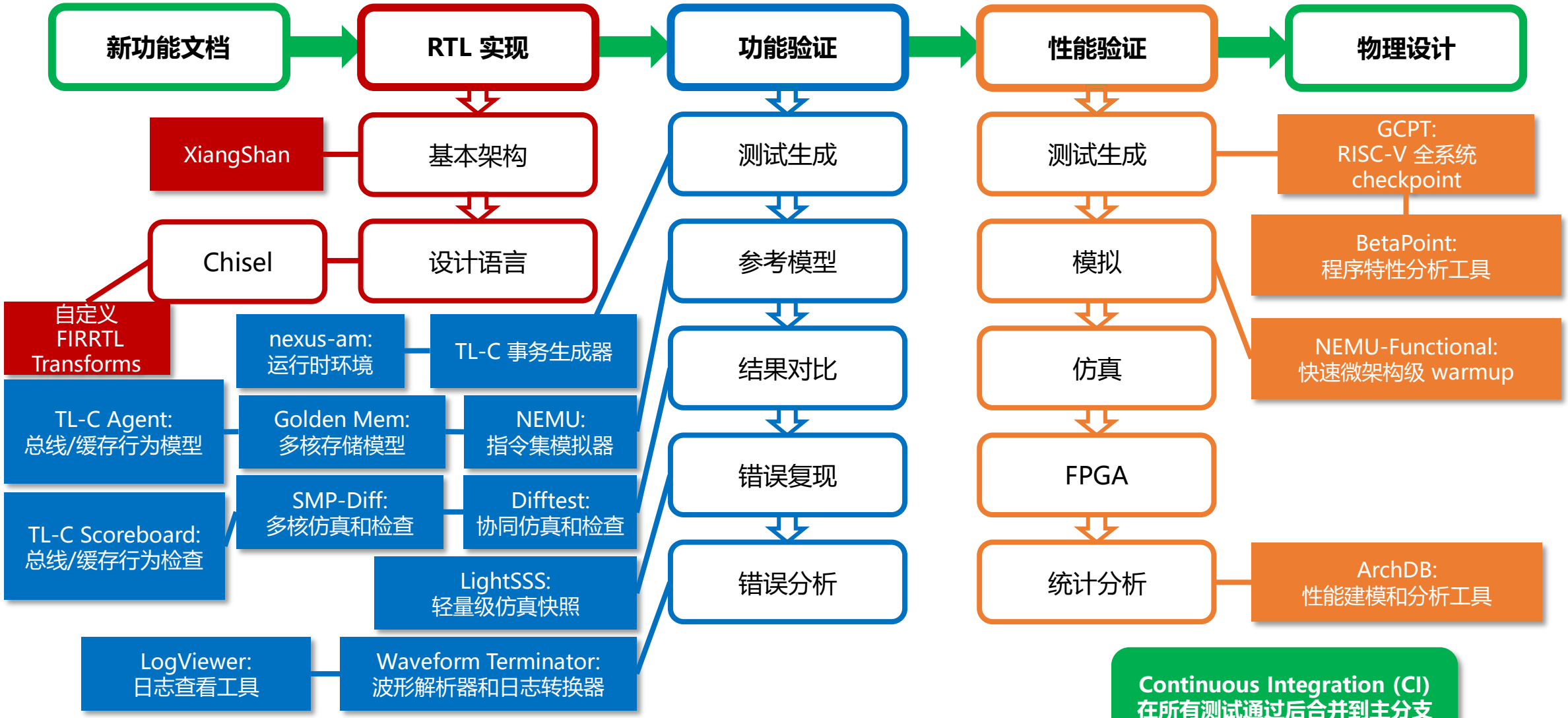
- 前端
  - BPU、FTQ、IFU、IBuffer、ICache
- 后端
  - CtrlBlock、IntBlock、FloatBlock
- 访存
  - MemBlock 、MMU、DCache
- 缓存
  - L2/L3 Cache



敏捷开发流程和工具


新功能文档
RTL 实现
基本架构
设计语言
功能验证
测试生成
参考模型
结果对比
错误复现
错误分析
性能验证
测试生成
模拟
仿真
FPGA
统计分析
物理设计

敏捷开发流程和工具


新功能文档
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性能验证
物理设计
XiangShan
基本架构
Chisel
设计语言
自定义 FIRRTL Transforms
nexus-am: 运行时环境
TL-C 事务生成器
TL-C Agent: 总线/缓存行为模型
Golden Mem: 多核存储模型
NEMU: 指令集模拟器
TL-C Scoreboard: 总线/缓存行为检查
SMP-Diff: 多核仿真和检查
Difftest: 协同仿真和检查
LightSSS: 轻量级仿真快照
LogViewer: 日志查看工具
Waveform Terminator: 波形解析器和日志转换器
测试生成
参考模型
结果对比
错误复现
错误分析
测试生成
模拟
仿真
FPGA
统计分析
GCPT: RISC-V 全系统 checkpoint
BetaPoint: 程序特性分析工具
NEMU-Functional: 快速微架构级 warmup
ArchDB: 性能建模和分析工具
Continuous Integration (CI)
在所有测试通过后合并到主分支

在本次 tutorial 中，我们将

- 提供对云服务器的访问
- 准备好香山的开发环境
- 现场演示香山的开发工作流程

仿真

- 环境
- RTL 生成
- RTL 仿真

……

功能验证

- Nexus-AM
- NEMU
- Difftest

……

性能验证

- Perf. counter
- Constin
- Checkpoint

……

- ***需要：网络和 SSH***

演示指令

- shell 命令在**紫色框**中以前缀 $ 显示

```
$ echo "Hello, XiangShan"
$ echo "Have a nice day"
```

- **描述和注释**在**灰色框**中以前缀 # 显示

```
# Please prepare a laptop with an SSH client.
# Next, let's start the demo session !
```

现在试试看吧！

准备工作

- 登录云服务器
  - 对于 Windows 用户（推荐使用 Windows Terminal 和 PowerShell）

```
PS > curl https://openxiangshan.github.io/tutorial.pem -o tutorial.pem
PS > ssh -i "tutorial.pem" guest@123.56.80.238
```

  - 对于 Linux 和 Mac 用户

```
$ curl https://openxiangshan.github.io/tutorial.pem -o tutorial.pem
$ chmod 400 tutorial.pem
$ ssh -i "tutorial.pem" guest@123.56.80.238
```

准备工作

```
# 复制开发环境 xs-env 到您的路径
$ cp -r /opt/xs-env ~/<YOUR_NAME>

# 进入开发环境目录
$ cd ~/<YOUR_NAME>

# 设置环境变量
$ source env.sh
# SET XS_PROJECT_ROOT:                    /home/guest/YOUR_NAME
# SET NOOP_HOME (XiangShan RTL Home):     $XS_PROJECT_ROOT/XiangShan
# SET NEMU_HOME:                          $XS_PROJECT_ROOT/NEMU
# SET AM_HOME:                            $XS_PROJECT_ROOT/nexus-am
```

准备工作

```
# Project Structure
$ tree -d -L 1
.
├── NEMU
├── NEMU-ahead
├── XiangShan
├── XiangShan-Oracle
├── nexus-am
└── tutorial

# 进入 XiangShan 目录
$ cd XiangShan
```

Chisel 编译

- 使用 Verilator 编译 RTL 并构建仿真模拟器

```
$ make emu EMU_THREADS=2 -j8 &   # Run in background

Options:

    CONFIG=TutorialConfig        Configuration of XiangShan

    EMU_THREADS=2                Simulation threads

    EMU_TRACE=1                  Enable waveform dumping

    // WITH_DRAMSIM=1            Enable DRAMSim3 for DRAM simulation

    // WITH_CHISELDB = 1         Enable ChiselDB feature

    // WITH_CONSTANTIN = 1       Enable Constantin feature
```

- 编译大概需要 30 min

准备一个新终端

```
# 打开新的终端，重新登录云服务器
$ ssh -i "tutorial.pem" guest@<server_ip_address>

# 进入开发环境，设置环境变量
$ cd ~/<YOUR_NAME>
$ source env.sh

# 进入 tutorial 目录
$ cd tutorial
# 如没有特殊说明，后续我们都将在这个目录下进行操作
```

使用 Verilator 运行 RTL 仿真

- 使用准备好的 emu，即可运行仿真程序

```
# 运行仿真程序
$ ./emu -i hello.bin --no-diff 2>hello.err

# Some key options:
    -i
    -C / -I / -W
    --diff=PATH / --no-diff
```

这样我们就了解了香山的基本仿真过程。

那么接下来该干什么呢?

我们怎么才能

- **生成所需 workload**
- **查找并修复功能 bug**
- **进行性能分析**
- **进行微架构探索**

敏捷功能验证

Nexus-AM

生成测试

发现错误

difftest

NEMU

Waveform

ChiselDB

定位并
解决问题

保存
出错现场

LightSSS

Nexus-AM: 裸机运行时环境

- **目的**
  - 在没有操作系统的情况下**敏捷地**生成工作负载
  - 为**裸机**（如香山）提供运行时框架
- **Nexus-AM**
  - 轻量且易用
  - 实现了基本的**系统调用**接口和异常处理
  - 支持多种 **ISA 和配置**

Nexus-AM

- **动手试试：**编译 Coremark

```
$ bash build-am.sh
```

```
# cd $AM_HOME/apps/coremark
# make ARCH=riscv64-xs
# ls -l build
#     coremark-riscv64-xs.bin    程序的二进制镜像
#     coremark-riscv64-xs.elf    程序的 ELF 文件
#     coremark-riscv64-xs.txt    程序的反汇编
```

NEMU: ISA 参考设计

- **目的**
  - 可以作为验证的参考模型
  - 简单且高效
- **NEMU**
  - 和 Spike 类似的**指令集模拟器**
  - 经**优化**后，性能与 QEMU 相近
  - 提供了**一系列 API** 来辅助香山比较和验证**微架构**

NEMU

- **动手试试：**编译生成 NEMU

```
$ bash build-nemu.sh
```

```
# cd $NEMU_HOME
# make clean
# make riscv64-xs_defconfig
# make -j      将NEMU编译成裸机，从而可以运行之前步骤的Coremark
# make clean-softfloat
# make riscv64-xs-ref_defconfig
# make         将NEMU编译成香山的参考设计
```

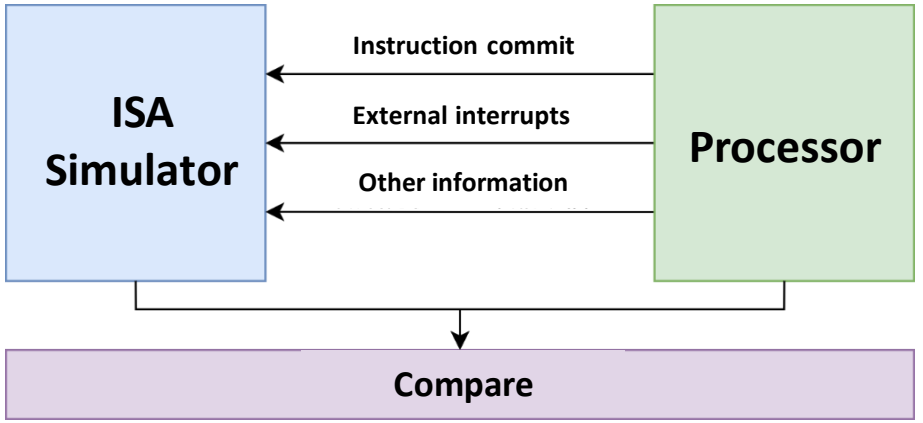
- **动手试试**：在 NEMU 上运行 Coremark

```
$ bash run-nemu.sh
```

```
# cd $NEMU_HOME
# ./build/riscv64-nemu-interpreter -b \                    连续运行，更快
$AM_HOME/apps/coremark/build/coremark-riscv64-xs.bin 运行Coremark
```

Difftest: 差分测试协同仿真框架

- **基本流程**
  - 处理器指令提交/其他信息更新
  - 模拟器执行相同指令
  - 对比待测设计和参考设计间的微架构状态
  - 中止或继续
- **作为处理器验证的基础设施**
  - 向 HDL（如 Chisel/Verilog）提供 API 接口
  - 支持 RTL 模拟器（如 Verilator, VCS）
  - 支持 RISC-V ISS（如 **NEMU**, **Spike**）作为参考设计
- **SMP-Difftest： SMP处理器上的协同仿真**
  - SMP Linux kernel 和多线程程序
  - 在线检查 cache 一致性和内存一致性



Basic architecture of DiffTest

```
while (1) {
  icnt = cpu_step();
  nemu_step(icnt);
  r1s = cpu _getregs();
  r2s = nemu_getregs();
  if (r1s != r2s) { abort(); }
}
```

Online checking

Difftest

- **动手试试**：在香山运行 Coremark，并与 NEMU 进行 difftest

```
# 运行 Coremark 需要约 2 分钟
$ bash run-emu.sh
```

```
# ./emu \
-i $AM_HOME/apps/coremark/build/coremark-riscv64-xs.bin \  使用 coremark.bin
--diff $NEMU_HOME/build/riscv64-nemu-interpreter-so \      与 NEMU difftest
2>perf.out     将标准错误输出重定向到文件
```

Difftest

```
./emu -i $AM_HOME/apps/coremark/build/coremark-riscv64-xs.bin --diff $NEMU_HOME/build/riscv64-nemu-interpreter-so
Emu compiled at Mar 24 2023, 20:33:03
Using simulated 32768B flash
[warning]no valid flash bin path, use preset flash instead
The image is /home/guest/xs-env-asplos2023/nexus-am/apps/coremark/build/coremark-riscv64-xs.bin
Using simulated 8192MB RAM
NemuProxy using /home/guest/xs-env-asplos2023/NEMU/build/riscv64-nemu-interpreter-so
The first instruction of core 0 has commited. Difftest enabled.
[NEMU] Can not find flash image: (null)
[NEMU] Use built-in image instead
[src/device/io/mmio.c:38,add_mmio_map] Add mmio map 'flash' at [0x0000000010000000, 0x000000000100fffff]
Running CoreMark for 1 iterations
2K performance run parameters for coremark.
CoreMark Size    : 666
Total time (ms)  : 4288
Iterations       : 1
Compiler version : GCC9.4.0
seedcrc          : 0xe9f5
[0]crclist       : 0xe714
[0]crcmatrix     : 0x1fd7
[0]crcstate      : 0x8e3a
[0]crcfinal      : 0xe714
Finised in 4288 ms.
==================================================
CoreMark Iterations/Sec 233
Core 0: HIT GOOD TRAP at pc = 0x80001c52
total guest instructions = 398,372
instrCnt = 398,372, cycleCnt = 517,099, IPC = 0.770398
Seed=0 Guest cycle spent: 517,103 (this will be different from cycleCnt if emu loads a snapshot)
Host time spent: 77,559ms
```

Difftest

- **动手试试**：用 difftest 触发 bug

```
$ bash run-emu-diff.sh
```

```
# ./emu-bug \
  -i $AM_HOME/apps/coremark/build/coremark-riscv64-xs.bin \
  --diff $NEMU_HOME/build/riscv64-nemu-interpreter-so    # 与 NEMU difftest
```

Difftest

- Difftest 会在比对失败时立即报错
  - 打印 PC、GPRs 等信息

```
============== Commit Group Trace (Core 0) ==============
commit group [00]: pc 0080000cdc cmtcnt 1
commit group [01]: pc 0080000ce0 cmtcnt 1
commit group [02]: pc 0080000ce2 cmtcnt 2
commit group [03]: pc 0080000cea cmtcnt 2
commit group [04]: pc 0080000cf0 cmtcnt 2
commit group [05]: pc 0080000cf4 cmtcnt 1
commit group [06]: pc 0080000cb0 cmtcnt 2
commit group [07]: pc 0080000cb6 cmtcnt 1
commit group [08]: pc 0080000cba cmtcnt 1
commit group [09]: pc 0080000cbc cmtcnt 2
commit group [10]: pc 0080000cc2 cmtcnt 1 ←
commit group [11]: pc 0080000cc4 cmtcnt 2
commit group [12]: pc 0080000ccc cmtcnt 1
commit group [13]: pc 0080000cce cmtcnt 1
commit group [14]: pc 0080000cd2 cmtcnt 2
commit group [15]: pc 0080000cd8 cmtcnt 1
```

```
==============  REF Regs  ==============
  $0: 0x0000000000000000   ra: 0x0000000080001620   sp: 0x000000008000cef0   gp: 0x0000000000000000
  tp: 0x0000000000000000   t0: 0x000000000000001f   t1: 0x0000000080003a08   t2: 0x0000000000000000
  s0: 0x0000000000007fff   s1: 0x0000000000000000   a0: 0x00000000800039e8   a1: 0x0000000000000000
  a2: 0x0000000000000000   a3: 0x0000000080003a18   a4: 0x0000000000000001   a5: 0x0000000000000009
  a6: 0x0000000000000001   a7: 0x0000000080003be4   s2: 0x0000000000000000   s3: 0x0000000000000000
  s4: 0x0000000000000000   s5: 0x0000000000000000   s6: 0x0000000000000000   s7: 0x0000000000000000
  s8: 0x0000000000000000   s9: 0x0000000000000000  s10: 0x0000000000000000  s11: 0x0000000000000000
  t3: 0x0000000080003be4   t4: 0x0000000080003bd8   t5: 0x0000000080003c54   t6: 0x000000000000001f
 ft0: 0xffffffff00000000  ft1: 0xffffffff00000000  ft2: 0xffffffff00000000  ft3: 0xffffffff00000000
 ft4: 0xffffffff00000000  ft5: 0xffffffff00000000  ft6: 0xffffffff00000000  ft7: 0xffffffff00000000
 fs0: 0xffffffff00000000  fs1: 0xffffffff00000000  fa0: 0xffffffff00000000  fa1: 0xffffffff00000000
 fa2: 0xffffffff00000000  fa3: 0xffffffff00000000  fa4: 0xffffffff00000000  fa5: 0xffffffff00000000
 fa6: 0xffffffff00000000  fa7: 0xffffffff00000000  fs2: 0xffffffff00000000  fs3: 0xffffffff00000000
 fs4: 0xffffffff00000000  fs5: 0xffffffff00000000  fs6: 0xffffffff00000000  fs7: 0xffffffff00000000
 fs8: 0xffffffff00000000  fs9: 0xffffffff00000000 fs10: 0xffffffff00000000 fs11: 0xffffffff00000000
 ft8: 0xffffffff00000000  ft9: 0xffffffff00000000 ft10: 0xffffffff00000000 ft11: 0xffffffff00000000
pc: 0x0000000080000cc4 mstatus: 0x8000000a00006000 mcause: 0x0000000000000000 mepc: 0x4ede2b1aa1cb2ef6
                       sstatus: 0x8000000200006000 scause: 0x0000000000000000 sepc: 0x0000000000000000
satp: 0x0000000000000000
mip: 0x0000000000000000 mie: 0x0000000000000000 mscratch: 0x0000000000000000 sscratch: 0x0000000000000000
mideleg: 0x0000000000000000 medeleg: 0x0000000000000000
mtval: 0x0000000000000000 stval: 0x91da2105e8dfee5b mtvec: 0x0000000000000000 stvec: 0x0000000000000000
privilege mode:3  pmp: below
 0: cfg:0x00 addr:0x0000000000000000| 1: cfg:0x00 addr:0x0000000000000000
 2: cfg:0x00 addr:0x0000000000000000| 3: cfg:0x00 addr:0x0000000000000000
 4: cfg:0x00 addr:0x0000000000000000| 5: cfg:0x00 addr:0x0000000000000000
 6: cfg:0x00 addr:0x0000000000000000| 7: cfg:0x00 addr:0x0000000000000000
 8: cfg:0x00 addr:0x0000000000000000| 9: cfg:0x00 addr:0x0000000000000000
10: cfg:0x00 addr:0x0000000000000000|11: cfg:0x00 addr:0x0000000000000000
12: cfg:0x00 addr:0x0000000000000000|13: cfg:0x00 addr:0x0000000000000000
14: cfg:0x00 addr:0x0000000000000000|15: cfg:0x00 addr:0x0000000000000000
priviledgeMode: 3
     a5 different at pc = 0x0080000cc2, right= 0x0000000000000009, wrong = 0x0000000000000000
Core 0: ABORT at pc = 0x80000cd2
total guest instructions = 1639
instrCnt = 1639, cycleCnt = 8726, IPC = 0.187829
Seed=0 Guest cycle spent: 8729 (this will be different from cycleCnt if emu loads a snapshot)
Host time spent: 1814ms
```

Difftest

- **动手试试：**在 difftest 检测出 bug 后生成波形

```
$ bash run-emu-dumpwave.sh
$ ls ../XiangShan/build | grep "vcd"   # 目录下应该有后缀名为 .vcd 的波形文件
```

```
# ./emu-bug \
-i $AM_HOME/apps/coremark/build/coremark-riscv64-xs.bin \
--diff $NEMU_HOME/build/riscv64-nemu-interpreter-so \
-b 1200 \        生成波形的起始周期。在上一步中，香山在约1600 个周期处报错结束
-e 1700 \        生成波形的结束周期
--dump-wave \    生成波形，之后会在$NOOP_HOME/build 目录下生成*.vcd 文件
```

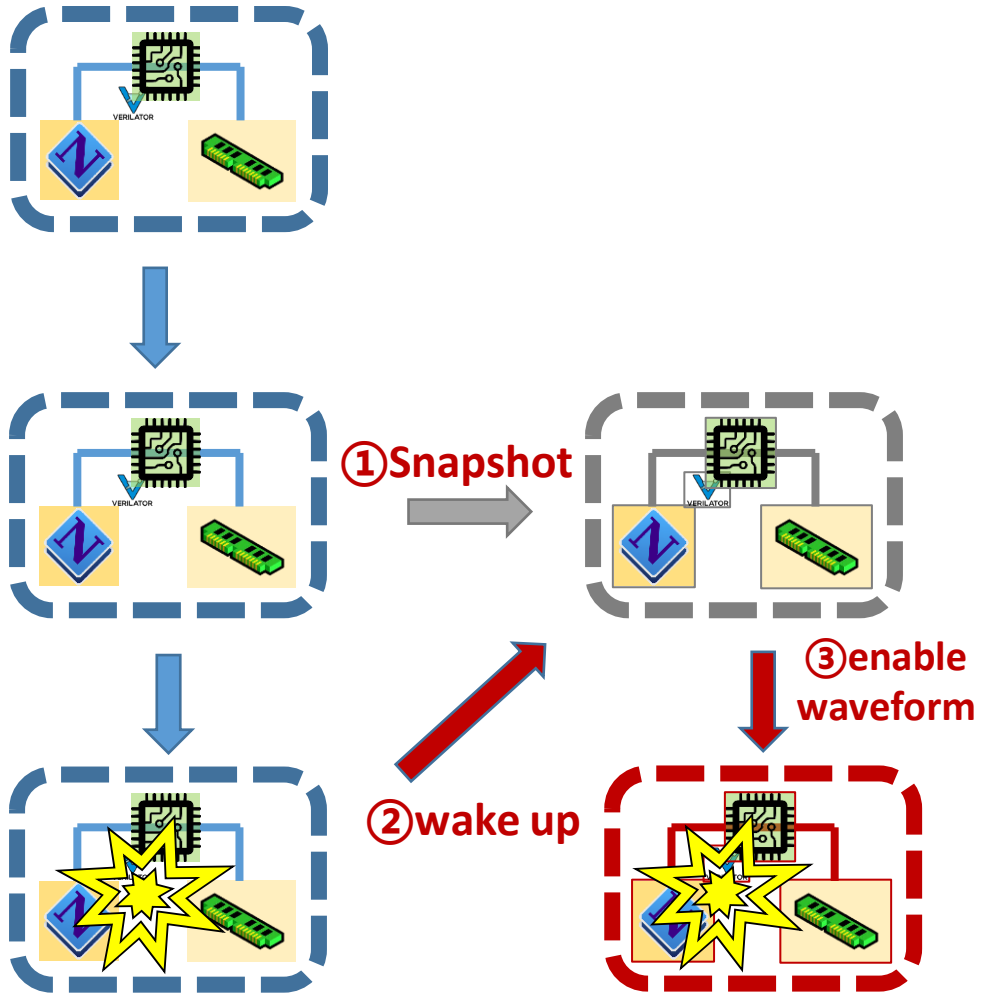
LightSSS: 一种基于内存的轻量级仿真快照

- **重跑仿真很费时间！**
  - **可以通过快照解决**

- **LightSSS：使用 fork() 对进程做快照**
  - Linux Kernel 写时复制机制

- **优点一：可移植性和可扩展性好**
  - 可以对任何外部模块做快照（如 C++）
  - 无需理解外部模块的细节

- **优点二：快照开销低**
  - 生成快照只需约 500 us
  - 远低于 Verilator 提供的 RTL 快照开销



LightSSS

- **动手试试：**用 LightSSS 生成波形，根据需求 debug

```
$ bash run-emu-lightsss.sh
```

```
# ./emu-bug \
-i $AM_HOME/apps/coremark/build/coremark-riscv64-xs.bin \
--diff $NEMU_HOME/build/riscv64-nemu-interpreter-so \
--enable-fork \     不再需要使用复杂的参数
2 > lightsss.err
```

LightSSS

- LightSSS 工作时你应该看到：

```
 4: cfg:0x00 addr:0x0000000000000000| 5: cfg:0x00 addr:0x0000000000000000
 6: cfg:0x00 addr:0x0000000000000000| 7: cfg:0x00 addr:0x0000000000000000
 8: cfg:0x00 addr:0x0000000000000000| 9: cfg:0x00 addr:0x0000000000000000
10: cfg:0x00 addr:0x0000000000000000|11: cfg:0x00 addr:0x0000000000000000
12: cfg:0x00 addr:0x0000000000000000|13: cfg:0x00 addr:0x0000000000000000
14: cfg:0x00 addr:0x0000000000000000|15: cfg:0x00 addr:0x0000000000000000
priviledgeMode: 3
     a5 different at pc = 0x0080000630, right= 0x0000000000000009, wrong = 0x0000000000000000
[FORK_INFO pid(20792)] the oldest checkpoint start to dump wave and dump nemu log...
[FORK_INFO pid(20792)] dump wave to /home/guest/xiangshan/XiangShan/build/2023-08-21@15:23:17_1.vcd...
NEMU dynamic_config update
  - ignore_illegal_mem_access 0
  - debug_difftest 1
The first instruction of core 0 has commited. Difftest enabled.
[NEMU] Can not find flash image: (null)
[NEMU] Use built-in image instead
```

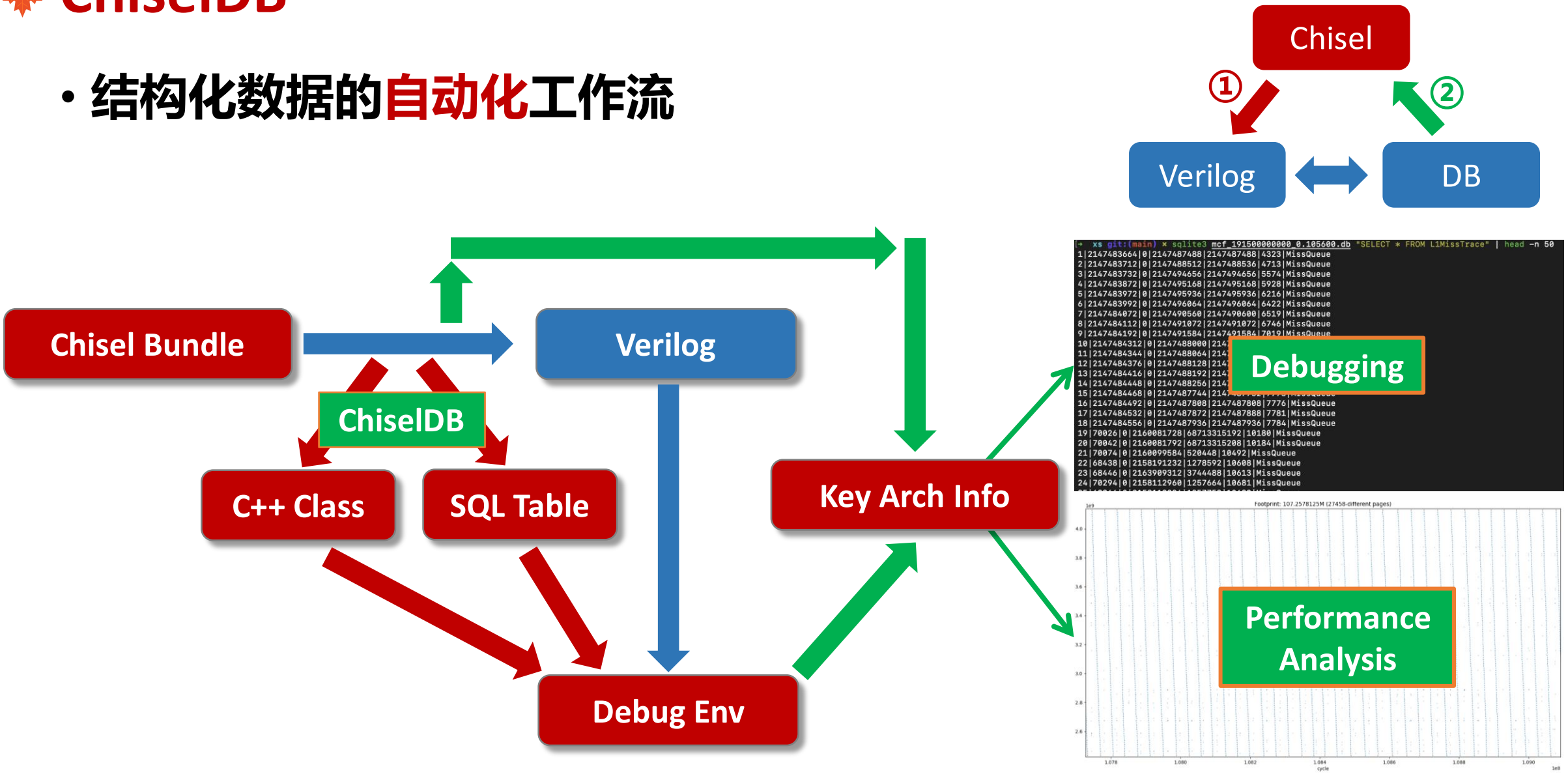
- 此后，仿真会从最近的快照处重启

ChiselDB: Debug 友好的结构化数据库

- **动机**
  - 波形占用空间**大**，且**难以用于**进一步分析
  - 需要分析类似访存事务 trace 的结构化数据
- **ChiselDB**
  - 在硬件层面的模块接口间插入探针
  - DPI-C：在 Chisel 代码中使用 C++ 函数传递数据
  - 在数据库中持久化存储，支持 SQL 查询

ChiselDB

- 结构化数据的**自动化**工作流



ChiselDB

- **源代码：** *XiangShan/utility/ChiselDB.scala*
- **使用方法：** 创建 Table

```
// API: def createTable[T <: Record](tableName: String, hw: T): Table[T]
import huancun.utils.ChiselDB

class MyBundle extends Bundle {
        val fieldA = UInt(10.W)
        val fieldB = UInt(20.W)
}
val table = ChiselDB.createTable("MyTableName", new MyBundle)
```

ChiselDB

- **使用方法：**添加寄存器探针

```
/* APIs
def log(data: T, en: Bool, site: String = "", clock: Clock, reset: Reset)
def log(data: Valid[T], site: String, clock: Clock, reset: Reset): Unit
def log(data: DecoupledIO[T], site: String, clock: Clock, reset: Reset): Unit
*/
table.log(
  data = my_data /* hardware of type T */,
  en = my_cond,   site = "MyCallSite",
  clock = clock,   reset = reset
)
```

ChiselDB

- **实例：** *XiangShan/src/main/scala/xiangshan/cache/mmu/L2TLB.scala*

```
class L2TlbMissQueueDB(implicit p: Parameters) extends TlbBundle {
   val vpn = UInt(vpnLen.W)
}

val L2TlbMissQueueInDB, L2TlbMissQueueOutDB = Wire(new L2TlbMissQueueDB)
L2TlbMissQueueInDB.vpn := missQueue.io.in.bits.vpn
L2TlbMissQueueOutDB.vpn := missQueue.io.out.bits.vpn

val L2TlbMissQueueTable = ChiselDB.createTable(
        "L2TlbMissQueue_hart" + p(XSCoreParamsKey).HartId.toString, new L2TlbMissQueueDB)

L2TlbMissQueueTable.log(L2TlbMissQueueInDB, missQueue.io.in.fire, "L2TlbMissQueueIn", clock, reset)
L2TlbMissQueueTable.log(L2TlbMissQueueOutDB, missQueue.io.out.fire, "L2TlbMissQueueOut", clock, reset)
```

- **动手试试：**分析 Cache 一致性违例

```
# 查看插入的bug – 我们将所有的Release 数据都设置成常量
$ cat cc_err.patch
```

```
--- a/src/main/scala/huancun/noninclusive/SinkC.scala
+++ b/src/main/scala/huancun/noninclusive/SinkC.scala
@@ -93,7 +93,7 @@ class SinkC(implicit p: Parameters) extends
BaseSinkC {
-       buffer(insertIdx)(count) := c.bits.data
+       buffer(insertIdx)(count) := 0xABCDEF.U
```

- **动手试试：**分析 Cache 一致性违例

```
# 编译运行（很费时，因此我们用已经编译好的emu）
# 通常使用`make emu -j4 EMU_THREADS=4 WITH_CHISELDB=1`命令进行编译
$ bash chiseldb_step1_run.sh
```

```
# ./emu-cc-err -i $NOOP_HOME/ready-to-run/linux.bin \
  --diff $NOOP_HOME/ready-to-run/riscv64-nemu-interpreter-so \
  --dump-db 2>linux.err
```

- **动手试试：**分析 Cache 一致性违例

```
# 分析
$ bash chiseldb_step2_analyze.sh
```

```
# 1. sqlite 查询所有在Eaddr(0x80000dc0)上的事务
# 2. 使用脚本解析TLLog
# sqlite3 $NOOP_HOME/build/*.db \
  "select * from TLLOG where ADDRESS=0x80000dc0" | \
  sh $NOOP_HOME/scripts/utils/parseTLLog.sh
```

ChiselDB

```
# 结果: [Time | To_From | Channel | Opcode | Permission | Address | Data(0)]

# 数据成功地从 L1I 传输到了 L2
1364 L2_L1I_0 C ReleaseData Shrink TtoN 80000dc0 689cf9796ec050ef

# 数据成功地从 L2 传输到了 L3
1365 L3_L2_0 C ReleaseData Shrink TtoN 80000dc0 689cf9796ec050ef

# 但是当 L1I 再次请求 Eaddr，从 L3 读取的数据却出错了
1796 L2_L1I_0 A AcquireBlock Grow NtoB 80000dc0
1797 L3_L2_0 A AcquireBlock Grow NtoB  80000dc0
1808 L3_L2_0 D GrantData Cap toT 80000dc0 0000000000abcdef
1809 L2_L1I_0 D GrantData Cap toT 80000dc0 0000000000abcdef

# 因此可以推断 L3 记录 Release Data 时出现了错误
```

敏捷性能验证

Chisel-based prototypes

功能点
代码实现

运行
性能测试

VERILATOR

umd-memsys/
DRAMsim3

DRAMsim3: a Cycle-accurate, Thermal-Capable DRAM Simulator

XSPerf

Constantin

Top-down analysis

性能分析

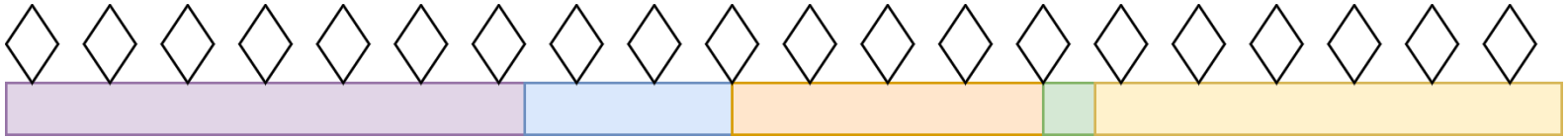
性能评估

RISC-V Checkpoint

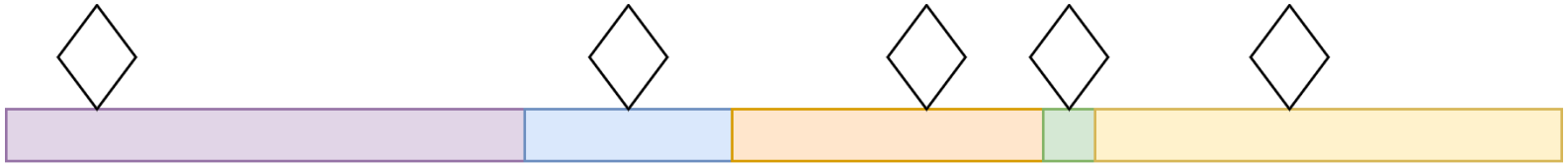
SimPoint

Checkpoint: 提高仿真性能评估并行度

- **Uniform Checkpoint**
  - 将程序等份划分成可并行执行的片段，均一采样



- **Simpoint Checkpoint**
  - 通过聚类分析，选择能够代表程序特性的片段，带权重采样



Checkpoint: Uniform Checkpoint

- step0: 为 checkpoints 准备 NEMU 环境

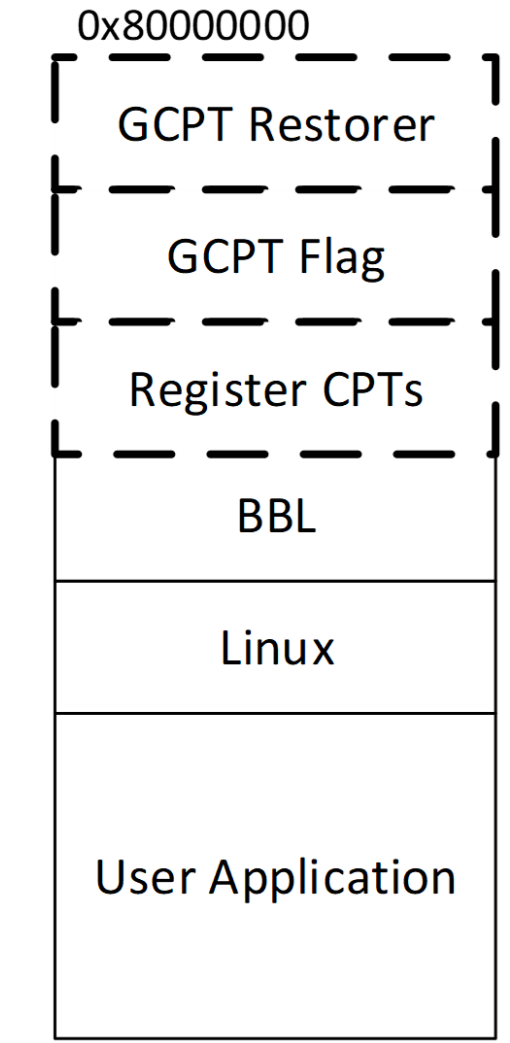
```
$ cd checkpoint      # 进入 checkpoint 目录
$ sh uniform_step0_prepare.sh
```

```
# uniform_step0_prepare.sh

# cd $NEMU_HOME

# git checkout tutorial
# git submodule update --init
# make clean
# make tutorial_defconfig
# make -j4

// 生成 gcpt restorer 的二进制文件
# cd resource/gcpt_restore && make -j4
```



Basic format of RISC-V Checkpoint

Checkpoint: Uniform Checkpoint

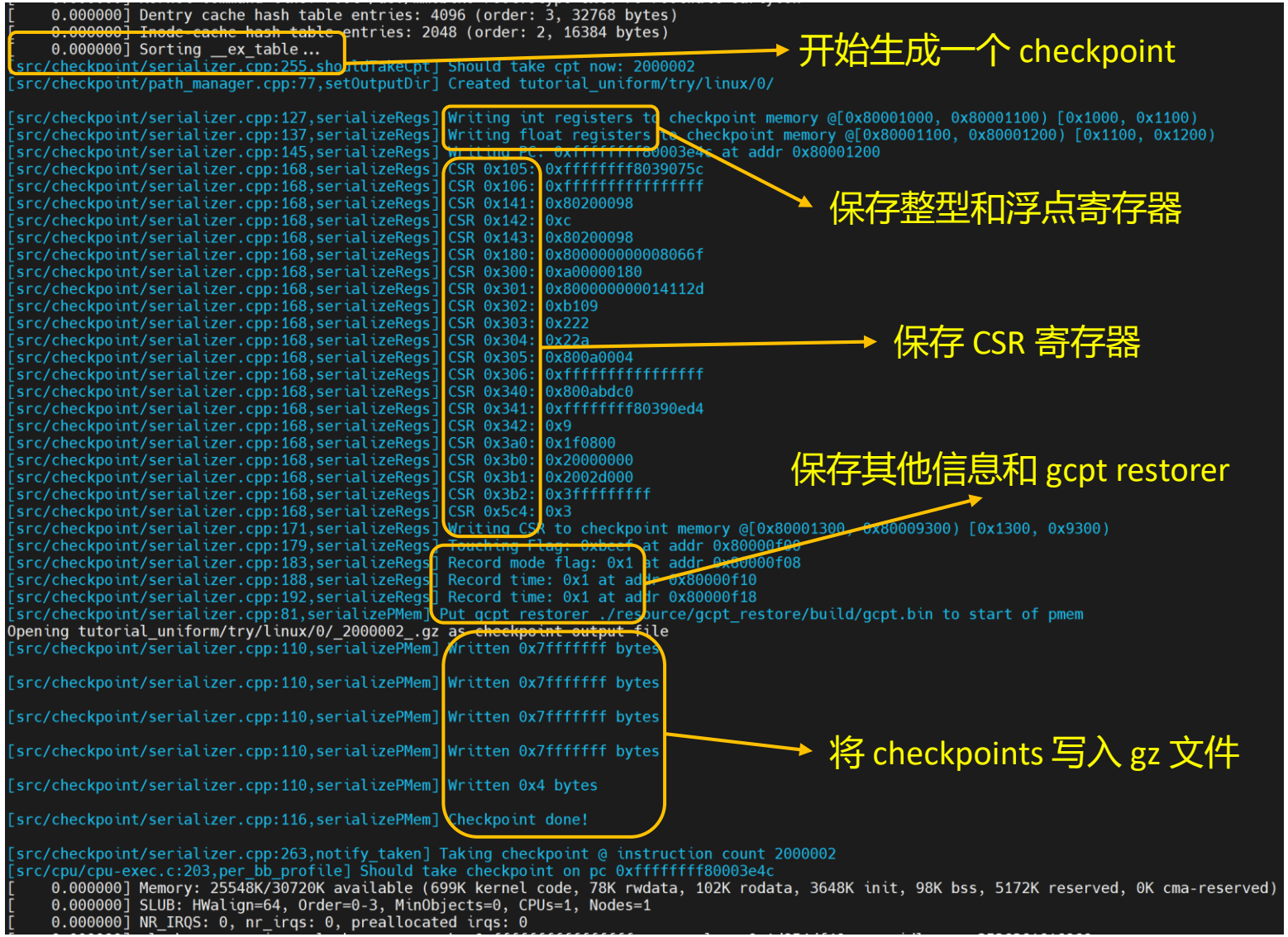
- **step1: 用 NEMU 生成 uniform checkpoints**

```
$ sh uniform_step1_gen.sh
```

```
# uniform_step1_gen.sh

# cd $NEMU_HOME
# rm -rf tutorial_uniform
# ./build/riscv64-nemu-interpreter
#     --cpt-interval 2000000   checkpoint的采样周期
#     -u                       按统一的间隔采样
#     -b                       以批处理模式运行
#     -D tutorial_uniform      指定生成 checkpoints 所在的目录
#     -C try                   指定任务名称
#     -w linux                 指定 workload
#     -r ./resource/gcpt_restore/build/gcpt.bin 上一步生成的 gcpt restorer 所在路径
#     --dont-skip-boot         启动后立即开始采样
#     -I 3000000               执行的最大指令数
#     ./ready-to-run/linux-0xa0000.bin
```

Checkpoint: Uniform Checkpoint



Checkpoint: Uniform Checkpoint

- **step2: 在 NEMU 或 XiangShan 中运行 uniform checkpoint**
- 以 NEMU 为例:

```
$ sh uniform_step2_run_nemu.sh
```

```
# uniform_step2_run_nemu.sh

# cd $NEMU_HOME

# ./build/riscv64-nemu-interpreter
#     -b                    以批处理模式运行
#     --restore             从 CPT FILE 中恢复
#     -I 1000000            执行的最大指令数
#     `find tutorial_uniform/try/linux/0/ -type f -name "*.gz" | tail -1`
                            上一步生成的 checkpoint 的路径
```

Checkpoint: Uniform Checkpoint

```
[src/monitor/monitor.c:103,parse_args] Restoring from checkpoint
[src/device/io/mmio.c:38,add_mmio_map] Add mmio map 'clint' at [0x0000000038000000, 0x000000003800ffff]
[src/isa/riscv64/init.c:100,init_isa] NEMU will start from pc 0x80000000
[src/monitor/image_loader.c:69,load_img] Loading Gcpt file form cmdline: tutorial_uniform/try/linux/0/_2000002_.gz

[src/monitor/image_loader.c:77,load_img] Loading GZ image tutorial_uniform/try/linux/0/_2000002_.gz
[src/monitor/image_loader.c:69,load_img] Loading Gcpt restorer form cmdline: (null)

[src/monitor/image_loader.c:71,load_img] No image is given. Use the default built-in image/restorer.
[src/device/io/port-io.c:30,add_pio_map] Add port-io map 'uartlite' at [0x00000000000003f8, 0x0000000000000404]
[src/device/io/mmio.c:38,add_mmio_map] Add mmio map 'uartlite' at [0x0000000040600000, 0x000000004060000c]
[src/device/io/port-io.c:30,add_pio_map] Add port-io map 'rtc' at [0x0000000000000048, 0x000000000000004f]
[src/device/io/mmio.c:38,add_mmio_map] Add mmio map 'rtc' at [0x00000000a1000048, 0x00000000a100004f]
[src/device/io/port-io.c:30,add_pio_map] Add port-io map 'screen' at [0x0000000000000100, 0x0000000000000107]
[src/device/io/mmio.c:38,add_mmio_map] Add mmio map 'screen' at [0x0000000040001000, 0x0000000040001007]
[src/device/io/mmio.c:38,add_mmio_map] Add mmio map 'vmem' at [0x0000000050000000, 0x00000000500752ff]
[src/device/io/port-io.c:30,add_pio_map] Add port-io map 'keyboard' at [0x0000000000000060, 0x0000000000000063]
[src/device/io/mmio.c:38,add_mmio_map] Add mmio map 'keyboard' at [0x00000000a1000060, 0x00000000a1000063]
[src/device/io/mmio.c:38,add_mmio_map] Add mmio map 'sdhci' at [0x0000000040002000, 0x000000004000207f]
[src/device/sdcard.c:137,init_sdcard] Can not find sdcard image:
[src/monitor/monitor.c:44,welcome] Debug: OFF
[src/monitor/monitor.c:49,welcome] Build time: 19:35:10, Mar 25 2023
Welcome to riscv64-NEMU!
For help, type "help"
[    0.000000] Memory: 25548K/30720K available (699K kernel code, 78K rwdata, 102K rodata, 3648K init, 98K bss, 5172K reserved, 0K cma-reserved)
[    0.000000] SLUB: HWalign=64, Order=0-3, MinObjects=0, CPUs=1, Nodes=1
[    0.000000] NR_IRQS: 0, nr_irqs: 0, preallocated irqs: 0
[    0.000000] clocksource: riscv_clocksource: mask: 0xffffffffffffffff max_cycles: 0x1d854df40, max_idle_ns: 3526361616960 ns
[    0.000000] console [hvc0] enabled
[    0.000000] console [hvc0] enabled
[    0.000000] bootconsole [early0] disabled
[    0.000000] bootconsole [early0] disabled
[    0.000000] Calibrating delay loop (skipped), value calculated using timer frequency.. 2.00 BogoMIPS (lpj=10000)
[    0.000000] pid_max: default: 4096 minimum: 301
[    0.000000] Mount-cache hash table entries: 512 (order: 0, 4096 bytes)
[    0.000000] Mountpoint-cache hash table entries: 512 (order: 0, 4096 bytes)
[    0.010000] clocksource: jiffies: mask: 0xffffffff max_cycles: 0xffffffff, max_idle_ns: 19112604462750000 ns
[    0.020000] clocksource: Switched to clocksource riscv_clocksource
```

从检查点恢复并加载 gz 文件

NEMU 将从检查点的位置开始执行

Checkpoint: Simpoint Checkpoint

- **step0: 为 checkpoints 准备 NEMU 环境**

```
$ sh simpoint_step0_prepare.sh
```

```
# simpoint_step0_prepare.sh

# cd $NEMU_HOME

# git checkout cpt-bk
# git submodule update --init
# cd resource/simpoint/simpoint_repo/analysiscode && make simpoint -j4
                                                    生成 simpoint generator 的二进制文件
# cd resource/gcpt_restore && make -j4   生成 gcpt restorer 的二进制文件

# cd $NEMU_HOME
# make clean
# make ISA=riscv64 XIANGSHAN=1 -j4       编译 NEMU
```

Checkpoint: Simpoint Checkpoint

- **step1: 执行一轮 workload，收集程序行为信息**

```
$ sh simpoint_step1_profiling.sh
```

```
# simpoint_step1_profiling.sh

# cd $NEMU_HOME
# rm -rf tutorial_simpoint

# ./build/riscv64-nemu-interpreter
#     -b                                    以批处理模式运行
#     -D $NEMU_HOME/tutorial_simpoint       指定生成 checkpoints 所在的目录
#     -C profiling                          指定任务名称
#     -w stream                             指定 workload
#     --simpoint-profile                    做 simpoint profiling
#     --interval 50000000                   指定 simpoint 的指令间隔
#     $XS_PROJECT_ROOT/tutorial/bin/stream-0xa0000.bin
```

Checkpoint: Simpoint Checkpoint

```
[src/isa/riscv64/exec/special.c,38,exec_nemu_trap] Start profiling, resetting inst count

-------------------------------------------------------------
STREAM version $Revision: 5.10 $
-------------------------------------------------------------
This system uses 4 bytes per array element.
-------------------------------------------------------------
Array size = 2000000 (elements), Offset = 0 (elements)
Memory per array = 7.6 MiB (= 0.0 GiB).
Total memory required = 22.9 MiB (= 0.0 GiB).
Each kernel will be executed 10 times.
 The *best* time for each kernel (excluding the first iteration)
 will be used to compute the reported bandwidth.
-------------------------------------------------------------
Your clock granularity/precision appears to be 2047 microseconds.
Each test below will take on the order of 102400 microseconds.
   (= 50 clock ticks)
Increase the size of the arrays if this shows that
you are not getting at least 20 clock ticks per test.
-------------------------------------------------------------
WARNING -- The above is only a rough guideline.
For best results, please be sure you know the
precision of your system timer.
-------------------------------------------------------------
Function    Best Rate MB/s  Avg time     Min time     Max time
Copy:            710.2     0.023438     0.022528     0.024576
Scale:           181.7     0.089884     0.088064     0.092160
Add:             217.0     0.112868     0.110592     0.114688
Triad:           172.3     0.140402     0.139264     0.141312
-------------------------------------------------------------
Solution Validates: avg error less than 1.000000e-06 on all three arrays
-------------------------------------------------------------
[src/monitor/cpu-exec.c,110,cpu_exec] nemu: HIT GOOD TRAP at pc = 0x0000002aaaaaa5f6
```

NEMU 会在执行 STREAM 程序的过程中进行分析

Checkpoint: Simpoint Checkpoint

- **step2: 进行聚类，得到权重最高的多个程序片段**

```
$ sh simpoint_step2_cluster.sh
```

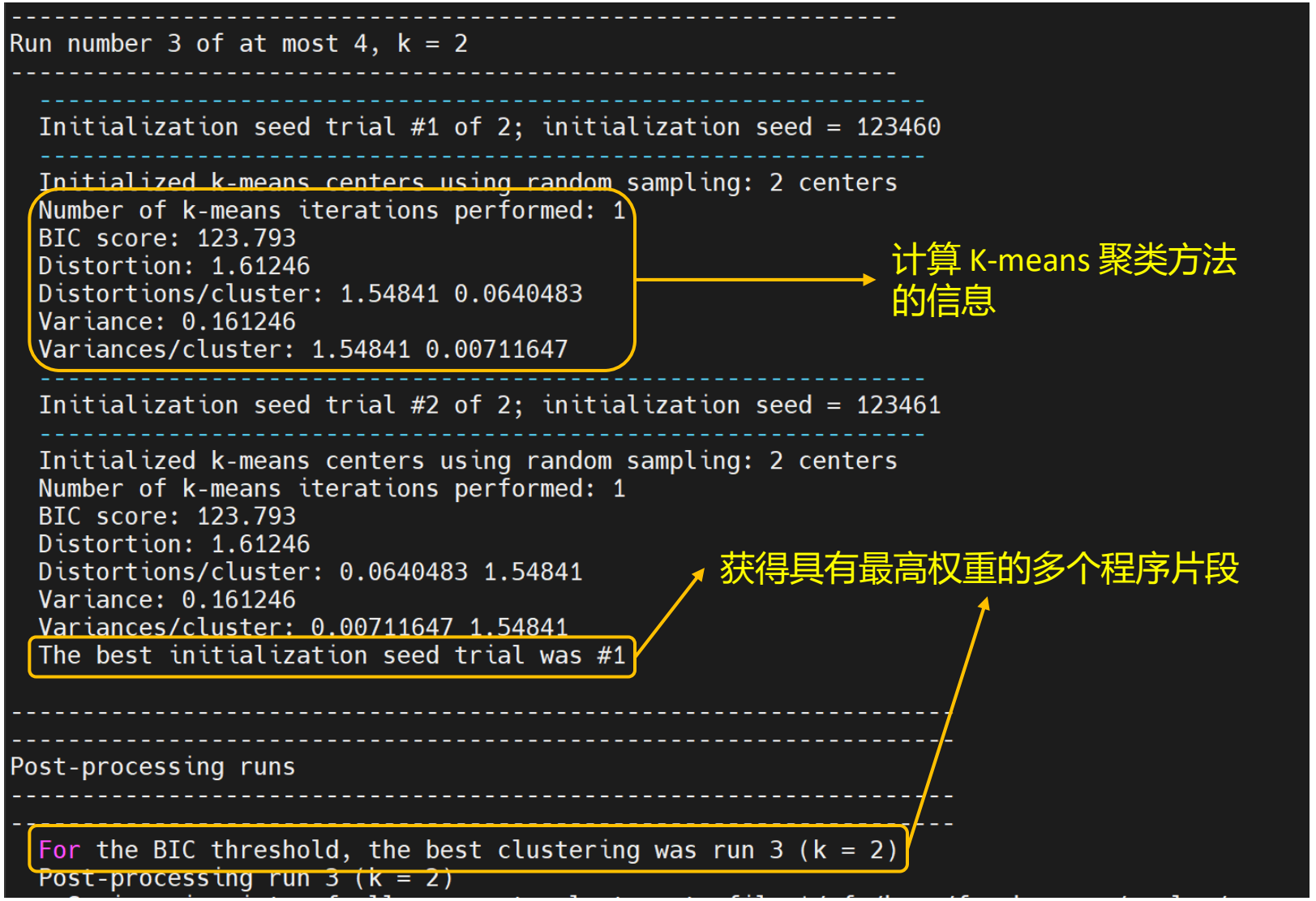
```
# simpoint_step2_cluster.sh

# cd $NEMU_HOME

# mkdir -p $NEMU_HOME/tutorial_simpoint/cluster/stream
# export CLUSTER=$NEMU_HOME/tutorial_simpoint/cluster/stream

# ./resource/simpoint/simpoint_repo/bin/simpoint
#     -loadFVFile ./tutorial_simpoint/profiling/simpoint_bbv.gz  load a frequency vector file
#     -saveSimpoints $CLUSTER/simpoints0                         file to save simpoints
#     -saveSimpointWeights $CLUSTER/weights0                     file to save simpoint weights
#     -inputVectorsGzipped                                       input vectors have been compressed with gzip
#     -maxK 3                 maximum number of clusters to use
#     -numInitSeeds 2         times of different random initialization for each run, taking only the best clustering
#     -iters 1000             maximum number of iterations that should perform
#     -seedkm 123456          random seed for choosing initial k-means centers
#     -seedproj 654321        random seed for random linear projection
```

Checkpoint: Simpoint Checkpoint



Checkpoint: Simpoint Checkpoint

- **step3: 根据聚类结果，生成对应的 Checkpoints**

```
$ sh simpoint_step3_take_cpt.sh          # 大约需要 3 分钟
```

```
# simpoint_step3_take_cpt.sh

# cd $NEMU_HOME
# rm -rf $NEMU_HOME/tutorial_simpoint/stream/take_cpt

# ./build/riscv64-nemu-interpreter
#     -b                                  以批处理模式运行
#     -D tutorial_simpoint                指定生成 checkpoints 所在的目录
#     -C take_cpt                         指定任务名称
#     -w stream                           指定 workload
#     -S ./tutorial_simpoint/cluster      simpoints 聚类结果所在目录
#     --checkpoint-interval 50000000      指定 simpoint 的指令间隔
#     $XS_PROJECT_ROOT/tutorial/bin/stream-0xa0000.bin
```

Checkpoint: Simpoint Checkpoint

Checkpoint: Simpoint Checkpoint

- **step4: 在 NEMU 或 XiangShan 中运行 simpoint checkpoint**
- 以 XiangShan 为例：

```
$ sh simpoint_step4_run_xs.sh
```

```
# simpoint_step4_run_xs.sh

$XS_PROJECT_ROOT/tutorial/emu
    -i `find $NEMU_HOME/tutorial_simpoint/ -type f -name "*_.gz" | tail -1`
    --diff $NOOP_HOME/ready-to-run/riscv64-nemu-interpreter-so
    --max-cycles=100000
    2>simpoint.err
```

XSPerf: 仿真性能计数器

- **两种类型**
  - **Accumulation**：基础的累加型计数器
  - **Histogram**：统计数值分布

Accumulation:

[PERF][time=10000] ctrlBlock.rob: commitInstr, 1500

[PERF][time=10000] ctrlBlock.rob: waitLoadCycle, 800

Histogram:

[PERF][time=10000] l2cache: acquire_period_10_20, 15

[PERF][time=10000] l2cache: acquire_period_20_30, 200

[PERF][time=10000] l2cache: acquire_period_30_40, 60

仿真性能计数器

- **使用方法**
  - 在想要加计数器的位置添加代码 `XSPerfAccumulate('name', signal)` 或 `XSPerfHistogram('name', signal)`
  - 默认会在仿真结束后打印输出
  - 设置 `DebugOptions(EnablePerfDebug = false)` 可以关闭计数器

```
# 回到 tutorial 目录
$ cd ..
$ bash run-emu-perf.sh
```

```
# ./emu -i hello.bin \
  --diff $NEMU_HOME/build/riscv64-nemu-interpreter-so 2>perf.err
```

```
$ cat perf.err
```

仿真性能计数器

```
[PERF ][time=              2893] TOP.SimTop.l_soc.core_with_l2.core.ctrlBlock.decode: utilization,                1183
[PERF ][time=              2893] TOP.SimTop.l_soc.core_with_l2.core.frontend.bpu.predictors.components_3.tables_0.wrbypass: wrbypass_hit,                    0
[PERF ][time=              2893] TOP.SimTop.l_soc.core_with_l2.core.frontend.icache.missUnit.entries_1: entryPenalty1,                  714
[PERF ][time=              2893] TOP.SimTop.l_soc.core_with_l2.core.ctrlBlock.decode: waitInstr,                414
[PERF ][time=              2893] TOP.SimTop.l_soc.core_with_l2.core.frontend.bpu.predictors.components_3.tables_0.wrbypass: wrbypass_miss,                     0
[PERF ][time=              2893] TOP.SimTop.l_soc.core_with_l2.core.ctrlBlock.decode: stall_cycle,                 393
[PERF ][time=              2893] TOP.SimTop.l_soc.core_with_l2.core.frontend.icache.missUnit.entries_1: entryReq1,                   14
[PERF ][time=              2893] TOP.SimTop.l_soc.core_with_l2.core.frontend.bpu.predictors.components_3.tables_1.wrbypass: wrbypass_hit,                    0
[PERF ][time=              2893] TOP.SimTop.l_soc.core_with_l2.core.frontend: FrontendBubble,               4085
[PERF ][time=              2893] TOP.SimTop.l_soc.core_with_l2.core.frontend.icache.missUnit.entries_0: entryPenalty0,                  248
[PERF ][time=              2893] TOP.SimTop.l_soc.core_with_l2.core.frontend.bpu.predictors.components_3.tables_1.wrbypass: wrbypass_miss,                     2
[PERF ][time=              2893] TOP.SimTop.l_soc.core_with_l2.core.frontend.ibuffer: utilization,                1826
[PERF ][time=              2893] TOP.SimTop.l_soc.core_with_l2.core.frontend.icache.missUnit.entries_0: entryReq0,                    6
[PERF ][time=              2893] TOP.SimTop.l_soc.core_with_l2.core.frontend.ibuffer: util_0_1,               2029
[PERF ][time=              2893] TOP.SimTop.l_soc.core_with_l2.core.frontend.ibuffer: util_1_2,                541
[PERF ][time=              2893] TOP.SimTop.l_soc.core_with_l2.misc.busPMU: dcache_bank_0_A_channel_fire,                    8
[PERF ][time=              2893] TOP.SimTop.l_soc.core_with_l2.core.frontend.ibuffer: util_2_3,                 45
[PERF ][time=              2893] TOP.SimTop.l_soc.core_with_l2.misc.busPMU: dcache_bank_0_A_channel_stall,                    0
[PERF ][time=              2893] TOP.SimTop.l_soc.core_with_l2.core.frontend.ibuffer: util_3_4,                107
[PERF ][time=              2893] TOP.SimTop.l_soc.core_with_l2.core.exuBlocks.scheduler.rs_4.staRS_0.oldestSelection: oldest_override_0,                    0
[PERF ][time=              2893] TOP.SimTop.l_soc.core_with_l2.misc.busPMU: dcache_bank_0_A_channel_PutFullData_fire,                    0
[PERF ][time=              2893] TOP.SimTop.l_soc.core_with_l2.core.frontend.ibuffer: util_4_5,                 44
[PERF ][time=              2893] TOP.SimTop.l_soc.core_with_l2.core.exuBlocks.scheduler.rs_4.staRS_0.oldestSelection: oldest_same_as_selected_0,                    0
[PERF ][time=              2893] TOP.SimTop.l_soc.core_with_l2.misc.busPMU: dcache_bank_0_A_channel_PutFullData_stall,                    0
[PERF ][time=              2893] TOP.SimTop.l_soc.core_with_l2.core.frontend.ibuffer: util_5_6,                 85
[PERF ][time=              2893] TOP.SimTop.l_soc.core_with_l2.core.exuBlocks.scheduler.rs_4.staRS_0.oldestSelection: oldest_override_1,                    0
[PERF ][time=              2893] TOP.SimTop.l_soc.core_with_l2.misc.busPMU: dcache_bank_0_A_channel_PutPartialData_fire,                    0
[PERF ][time=              2893] TOP.SimTop.l_soc.core_with_l2.core.frontend.ibuffer: util_6_7,                 13
[PERF ][time=              2893] TOP.SimTop.l_soc.core_with_l2.core.exuBlocks.scheduler.rs_4.staRS_0.oldestSelection: oldest_same_as_selected_1,                    0
[PERF ][time=              2893] TOP.SimTop.l_soc.core_with_l2.misc.busPMU: dcache_bank_0_A_channel_PutPartialData_stall,                    0
[PERF ][time=              2893] TOP.SimTop.l_soc.core_with_l2.core.frontend.ibuffer: util_7_8,                 27
[PERF ][time=              2893] TOP.SimTop.l_soc.core_with_l2.core.memBlock.dtlb_st_tlb_st.entries: port0_np_sp_multi_hit,                    0
[PERF ][time=              2893] TOP.SimTop.l_soc.core_with_l2.misc.busPMU: dcache_bank_0_A_channel_ArithmeticData_fire,                    0
[PERF ][time=              2893] TOP.SimTop.l_soc.core_with_l2.core.frontend.ibuffer: full,                862
[PERF ][time=              2893] TOP.SimTop.l_soc.core_with_l2.core.memBlock.dtlb_st_tlb_st.entries: port1_np_sp_multi_hit,                    0
[PERF ][time=              2893] TOP.SimTop.l_soc.core_with_l2.misc.busPMU: dcache_bank_0_A_channel_ArithmeticData_stall,                    0
[PERF ][time=              2893] TOP.SimTop.l_soc.core_with_l2.core.frontend.ibuffer: exHalf,                125
```

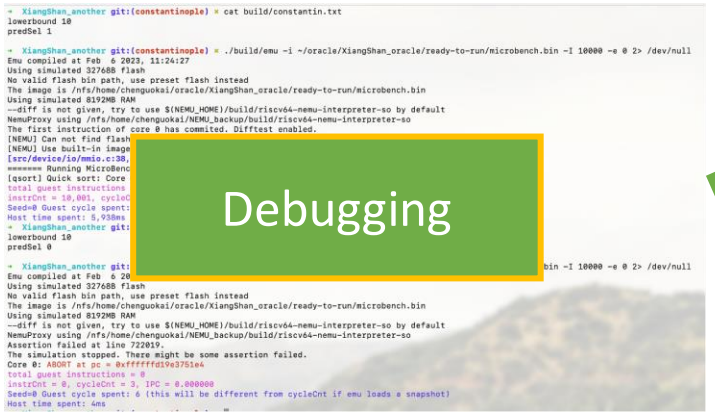
更多解析脚本：https://github.com/OpenXiangShan/env-scripts/blob/main/perf/perf.py

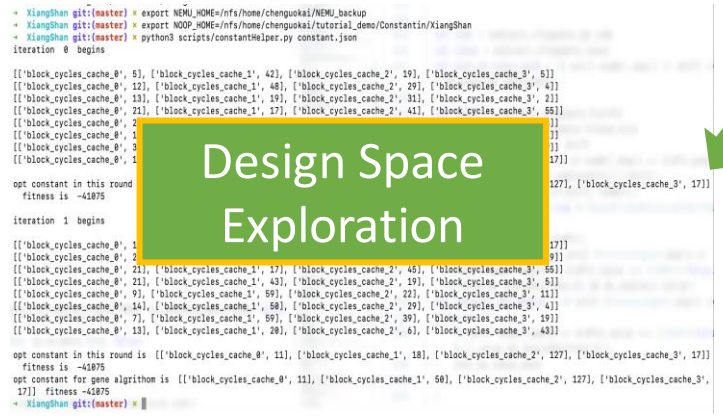
Constantin: 运行时参数调控框架

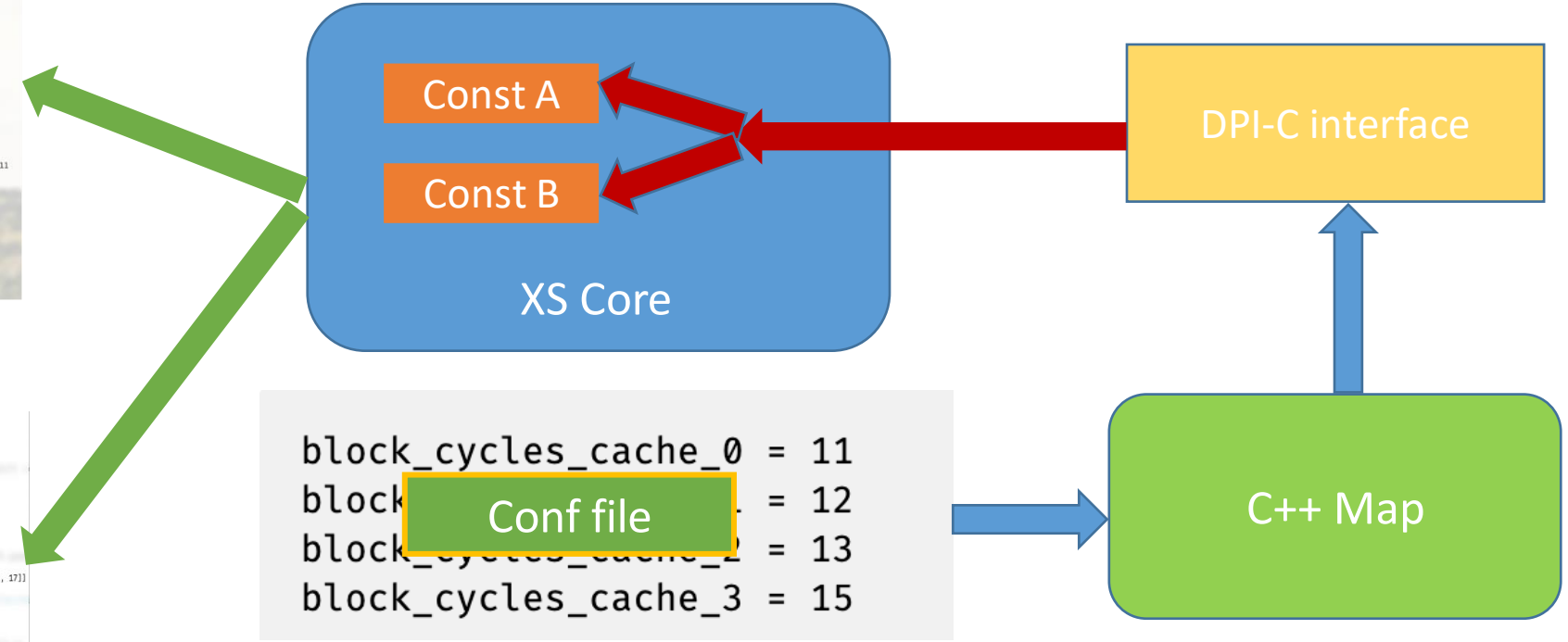
- **动机**
  - 在不同参数配置下测试、对比性能
  - 发现 Bug 后重新编译很耗时
  - 在运行时改变常量参数值
- **设计方法**
  - 在 Chisel 代码中，利用 DPI-C 接口调用 C++ 函数
  - 可以在仿真运行时而不是编译时配置信号值

Constantin

- 常量值仅在运行时保持恒定







Constantin

- **使用方法：**创建信号

```
// API: def createRecord(constName: String): UInt
import utility.Constantin

val block_cycles_cache = RegInit(VecInit(Seq(11.U(ReSelectLen.W),
18.U(ReSelectLen.W), 127.U(ReSelectLen.W), 17.U(ReSelectLen.W))))
block_cycles_cache(0) := Constantin.createRecord("block_cycles_cache_0")
block_cycles_cache(1) := Constantin.createRecord("block_cycles_cache_1")
block_cycles_cache(2) := Constantin.createRecord("block_cycles_cache_2")
block_cycles_cache(3) := Constantin.createRecord("block_cycles_cache_3")
```

Constantin

- **使用方法：**配置文件

```
// 格式：信号名 取值
// 默认路径: ${NOOP_HOME}/build/constantin.txt

block_cycles_cache_0 11
block_cycles_cache_1 18
block_cycles_cache_2 127
block_cycles_cache_3 17
```

Constantin

- **动手试试：** 自动求解最优的参数值

```
# Patch: 打开 AutoSolving
$ cat utility.patch
```

```
- def AutoSolving = false
+ def AutoSolving = true
```

```
# Patch: 创建目标信号
$ cat xs.patch
```

```
+ block_cycles_cache(0) := Constantin.createRecord("block_cycles_cache_0")
+ block_cycles_cache(1) := Constantin.createRecord("block_cycles_cache_1")
+ block_cycles_cache(2) := Constantin.createRecord("block_cycles_cache_2")
+ block_cycles_cache(3) := Constantin.createRecord("block_cycles_cache_3")
```

Constantin

- **动手试试：**自动求解最优的参数值

```
# 由于编译很费时，我们只在这里展示命令

# 应用前面的两个 patches
# cd $XS_PROJECT_ROOT/XiangShan && git apply ../tutorial/xs.patch
# cd utility && git apply ../../tutorial/utility.patch

# 编译
# make emu CONFIG=TutorialConfig EMU_THREADS=1 \
  EMU_TRACE=1 WITH_CONSTANTIN=1 -j8 # Enables support in Difftest framework
```

Constantin

- **动手试试：**自动求解最优的参数值

```
# 手动设置常量的赋值
$ sh constantin-basic.sh
```

```
# cat constantin.txt | ${XS_PROJECT_ROOT}/tutorial/emu-constantin \
  -i ./ready-to-run/linux.bin \
  --diff ./ready-to-run/riscv64-nemu-interpreter-so 2>constantin.err
# 从配置文件中读取常数值到emu
4
block_cycles_cache_0 11
block_cycles_cache_1 12
block_cycles_cache_2 13
block_cycles_cache_3 15
```

Constantin

- **动手试试：**自动求解最优的参数值

```
# 自动参数求解的配置文件
$ cat constantin.json
```

- **参数包含**
  - 信号的性质
  - 自动求解目标
  - 遗传算法的参数
  - XS 模拟器的参数

Constantin

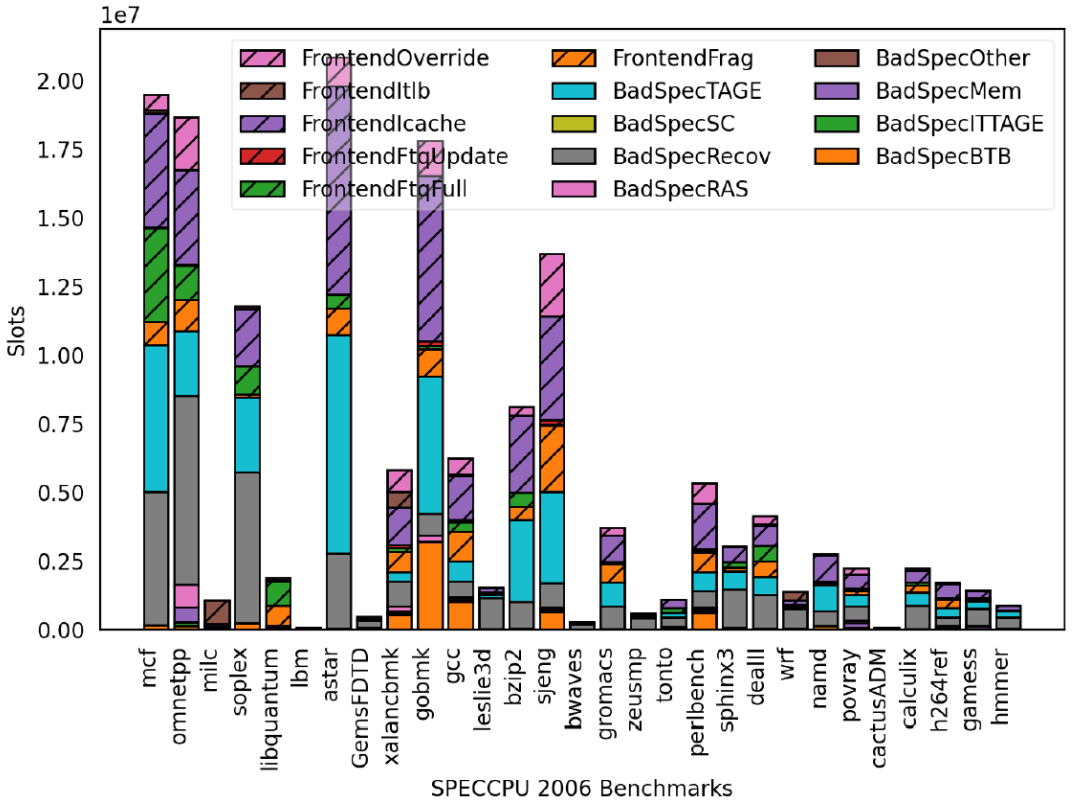
- **动手试试：**自动求解最优的参数值

```
# 运行自动求解器，输出当前得到的最优解
$ sh constantin-solve.sh
```

```
# 生成的最优参数结果
opt constant for gene algrithom is
[['block_cycles_cache_0', XXX], ['block_cycles_cache_1', XXX],
 ['block_cycles_cache_2', XXX],  ['block_cycles_cache_3', XXX]]  fitness 0
```

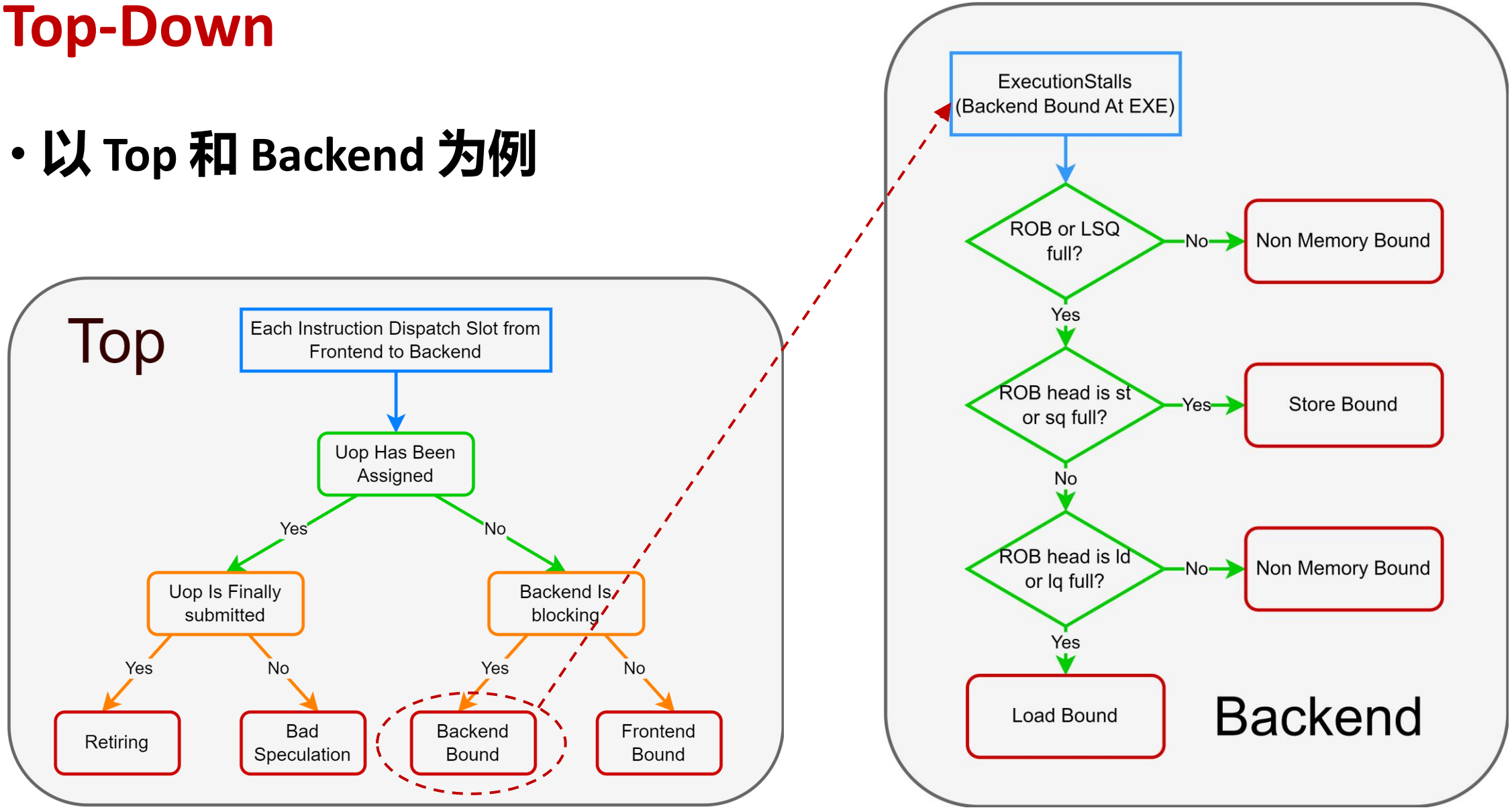
Top-Down: 性能分析模型

- **目的**
  - 将分散的性能事件**有层次地**组织起来
  - **精确**计算性能事件对处理器性能的影响
- **Top-Down on XiangShan**
  - 对 RISC-V 指令集进行**针对性优化适配**
  - 针对香山的微架构进行**性能计数器**优化
  - 进一步完善 Top-Down 模块的**层次化设计**
  - 不会造成性能事件的重复或遗漏
  - 不需要提前假设性能事件的阻塞周期



Top-Down

- 以 Top 和 Backend 为例



Top-Down

- 在 RTL 代码中设置性能计数器

Dispatch.scala

```
val stallReason = Wire(chiselTypeOf(io.stallReason.reason))
// ...
TopDownCounters.values.foreach(ctr =>
  XSPerfAccumulate(ctr.toString(), PopCount(stallReason.map(_ === ctr.id.U)))
)
```

- 运行仿真并收集性能计数器数据

Top-Down

- 用 Top-Down 方法进行层次分析

```
env-scripts: perf/top_down/configs.py


xs_coarse_rename_map = {
  'OverrideBubble': 'MergeFrontend',
  'FtqFullStall': 'MergeFrontend',
  ‘IntDqStall': 'MergeCoreDQStall',  # 将性能计数器归因到 Top-Down 的各个层次之中
  'FpDqStall': 'MergeCoreDQStall'
}
```

- 获取分析结果并进行有针对性的优化

Top-Down

- **动手试试：使用 Top-Down 工具分析阻塞原因**

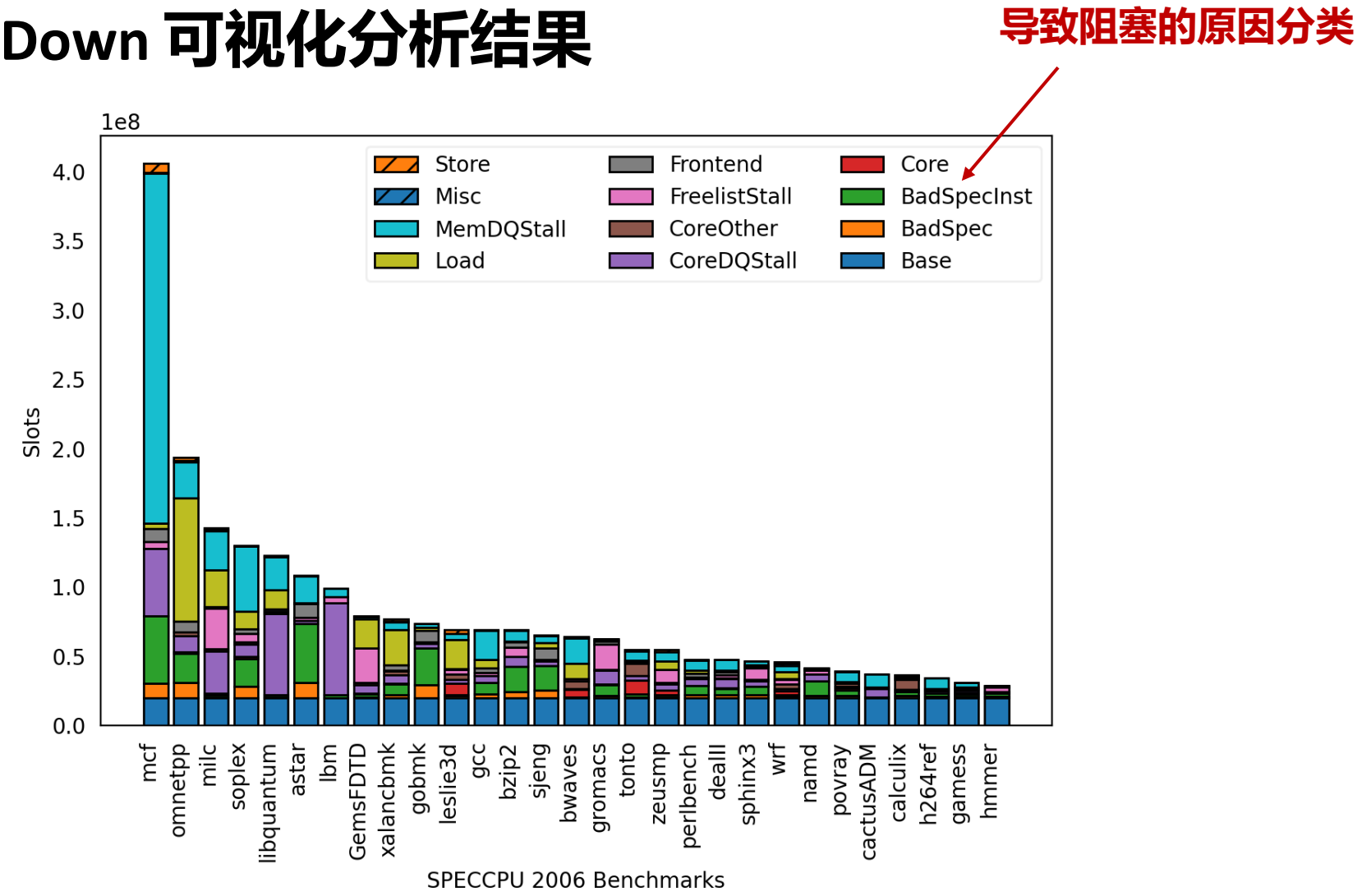
```
# 运行 Top-Down 分析工具
$ bash topdown.sh
```

```
# cd ${XS_PROJECT_ROOT}/env-scripts/perf/top_down && \
  python3 top_down.py \
  -s /opt/SPEC06_EmuTasks_topdown # 指定性能计数器路径

# ls ${XS_PROJECT_ROOT}/env-scripts/perf/top_down/results
result.png  results.csv  results-weighted.csv # 输出分析数据和可视化分析结果
```

Top-Down

- 示例：Top-Down 可视化分析结果



运行编译结果

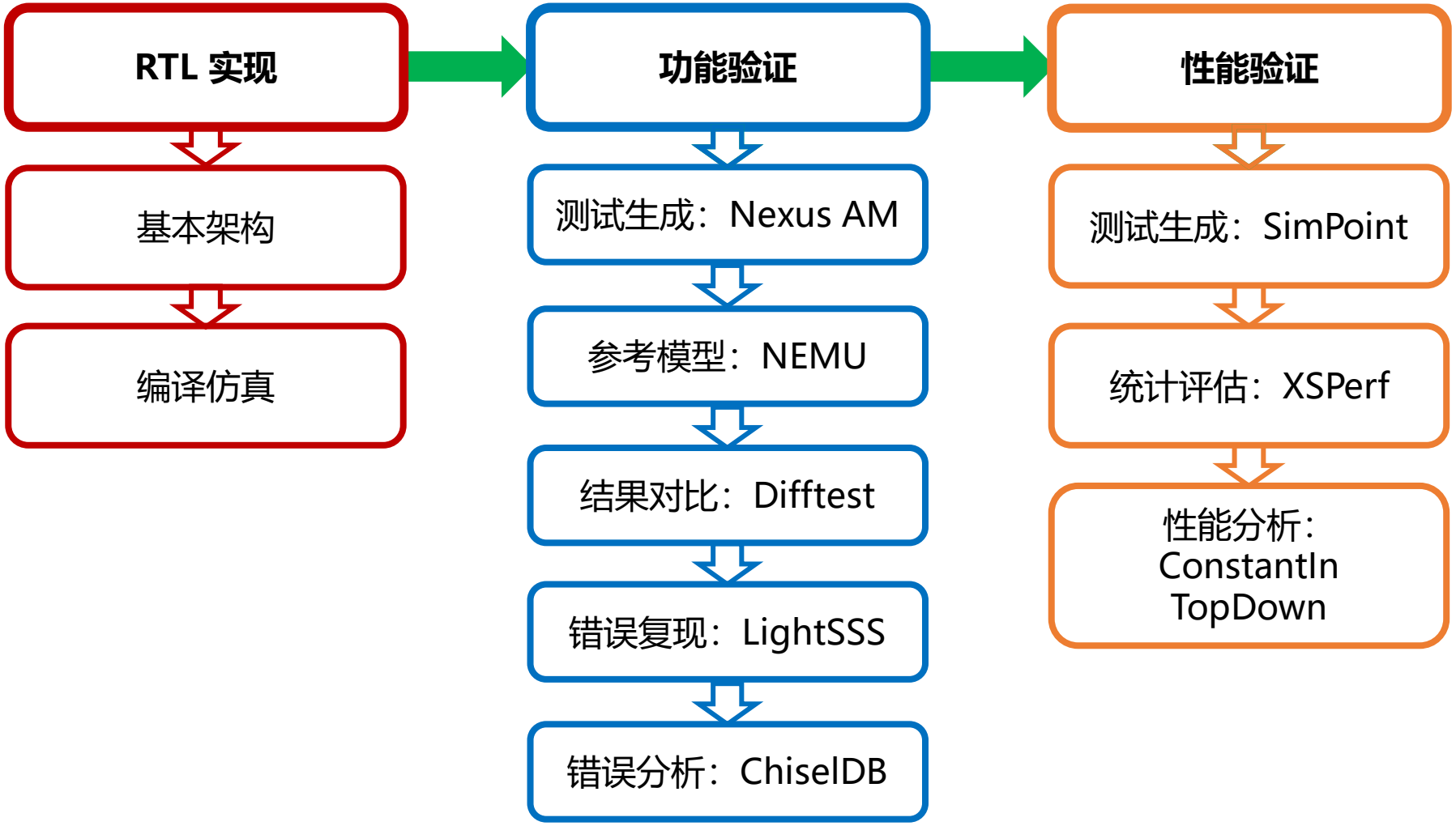
- 回到最开始编译 emu 的 shell 界面
- 可以运行刚刚编译完成的 emu 仿真

```
$ cd $NOOP_HOME
$ ./build/emu --help          (automatically runs with EMU_THREADS threads)
# Some Options:
    -i                        Workload to run
    -C / -I / -W              Max cycles /Max Insts / Warmup Insts
    --diff=PATH / --no-diff   Compare with NEMU for difftest / disable difftest
```

Example： *(use tab for command completion)*

```
$ ./build/emu -i ../tutorial/hello.bin --diff ./ready-to-run/riscv64-nemu-
interpreter-so 2> perf.err
```

小结 – 香山敏捷开发流程与工具



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