Methodology for Implementation of Custom Instructions in RISC-V Architecture

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Agenda

- Who is adopting RISC-V and why…

There are and will be many different RISC-V CPU developers:

- There are and will be many different RISC-V CPU developers:
  - Develop internal cores for SoCs
    - e.g. Nvidia, …
  - Deliver RTL IP as a business (like Arm, MIPS, just for RISC-V)
    - e.g. Andes, Codasip, Syntacore, Incore, …
  - Develop for internal use but make available as open source
    - e.g. Western Digital, …
  - Develop and use open source as a business opportunity
    - e.g. SiFive, …
  - Purchase processor IP and develop semiconductor products
    - e.g. Microsemi SoC FPGAs, …
  - Download and use open source RTL in their products
    - e.g. Google, …
  - …

RISC-V CPU Adopters: (above & below the line)

New architectures (ML, IoT), arrays of processors, custom features, high performance, feature control (efficiency), large SoC design, architecture innovation, …

Key requirement: ‘freedom to innovate’

Researchers, education, open source community, freely available, no license cost or restriction, …

Key requirement: ‘free’

Many (above the line) adopters of RISC-V want to add their own custom extension instructions

- Traditional ISA choice has been hard if you want to add your own custom processor instructions to an ISA
- RISC-V as an open standard has specific regions of instruction decode space specifically allocated for users to add their own instructions

- Challenges
  - How to choose the processor IP starting point
  - How to add instructions to processor RTL
  - How to verify the complete RTL
  - How to evaluate effectiveness and performance gains of new instructions
  - How to enable software development utilizing the new instructions

Agenda

- Who is adopting RISC-V and why…
- Adding custom instructions to RISC-V processors

Processor IP and Custom Instructions

- Processor IP vendors
  - Provide high quality RTL
  - Provide methodology for adding custom instructions
    - How to verify custom instructions?
- Open source RTL
  - Should be high quality
    - How has open source been verified?
  - Add custom instructions by modifying RTL
    - How to verify custom instructions?
- Roll-your-own
  - Starting from scratch on RTL requires significant implementation expertise
  - Just build in custom instructions from beginning
  - How to verify complete processor implementation?

Key Challenge of Optimizing Custom Instructions Requires New Methodology, Tools

- How to choose the processor IP starting point
- How to add instructions to processor RTL
- How to verify the complete RTL
- **How to evaluate effectiveness and performance gains of new instructions**
- How to enable software development utilizing the new instructions

➢ **Extend instruction accurate simulation tools and models to support analysis and optimization of custom instructions**

Agenda

- Who is adopting RISC-V and why…
- Adding custom instructions to RISC-V processors
- Custom instruction optimization flow

Custom Instruction Optimization Flow

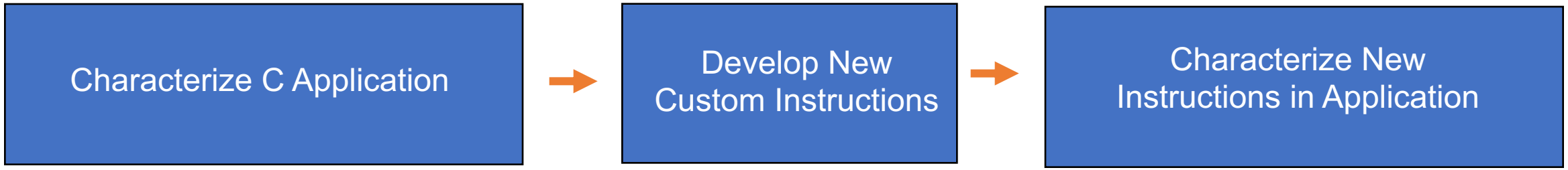
- Show the flow used when designing new instructions to improve performance of applications running on a RISC-V processor
  - Allows evaluation and firming up of the instructions
  - Gets to the specification of the instructions needed to be implemented in RTL
- Introduce the technologies & tools needed for each stage

- Application software used for this walk-through is a character stream encoder, based on ChaCha20 encryption algorithm
  - Instruction Extensions to RISC-V courtesy of Cerberus Security Laboratories Ltd
  - https://cerberus-laboratories.com

Flow to add new custom instructions

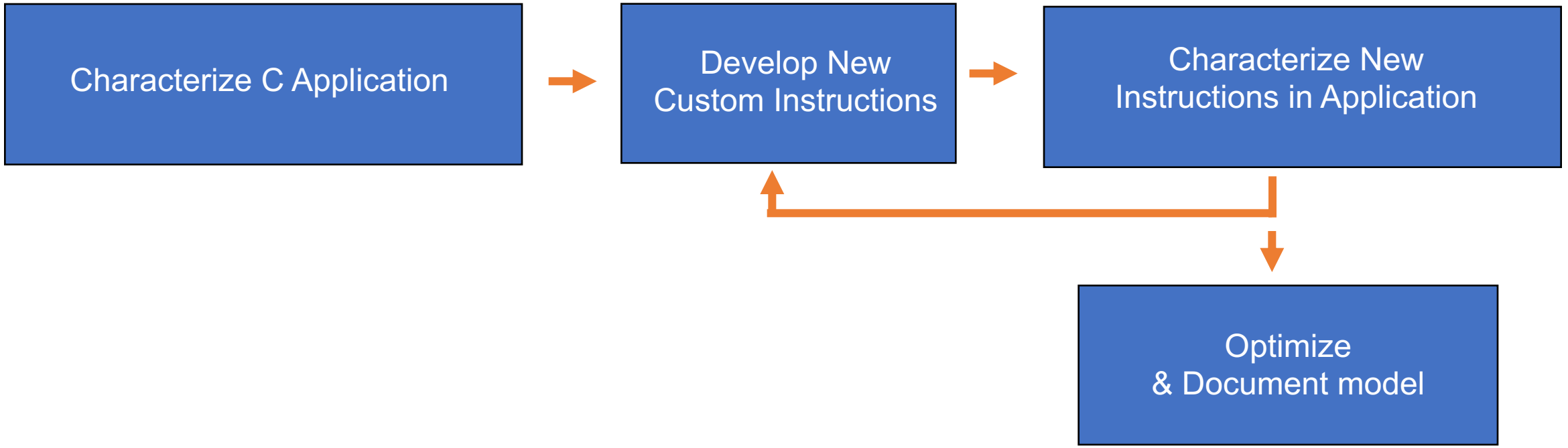
Flow to add new custom instructions

Flow to add new custom instructions

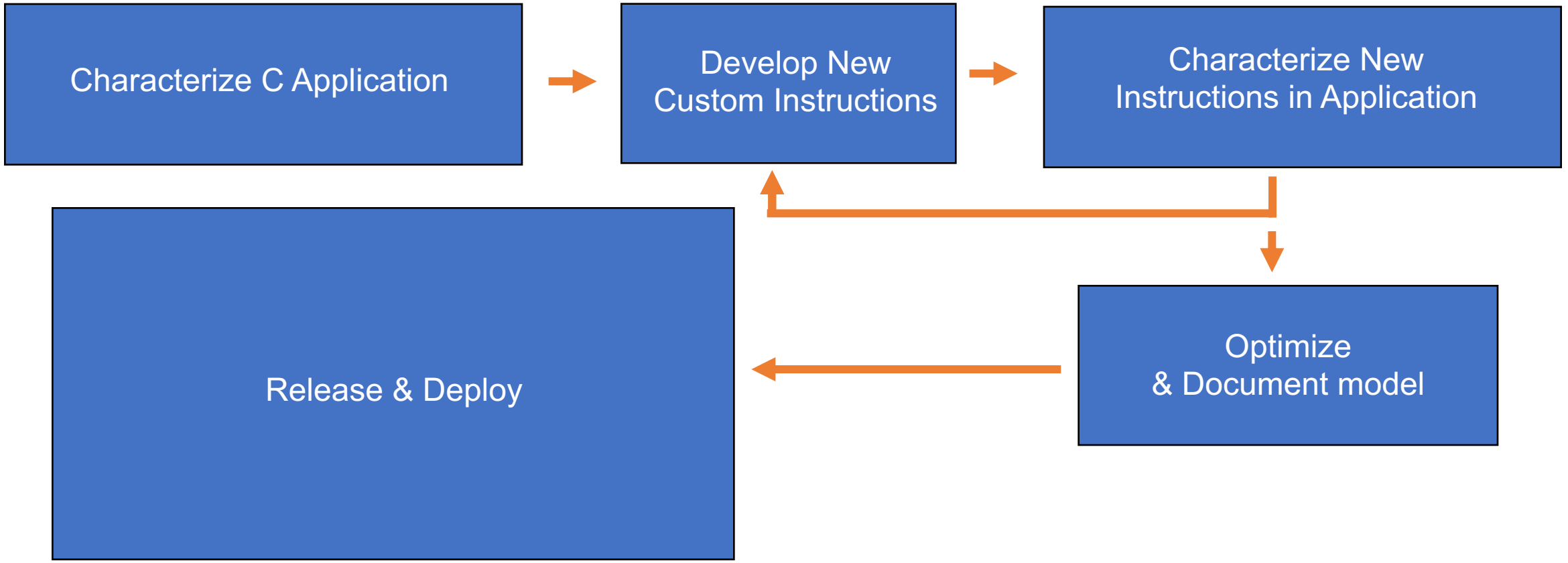


Flow to add new custom instructions

Flow to add new custom instructions

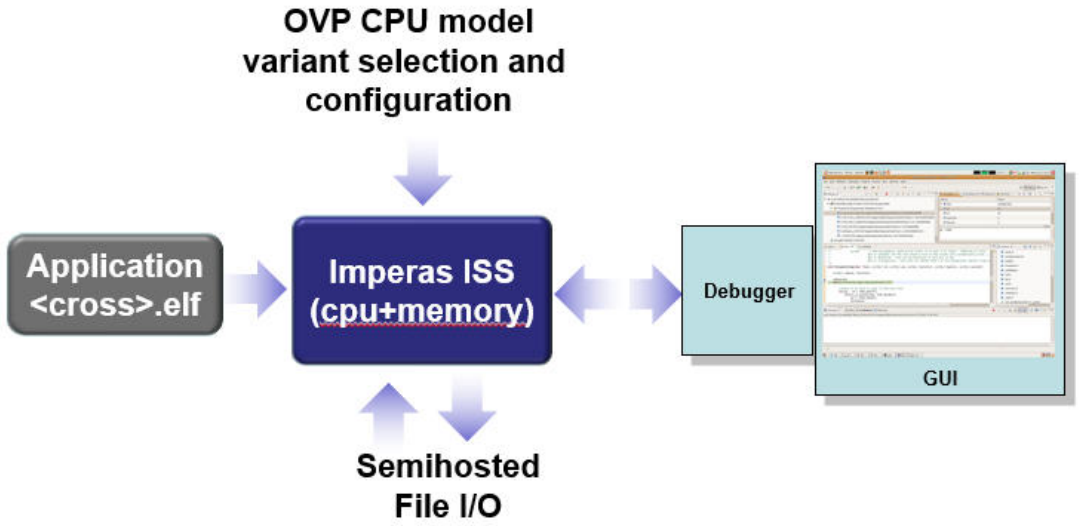


Flow to add new custom instructions

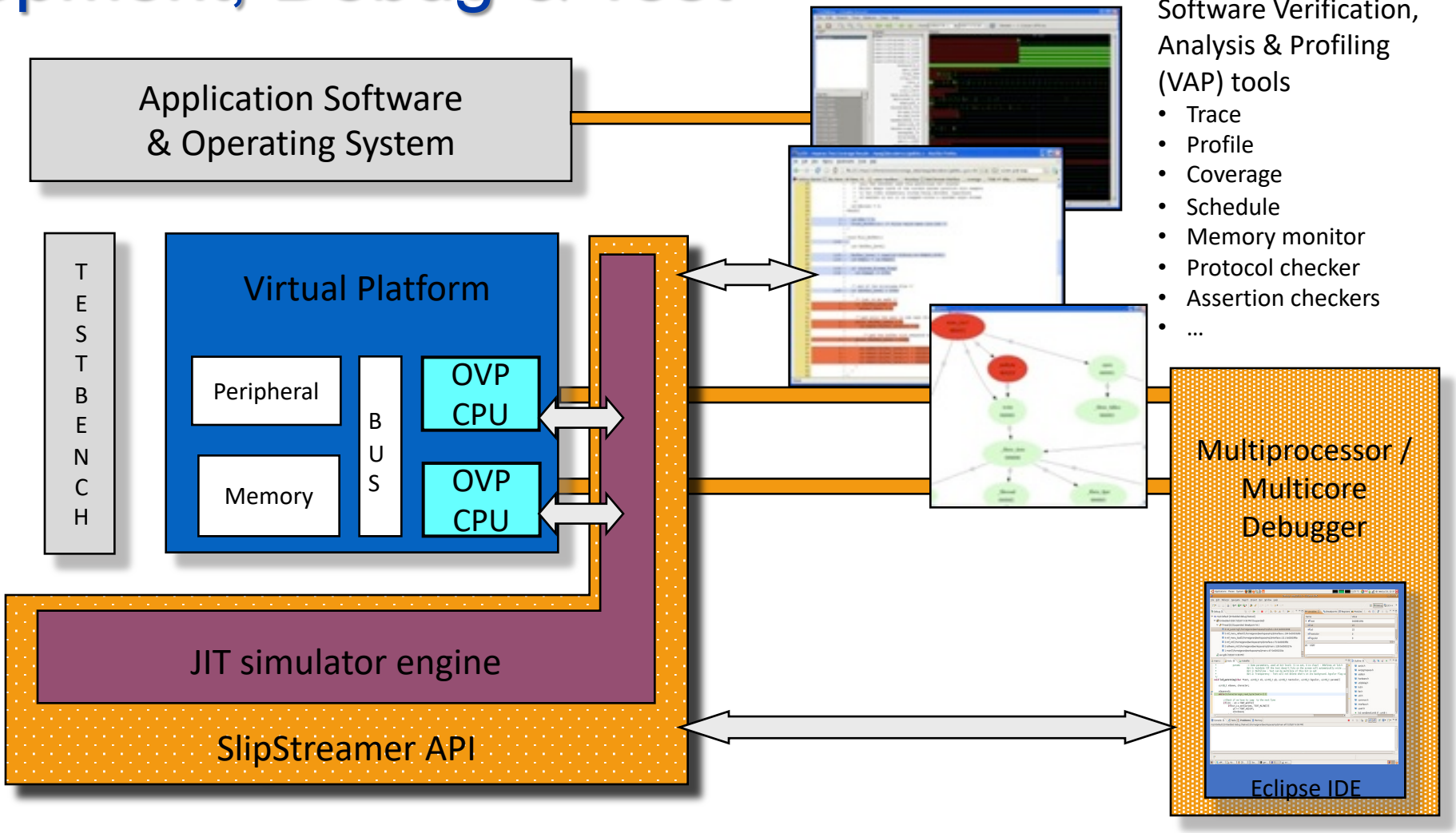


The first thing needed is a simulator – think ISS, however …

- Simulator and model need to have ability to extend to allow custom instructions and new tools
- Ease of use also important
- Need to have a business-friendly open source license



Imperas Tools for Embedded Software Development, Debug & Test



Software Verification, Analysis & Profiling (VAP) tools

- Trace
- Profile
- Coverage
- Schedule
- Memory monitor
- Protocol checker
- Assertion checkers
- …

Flow to add new custom instructions

Characterize C Application

- Instruction Accurate Simulation
- Trace / Debug
- Timing Simulation
- Function Timing / Profiling

Instruction Accurate simulation of C application

- Cross compiled C application targeting RV32IM
  - Character stream encoder, with ChaCha20 encryption algorithm
- IA simulation
  - Imperas RISC-V ISS with configurable model of RISC-V specification selecting RV32IM
- Semihosting
  - Enables bare metal application to very simply access host I/O

➢runs fast
- Over 1 billion instructions a second (standard PC)
  - Linux and Windows supported host OS

test_c.c

```
unsigned int processLine(unsigned int res, unsigned int word){
    res = qr1_c(res, word);
    res = qr2_c(res, word);
    res = qr3_c(res, word);
    res = qr4_c(res, word);
    res = qr1_c(res, word);
    res = qr2_c(res, word);
    res = qr3_c(res, word);
    res = qr4_c(res, word);
    return res;
}

int main(void) {
    const char *customData = "application/custom.data";
    FILE *fp = fopen(customData, "r");
    if (fp) {
        unsigned int res = 0x84772366;
        unsigned int word;
        unsigned int cnt=0;
        unsigned int iter=0;
        while (iter++ < 16) {
            while (fread(&word,sizeof(unsigned int), 1, fp)) {
                res = processLine(res, word);
            }
            rewind(fp);
        }
        fclose(fp);
        printf("RES = %08
    } else {
        printf("Failed to
    }

    return 0;
}
```

```
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CpuManagerMulti started: Thu Aug 23 11:19:21 2018

Info (OR_OF) Target 'iss/cpu0' has object file read from 'application/test_c.RISCV32.elf'
Info (OR_PH) Program Headers:
Info (OR_PH) Type           Offset   VirtAddr   PhysAddr   FileSiz    MemSiz     Flags Align
Info (OR_PD) LOAD           0x00000000 0x00010000 0x00010000 0x000173c8 0x000173c8 R-E   1000
Info (OR_PD) LOAD           0x000173c8 0x000283c8 0x000283c8 0x000009c0 0x00000a24 RW-   1000
Info (OR_OF) Target 'iss/cpu0' has object file read from 'application/exception.RISCV32.elf'
Info (OR_PH) Program Headers:
Info (OR_PH) Type           Offset   VirtAddr   PhysAddr   FileSiz    MemSiz     Flags Align
Info (OR_PD) LOAD           0x00001000 0x00000000 0x00000000 0x0000000c 0x0000000c R-E   1000
RES = 84772366
Info
Info ----------------------------------------------------------------
Info CPU 'iss/cpu0' STATISTICS
Info   Type                 : riscv (RV32IM)
Info   Nominal MIPS         : 100
Info   Final program counter : 0x100ac
Info   Simulated instructions: 1,289,380,976
Info   Simulated MIPS       : 1151.2
Info ----------------------------------------------------------------
Info
Info ----------------------------------------------------------------
Info SIMULATION TIME STATISTICS
Info   Simulated time       : 12.89 seconds
Info   User time            : 1.10 seconds
Info   System time          : 0.02 seconds
Info   Elapsed time         : 1.14 seconds
Info   Real time ratio      : 11.31x faster
Info ----------------------------------------------------------------

CpuManagerMulti finished: Thu Aug 23 11:19:22 2018
```

Cycle Approximate simulation C application

- Same C application
- IA simulation + timing Estimation (IA+E)
  - Includes annotated timing estimation for RV32IM processor
- Same simulation data results, different timing as now counting cycles
- Shows how long algorithm will take to execute

➢Extends simulated time
  - Was 12.89 secs now takes 16.59 secs

```
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CpuManagerMulti started: Thu Aug 23 11:27:16 2018


Info (OR_OF) Target 'iss/cpu0' has object file read from 'application/test_c.RISCV32.elf'
Info (OR_PH) Program Headers:
Info (OR_PH) Type           Offset     VirtAddr   PhysAddr   FileSiz    MemSiz     Flags Align
Info (OR_PD) LOAD           0x00000000 0x00010000 0x00010000 0x000173c8 0x000173c8 R-E   1000
Info (OR_PD) LOAD           0x000173c8 0x000283c8 0x000283c8 0x000009c0 0x00000a24 RW-   1000
Info (OR_OF) Target 'iss/cpu0' has object file read from 'application/exception.RISCV32.elf'
Info (OR_PH) Program Headers:
Info (OR_PH) Type           Offset     VirtAddr   PhysAddr   FileSiz    MemSiz     Flags Align
Info (OR_PD) LOAD           0x00001000 0x00000000 0x00000000 0x0000000c 0x0000000c R-E   1000
Info (CMD_CC) calling 'iss/cpu0/exTT/cpucycles'
Info (CPUEST_CMD) iss/cpu0: cpucycles on: time stretch enabled
RES = 84772366
Info
Info ------------------------------------------------------
Info CPU 'iss/cpu0' STATISTICS
Info   Type                 : riscv (RV32IM)
Info   Nominal MIPS         : 100
Info   Final program counter : 0x100ac
Info   Simulated instructions: 1,289,380,976
Info   Simulated MIPS       : 156.3
Info ------------------------------------------------------
Info
Info ------------------------------------------------------
Info SIMULATION TIME STATISTICS
Info   Simulated time       : 16.59 seconds
Info   User time            : 8.02 seconds
Info   System time          : 0.23 seconds
Info   Elapsed time         : 8.58 seconds
Info   Real time ratio      : 1.93x faster
Info ------------------------------------------------------

CpuManagerMulti finished: Thu Aug 23 11:27:25 2018


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Info (CPUEST_RSLT) Estimated execution time 16.59 seconds, clock cycles 1,659,204,454
Use script lastRun.sh to rerun with current settings
```

Function Profile C Application

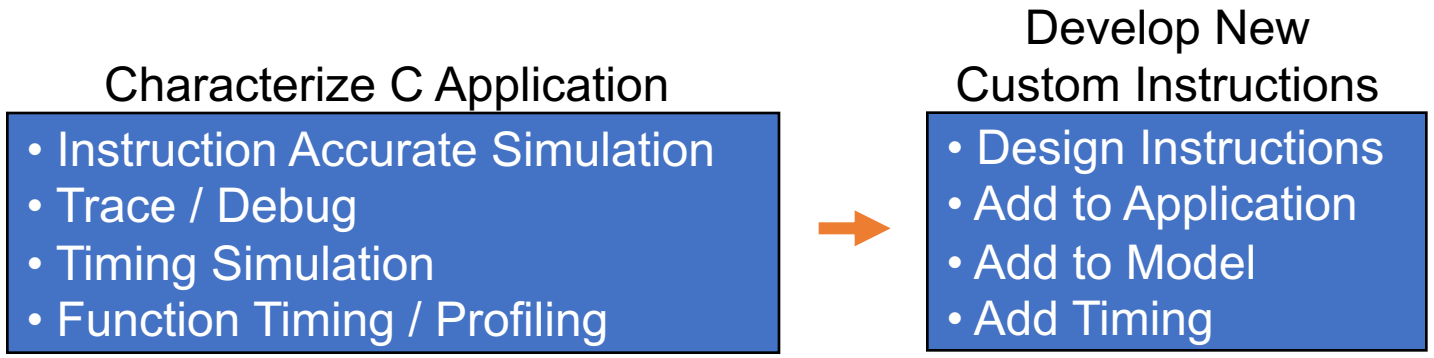
- Same C application
- IA+E simulation
- Sampled profiling with call stack analysis

➢Shows proportion of time spent in each application function

  ➢21.35% spent in processLine

Name (location)	Arcs in	Samples In	Arcs out	From/To this	Percentage (%)
Platform: iss					
Processor: iss/cpu0					
Process: 0_None		1659204277			
_fread_r	598189652	596534872	1654780		35.95%
processLine	925852930	354236017	571616913		21.35%
qr4_c	150627639	150627639	0		9.08%
qr1_c	146083640	146083640	0		8.8%
qr2_c	137682652	137682652	0		8.3%
qr3_c	137222982	137222982	0		8.27%
__libc_init_array	0	135154865	1524049412		8.15%
__srefill_r	1654780	1024985	629795		0.06%
__sread	629637	321116	308521		0.02%
_read_r	308521	308521	0		0.02%
_fseeko_r	2706	2126	580		0.0%
_vfprintf_r	1874	764	1110		0.0%
__sfvwrite_r	848	752	96		0.0%
rewind	3267	561	2706		0.0%
_close_r	357	357	0		0.0%
_malloc_r	323	297	26		0.0%
__sseek	528	288	240		0.0%
_lseek_r	240	240	0		0.0%
__sfmoreglue	399	224	175		0.0%
_fclose_r	734	204	530		0.0%

Flow to add new custom instructions



Add custom instructions to application

- Inline assembly using new instructions replacing C code
- 4 new instructions
- Cross Compile using standard tool
- Run on IA simulator

➢ Unimplemented instruction exception
  - As the instructions have not yet been added to the simulator model

```
// Custom instruction test for Chacha20
#include <stdio.h>

unsigned int processLine(unsigned int input, unsigned int word){
    unsigned int res = input;
    asm __volatile__("mv x10, %0" :: "r"(res));
    asm __volatile__("mv x11, %0" :: "r"(word));
    asm __volatile__(".word 0x00B5050B\n" ::: "x10");      // QR1
    asm __volatile__(".word 0x00B5150B\n" ::: "x10");      // QR2
    asm __volatile__(".word 0x00B5250B\n" ::: "x10");      // QR3
    asm __volatile__(".word 0x00B5350B\n" ::: "x10");      // QR4
    asm __volatile__(".word 0x00B5050B\n" ::: "x10");      // QR1
    asm __volatile__(".word 0x00B5150B\n" ::: "x10");      // QR2
    asm __volatile__(".word 0x00B5250B\n" ::: "x10");      // QR3
    asm __volatile__(".word 0x00B5350B\n" ::: "x10");      // QR4
    asm __volatile__("mv %0,x10" : "=r"(res));
    return res;
}

int mai
    con
    FIL
    if
```

```
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CpuManagerMulti started: Thu Aug 23 11:34:51 2018

Info (OR_OF) Target 'iss/cpu0' has object file read from 'application/test_custom.RISCV32.elf'
Info (OR_PH) Program Headers:
Info (OR_PH) Type           Offset     VirtAddr   PhysAddr   FileSiz    MemSiz     Flags Align
Info (OR_PD) LOAD           0x00000000 0x00010000 0x00010000 0x00017270 0x00017270 R-E   1000
Info (OR_PD) LOAD           0x00017270 0x00028270 0x00028270 0x000009c0 0x00000a24 RW-   1000
Info (OR_OF) Target 'iss/cpu0' has object file read from 'application/exception.RISCV32.elf'
Info (OR_PH) Program Headers:
Info (OR_PH) Type           Offset     VirtAddr   PhysAddr   FileSiz    MemSiz     Flags Align
Info (OR_PD) LOAD           0x00001000 0x00000000 0x00000000 0x0000000c 0x0000000c R-E   1000
Warning (RISCV_AIF) CPU 'iss/cpu0' 0x00010248 00b5050b custom1: Illegal instruction - extension X (non-standard extensions present) absent or inactive
Info
Info ----------------------------------------------------
Info CPU 'iss/cpu0' STATISTICS
Info   Type                : riscv (RV32IM)
Info   Nominal MIPS        : 100
Info   Final program counter : 0x102e4
Info   Simulated instructions: 1,340
Info   Simulated MIPS      : run too short for meaningful result
Info ----------------------------------------------------
Info
Info ----------------------------------------------------
Info SIMULATION TIME STATISTICS
Info   Simulated time      : 0.00 seconds
Info   User time           : 0.01 seconds
Info   System time         : 0.00 seconds
Info   Elapsed time        : 0.01 seconds
Info ----------------------------------------------------

CpuManagerMulti finished: Thu Aug 23 11:34:51 2018
```

Add custom instructions to model

- Use standard Open Virtual Platforms (OVP) instruction modeling APIs to add new instructions (and optional state) as ***new extension library***
  - Easy to extend decode table, add efficient behavioral JIT code
  - Optionally can call directly into user's provided C function of behavior
- Compile and link model extension library
- Simulate IA with ISS plus standard model extended with new library

➢ Instruction count and simulated time have reduced (IA)

```
//
// Create the RISCV decode table
//
static vmidDecodeTableP createDecodeTable(void) {

    vmidDecodeTableP table = vmidNewDecodeTable(RISCV_INSTR_BITS, RISCV_EIT_LAST);

    // R-Type instruction in custom-0 encoding space:
    // opcode [6:0]  = 00 010 11
    // funct3[14:12] = 0,1,2,3 (QR1-4)
    // funct7[31:25] = 0000000
    // rs1[19:15]
    // rs2[24:20]
    // rd[11:7]

    // handle custom instruction
    DECODE_ENTRY(0, CHACHA20QR1, "|0000000.........000.....0001011|");
    DECODE_ENTRY(0, CHACHA20QR2, "|0000000.........001.....0001011|");
    DECODE_ENTRY(0, CHACHA20QR3, "|0000000.........010.....0001011|");
    DECODE_ENTRY(0, CHACHA20QR4, "|0000000.........011.....0001011|");

    return table;
}
```

```
//
// Emit code implementing exchange instruction
//
static void emitChaCha20(
    vmiProcessorP processor,
    vmiosObjectP  object,
    Uns32         instruction,
    Uns32         rotl
) {

    // extract instruction fields
    Uns32 rd  = RD(instruction);
    Uns32 rs1 = RS1(instruction);
    Uns32 rs2 = RS2(instruction);

    vmiReg reg_rs1 = vmimtGetExtReg(processor,  &object->rs1);
    vmiReg reg_rs2 = vmimtGetExtReg(processor,  &object->rs2);
    vmiReg reg_tmp = vmimtGetExtTemp(processor, &object->tmp);

    vmimtGetR(processor, RISCV_REG_BITS, reg_rs1, object->riscvRegs[rs1]);
    vmimtGetR(processor, RISCV_REG_BITS, reg_rs2, object->riscvRegs[rs2]);
    vmimtBinopRRR(32, vmi_XOR, reg_tmp, reg_rs1, reg_rs2, 0);
    vmimtBinopRC(32, vmi_ROL, reg_tmp, rotl, 0);

    vmimtSetR(processor, RISCV_REG_BITS, object->riscvRegs[rd], reg_tmp);
}
```

```
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CpuManagerMulti started: Thu Aug 23 11:41:32 2018

Info (OP_LPR) Processor  iss/cpu0                              $IMPERAS_VLNV/riscv.ovpworld.or
Info (OR_DF) Target 'iss/cpu0' has object file read from 'application/test_custom,RISCV32,elf'
Info (OR_PH) Program Headers:
Info (OR_PH) Type           Offset     VirtAddr   PhysAddr   FileSiz    MemSiz     Flags Align
Info (OR_PD) LOAD           0x00000000 0x00010000 0x00010000 0x00017270 0x00017270 R-E   1000
Info (OR_PD) LOAD           0x00017270 0x00028270 0x00028270 0x000009c0 0x00000a24 RW-   1000
Info (OR_DF) Target 'iss/cpu0' has object file read from 'application/exception,RISCV32,elf'
Info (OR_PH) Program Headers:
Info (OR_PH) Type           Offset     VirtAddr   PhysAddr   FileSiz    MemSiz     Flags Align
Info (OR_PD) LOAD           0x00001000 0x00000000 0x00000000 0x0000000c 0x0000000c R-E   1000
Info (OP_PEX) Extension  iss/cpu0/riscv32Newlib                $IMPERAS_VLNV/riscv.ovpworld.org/semihosting/riscv32Newlib/1.0/model
Info (OP_PEX) Extension  iss/cpu0/exInst                       instructionExtensionLib
RES = 84772366
Info
Info ----------------------------------------------------
Info CPU 'iss/cpu0' STATISTICS
Info   Type                 : riscv (RV32IM)
Info   Nominal MIPS         : 100
Info   Final program counter : 0x100ac
Info   Simulated instructions: 677,012,570
Info   Simulated MIPS       : 1301.9
Info ----------------------------------------------------
Info
Info ----------------------------------------------------
Info SIMULATION TIME STATISTICS
Info   Simulated time       : 6.77 seconds
Info   User time            : 0.50 seconds
Info   System time          : 0.02 seconds
Info   Elapsed time         : 0.53 seconds
Info   Real time ratio      : 12.81x faster
Info ----------------------------------------------------

CpuManagerMulti finished: Thu Aug 23 11:41:33 2018
```

Cycle Approximate simulation including custom instructions

- IA simulation + timing annotation + custom instructions
  - Includes timing estimation for RV32IM processor
  - Need to add timing estimation for new custom instructions
- Simulate using C code application with inline assembler of custom extensions
- IA simulator + timing tool + custom extension instruction library

➢ See estimated improvement in throughput of application on new processor
  ➢ Was (IA) 6.77 secs now (CA) 9.21 secs

test_c.c | test_custom.c | customChaCha20.c | riscv32.c

```
        case IC_mdu_mul : {
            cycles = 5;         // Specify cycles for instruction group
            break;
        }
        case IC_mdu_div : {
            cycles = 16;        // Specify cycles for instruction group
            break;
        }
        case IC_custom : {
                                // chacha20qr1-chacha20qr4 group same cycles
            cycles = 2;         // Specify cycles for instruction group
            break;
        }
        default: {
            VMI_ABORT("Invalid instructionCLassE value %d (%s)\n", iClass, instrClassName(iClass));
            break;
        }

    }

    if (runtimeCB) { // division run-time callback
        emitCycleEstimation(processor,object,thisPC,regSource1,regSource2,mduMode,iClass,runtimeCB);
    } else {
        addCycleCount(object, thisPC, cycles, iClass);
    }

    // Update previous morph time instruction info
```

```
Info (CPUEST_CMD) iss/cpu0: cpucycles on: time stretch enabled
RES = 84772366
Info
Info ------------------------------------------------------
Info CPU 'iss/cpu0' STATISTICS
Info   Type                : riscv (RV32IM)
Info   Nominal MIPS        : 100
Info   Final program counter : 0x100ac
Info   Simulated instructions: 677,012,570
Info   Simulated MIPS      : 123.1
Info ------------------------------------------------------
Info
Info ------------------------------------------------------
Info SIMULATION TIME STATISTICS
Info   Simulated time      : 9.21 seconds
Info   User time           : 5.30 seconds
Info   System time         : 0.20 seconds
Info   Elapsed time        : 5.73 seconds
Info   Real time ratio     : 1.61x faster
Info ------------------------------------------------------

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Info (CPUEST_RSLT) Estimated execution time 9.21 seconds, clock cycles 921,006,928
Use script lastRun.sh to re-run with current settings
```
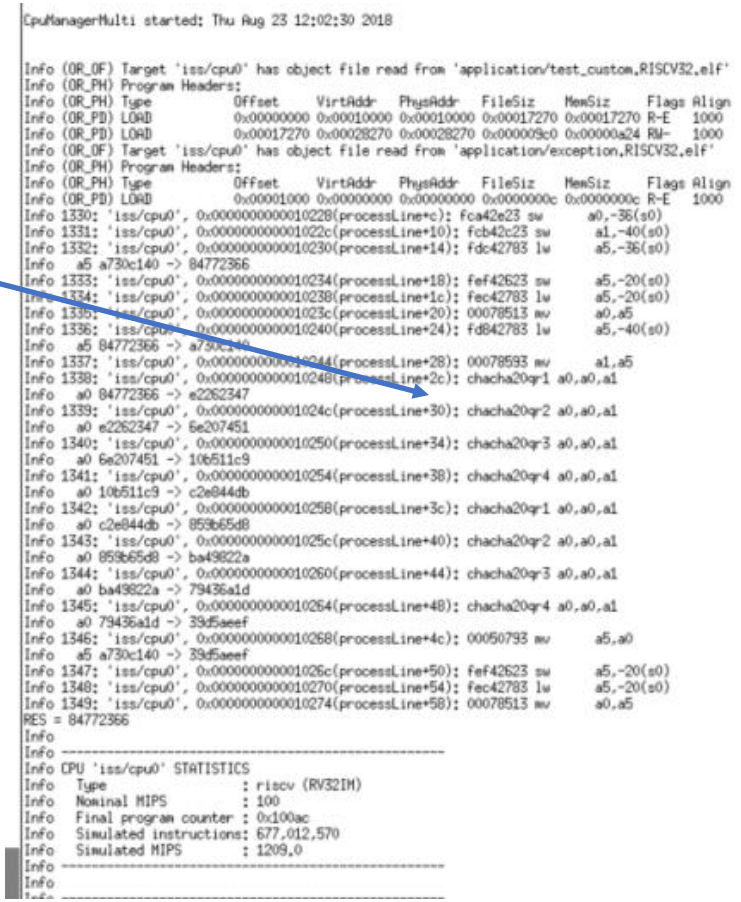
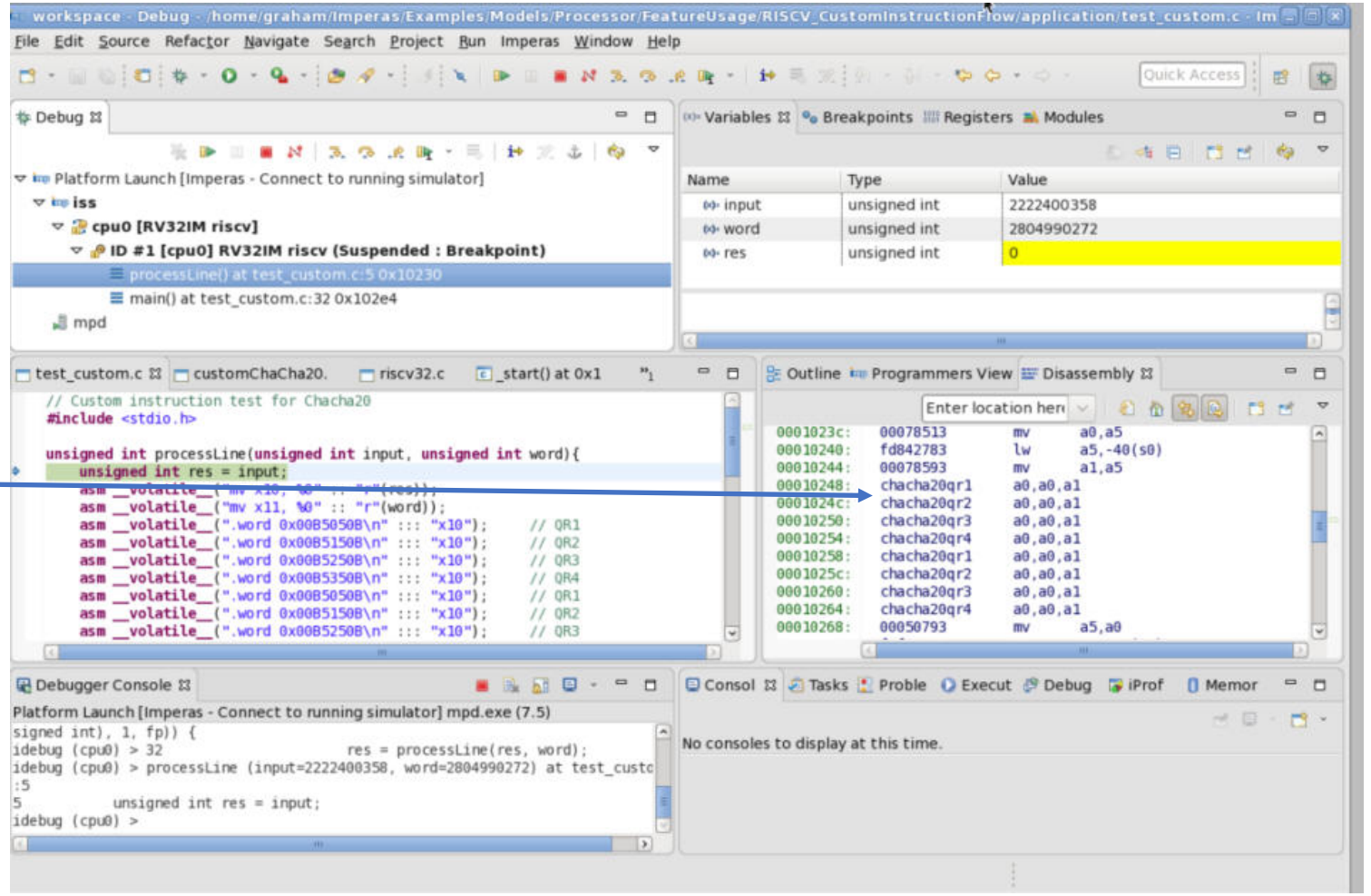

Trace custom instructions

- Simulator has many trace features built in
- See new custom instructions in trace disassembly
- Can select when/where to turn trace on/off
  - Very efficient tracing



Debug custom instructions

- Imperas MPD is Eclipse based source code debug tool
- Can debug using source line or instruction level
- See new custom instructions and any new additional state registers

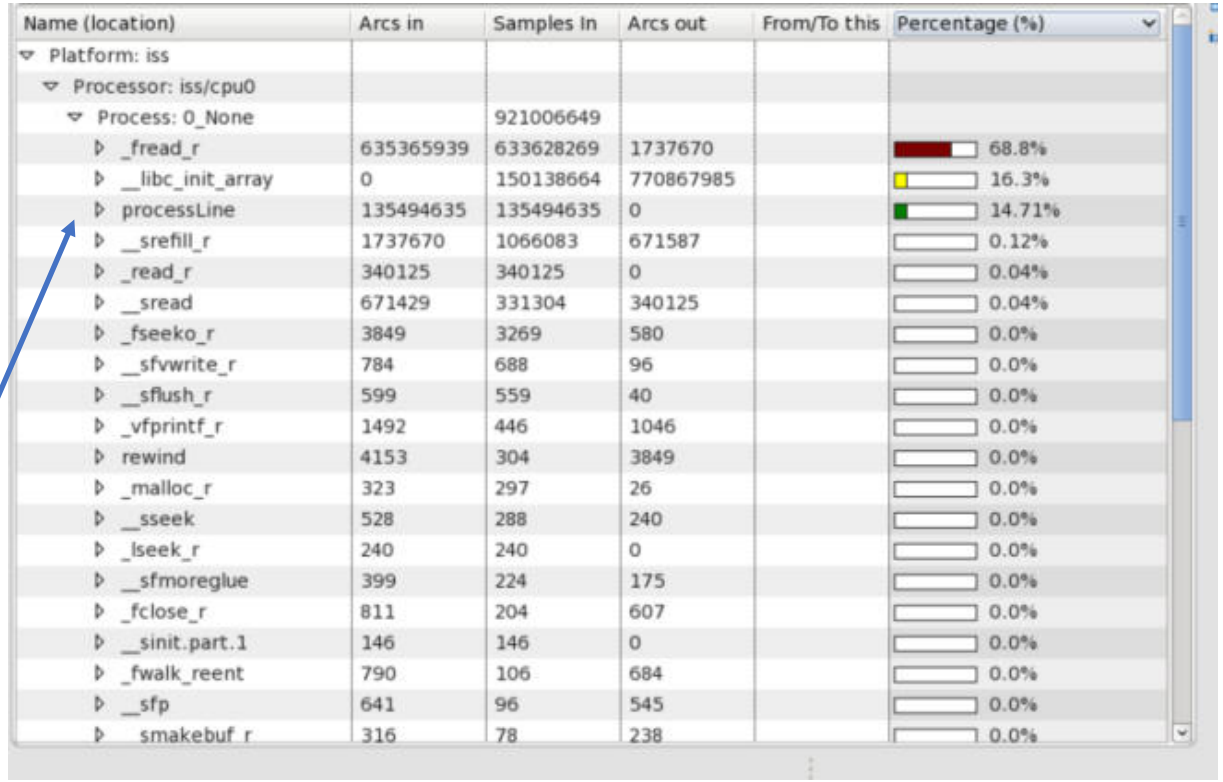


Function Profile custom instructions application

- IA simulation + timing annotation + custom instructions with sampled profiling

➢Shows where slowest function is
  - Now much faster…

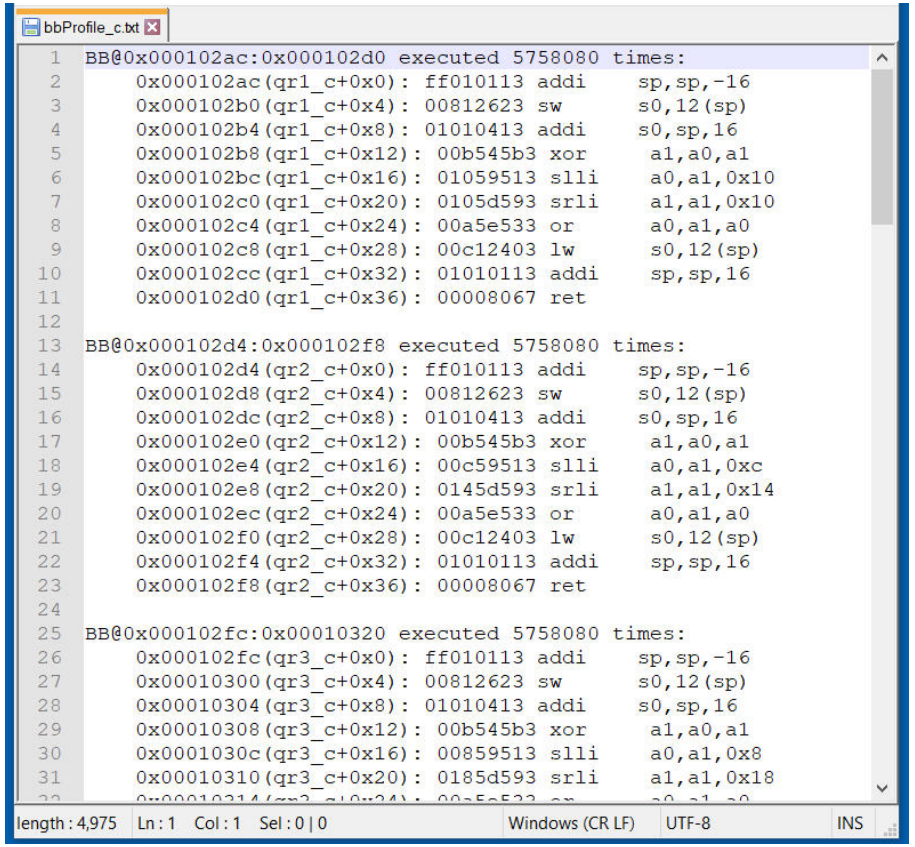
➢Shows benefits of using custom instructions
  - ➢processLine was 21.35% now 16.3%



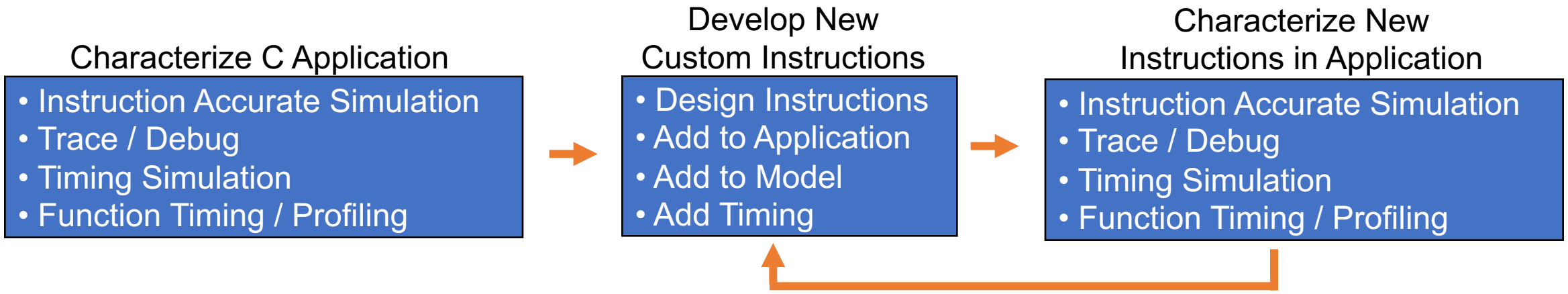
Name (location)	Arcs in	Samples in	Arcs out	From/To this	Percentage (%)
Platform: iss					
Processor: iss/cpu0					
Process: 0_None		921006649			
_fread_r	635365939	633628269	1737670		68.8%
__libc_init_array	0	150138664	770867985		16.3%
processLine	135494635	135494635	0		14.71%
__srefill_r	1737670	1066083	671587		0.12%
_read_r	340125	340125	0		0.04%
__sread	671429	331304	340125		0.04%
_fseeko_r	3849	3269	580		0.0%
__sfvwrite_r	784	688	96		0.0%
__sflush_r	599	559	40		0.0%
_vfprintf_r	1492	446	1046		0.0%
rewind	4153	304	3849		0.0%
_malloc_r	323	297	26		0.0%
__sseek	528	288	240		0.0%
_lseek_r	240	240	0		0.0%
__sfmoreglue	399	224	175		0.0%
_fclose_r	811	204	607		0.0%
__sinit.part.1	146	146	0		0.0%
_fwalk_reent	790	106	684		0.0%
__sfp	641	96	545		0.0%
__smakebuf_r	316	78	238		0.0%

Basic Block (BB) Profile custom instructions application

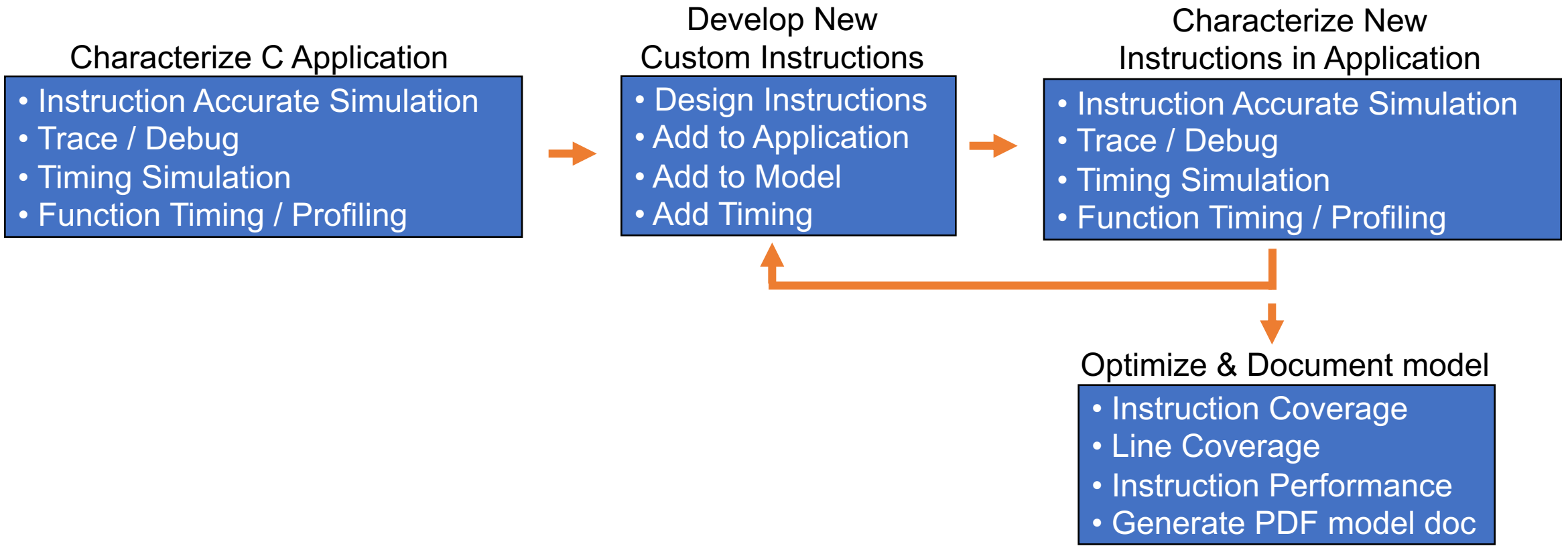
- IA simulation + timing annotation + custom instructions with detailed BB profiling
- Shows where expensive instruction sequences are
- Allows understanding of instruction performance
  - Useful for Compiler teams
  - Useful for Hardware teams



Flow to add new custom instructions



Flow to add new custom instructions

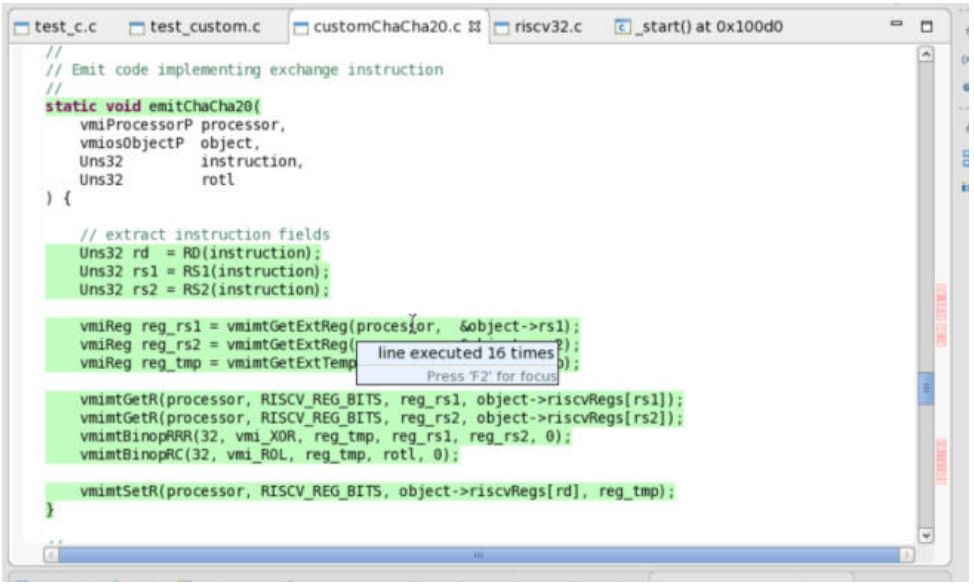


Further tools for model developers

- Model source line coverage
  - To see how completely the tests exercise the model

type filter text

Name	Total Lines	Instrumente	Executed Lir	Coverage %
Summary	16,900	4,411	2,834	64.25%
customChaCha20.c	374	87	42	48.28%
riscvBus.c	175	46	1	2.17%
riscvCSR.c	2,573	758	549	72.43%
riscvConfigList.c	70	2	0	0.0%
riscvDebug.c	527	167	72	43.11%
riscvDecode.c	1,599	360	164	45.56%
riscvDisassemble.c	514	185	185	100.0%
riscvDoc.c	725	143	30	20.98%
riscvExceptions.c	1,408	420	317	75.48%
riscvInfo.c	83	3	0	0.0%
riscvMain.c	383	147	25	17.01%
riscvMorph.c	2,887	1,032	776	75.19%
riscvParameters.c	589	145	9	6.21%
riscvRegisterTypes.h	115	10	6	60.0%
riscvSemiHost.c	44	6	3	50.0%
riscvStructure.h	204	4	2	50.0%
riscvUtils.c	493	122	45	36.89%
riscvVM.c	2,695	770	608	78.96%
vmiMt.h	1,442	4	0	0.0%



Further tools for model developers (2)

- Custom instruction coverage
  - To see that there are tests for new instructions

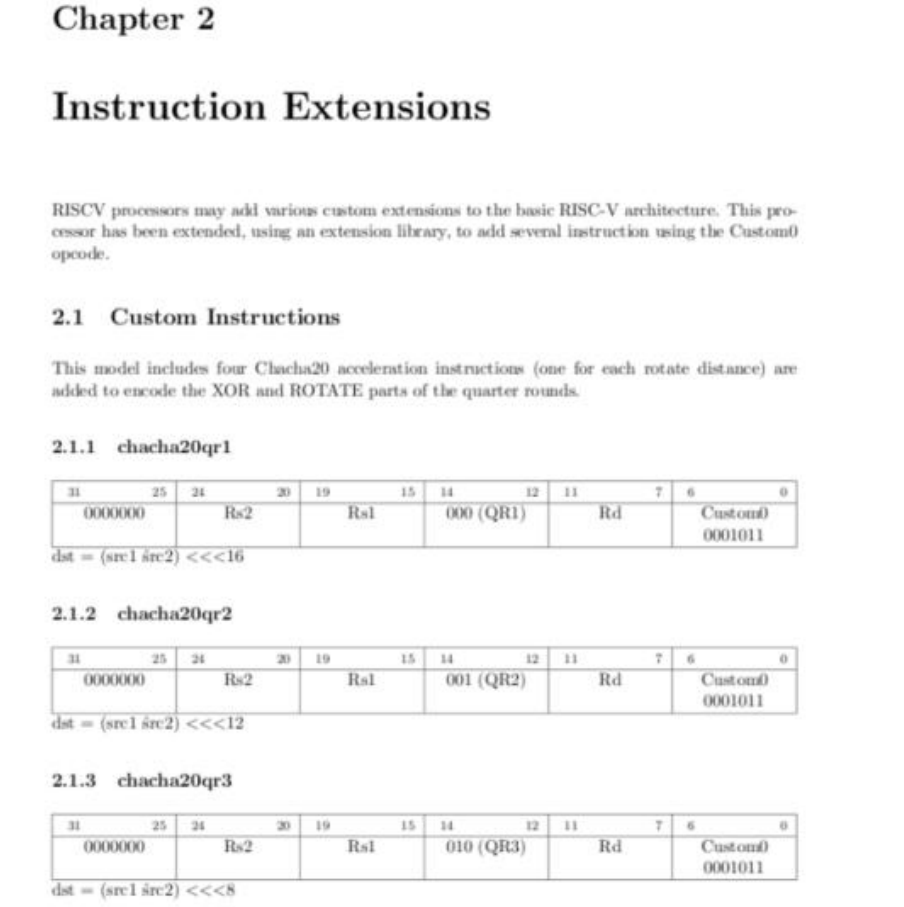
```
CpuManagerMulti finished: Thu Aug 23 12:09:15 2018

CpuManagerMulti (32-Bit) v99999999 Open Virtual Platform simulator from www.IMPERAS.com.
Visit www.IMPERAS.com for multicore debug, verification and analysis solutions.

* iss/cpu0: Instruction Profile Totals:
*         OpCode :    Pct : Count (Total instrs=      677012570)
* ---------------- : ------ : ----------
               sw : 19.87% :        134497608
               lw : 16.78% :        113575358
               sw : 13.05% :         88327451
             addi :  8.70% :         58868837
             andi :  4.97% :         33620233
             beqz :  4.35% :         29426103
             bnez :  3.73% :         25248055
              add :  3.73% :         25231546
             slli :  3.10% :         21020892
              ret :  2.49% :         16843028
              jal :  2.49% :         16843026
             srli :  2.48% :         16810160
             bltu :  2.48% :         16793686
             bgeu :  1.24% :          8421494
             bltz :  1.24% :          8421470
                j :  1.24% :          8388742
      chacha20qr1 :  1.24% :          8388608
      chacha20qr2 :  1.24% :          8388608
      chacha20qr3 :  1.24% :          8388608
      chacha20qr4 :  1.24% :          8388608
               lh :  0.63% :          4243601
            auipc :  0.62% :          4210858
              sub :  0.62% :          4210835
              xor :  0.62% :          4210707
              not :  0.62% :          4194307
              beq :  0.00% :            16546
             jalr :  0.00% :            16430
             blez :  0.00% :            16407
               sb :  0.00% :              206
              lhu :  0.00% :               97
               sh :  0.00% :               82
              lui :  0.00% :               67
               or :  0.00% :               50
              and :  0.00% :               49
              lbu :  0.00% :               47
              bne :  0.00% :               34
              ori :  0.00% :               29
               jr :  0.00% :               25
              bge :  0.00% :               17
              neg :  0.00% :               16
              blt :  0.00% :               12
             srai :  0.00% :                8
             bgtz :  0.00% :                7
             bgez :  0.00% :                6
              sll :  0.00% :                4
```

- Custom instruction profile
  - See how long the simulator takes to execute each instruction
  - Use to focus speed up simulation of instructions
  - Enables improvement of speed of simulation runs

```
-------------------------------------------------------------------------------
PROFILE REPORT
-------------------------------------------------------------------------------
    sw                  0.27s      88,327,451   3.1ps/instruction (iss/cpu0)
    lw                  0.20s     113,575,358   1.8ps/instruction (iss/cpu0)
    sw                  0.16s     134,497,608   1.2ps/instruction (iss/cpu0)
    ret                 0.07s      16,843,028   4.2ps/instruction (iss/cpu0)
    jal                 0.06s      16,843,026   3.6ps/instruction (iss/cpu0)
    addi                0.05s      58,868,837   0.8ps/instruction (iss/cpu0)
    andi                0.05s      33,620,233   1.5ps/instruction (iss/cpu0)
    add                 0.05s      25,231,546   2.0ps/instruction (iss/cpu0)
    auipc               0.04s       4,210,858   9.5ps/instruction (iss/cpu0)
    beqz                0.03s      29,426,103   1.0ps/instruction (iss/cpu0)
    bnez                0.03s      25,248,055   1.2ps/instruction (iss/cpu0)
    chacha20qr3         0.03s       8,388,608   3.6ps/instruction (iss/cpu0)
    (JIT translation)   0.03s           2,500   12.0ns/instruction
    bltu                0.02s      16,793,686   1.2ps/instruction (iss/cpu0)
    chacha20qr1         0.02s       8,388,608   2.4ps/instruction (iss/cpu0)
    lh                  0.02s       4,243,601   4.7ps/instruction (iss/cpu0)
    xor                 0.02s       4,210,707   4.7ps/instruction (iss/cpu0)
    slli                0.01s      21,020,892   0.5ps/instruction (iss/cpu0)
    srli                0.01s      16,810,160   0.6ps/instruction (iss/cpu0)
    bltz                0.01s       8,421,470   1.2ps/instruction (iss/cpu0)
    j                   0.01s       8,388,742   1.2ps/instruction (iss/cpu0)
    not                 0.01s       4,194,307   2.4ps/instruction (iss/cpu0)
    (unallocated)       0.01s
    bgeu                0.00s       8,421,494   0.0ps/instruction (iss/cpu0)
    chacha20qr2         0.00s       8,388,608   0.0ps/instruction (iss/cpu0)
    chacha20qr4         0.00s       8,388,608   0.0ps/instruction (iss/cpu0)
    sub                 0.00s       4,210,835   0.0ps/instruction (iss/cpu0)
    beq                 0.00s          16,546   0.0ps/instruction (iss/cpu0)
    jalr                0.00s          16,430   0.0ps/instruction (iss/cpu0)
    blez                0.00s          16,407   0.0ps/instruction (iss/cpu0)
    sb                  0.00s             206   0.0ps/instruction (iss/cpu0)
    lhu                 0.00s              97   0.0ps/instruction (iss/cpu0)
    sh                  0.00s              82   0.0ps/instruction (iss/cpu0)
    lui                 0.00s              67   0.0ps/instruction (iss/cpu0)
    or                  0.00s              50   0.0ps/instruction (iss/cpu0)
    and                 0.00s              49   0.0ps/instruction (iss/cpu0)
    lbu                 0.00s              47   0.0ps/instruction (iss/cpu0)
    bne                 0.00s              34   0.0ps/instruction (iss/cpu0)
    ori                 0.00s              29   0.0ps/instruction (iss/cpu0)
    jr                  0.00s              25   0.0ps/instruction (iss/cpu0)
    TOTAL               1.21s     677,012,570
-------------------------------------------------------------------------------
Info
```

Document custom instructions

- Imperas tools automatically generate a processor model document PDF
- Includes all base model registers and any new registers
- Provides detailed documentation of new custom instructions



Chapter 2

Instruction Extensions

RISCV processors may add various custom extensions to the basic RISC-V architecture. This processor has been extended, using an extension library, to add several instruction using the Custom0 opcode.

2.1 Custom Instructions

This model includes four Chacha20 acceleration instructions (one for each rotate distance) are added to encode the XOR and ROTATE parts of the quarter rounds.

2.1.1 chacha20qr1

31 25	24 20	19 15	14 12	11 7	6 0
0000000	Rs2	Rs1	000 (QR1)	Rd	Custom0 0001011

dst = (src1 ŝrc2) <<<16

2.1.2 chacha20qr2

31 25	24 20	19 15	14 12	11 7	6 0
0000000	Rs2	Rs1	001 (QR2)	Rd	Custom0 0001011

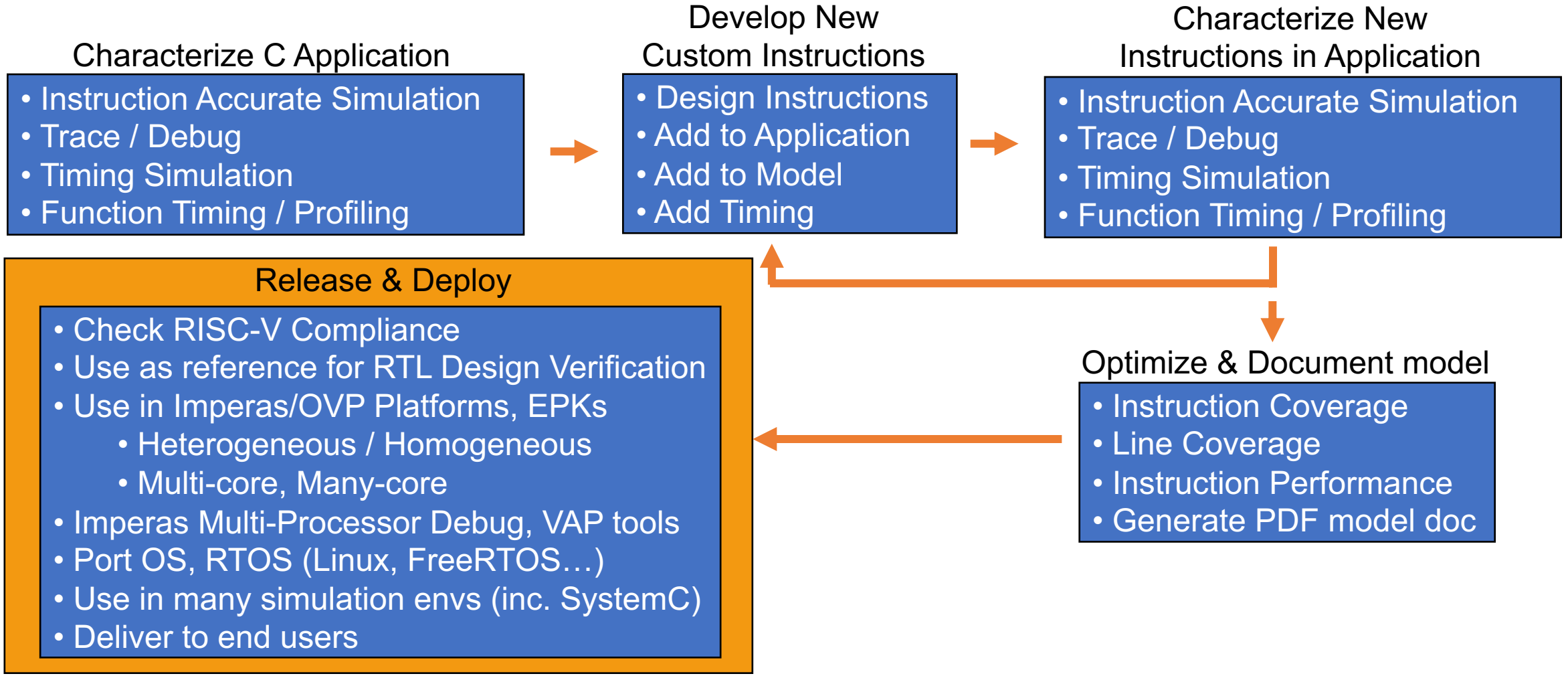
dst = (src1 ŝrc2) <<<12

2.1.3 chacha20qr3

31 25	24 20	19 15	14 12	11 7	6 0
0000000	Rs2	Rs1	010 (QR3)	Rd	Custom0 0001011

dst = (src1 ŝrc2) <<<8

Flow to add new custom instructions



Summary

- Custom instructions are a key value proposition of RISC-V
- Adding custom instructions requires solving the key challenge of how to optimize those instructions
- Instruction accurate (IA) simulation environment using IA models can be extended to enable custom instruction analysis
- Flow for optimizing custom instructions in RISC-V processors is being used in real designs

Thank You

- For more information:
  - LarryL@imperas.com
  - Imperas website: http://www.imperas.com/riscv/
  - Open Virtual Platforms (OVP): http://www.ovpworld.org/info_riscv