Modelling Communication Software Execution via Tracing

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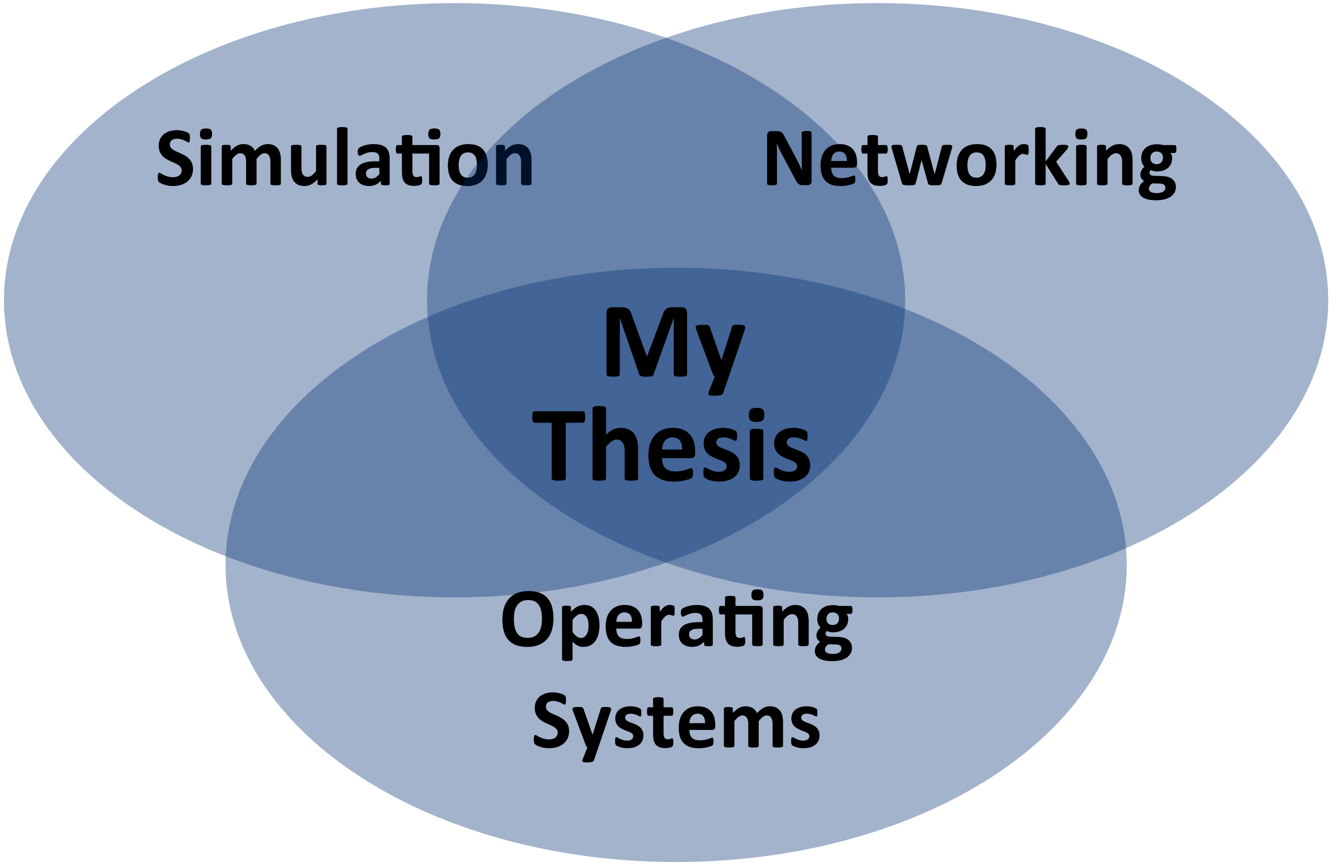
Outline

- Research Area
- My PhD-Work
  - Motivation
  - Overview of my work
  - Results
- Possible master thesis areas

Research Area



Simulation

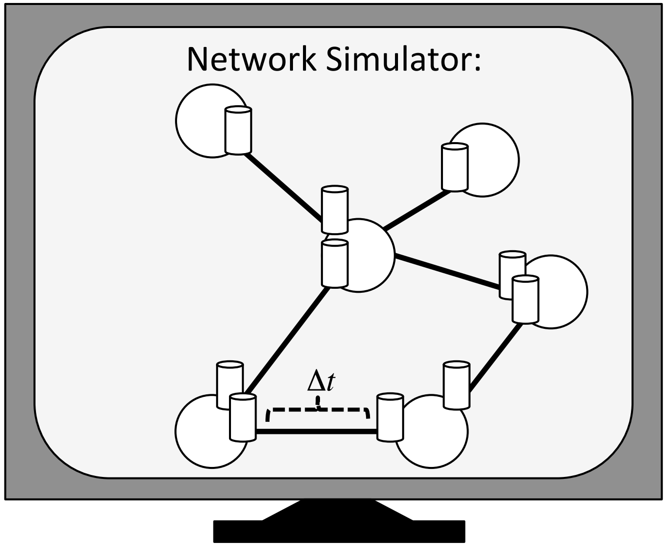
Networking

My Thesis

Operating Systems

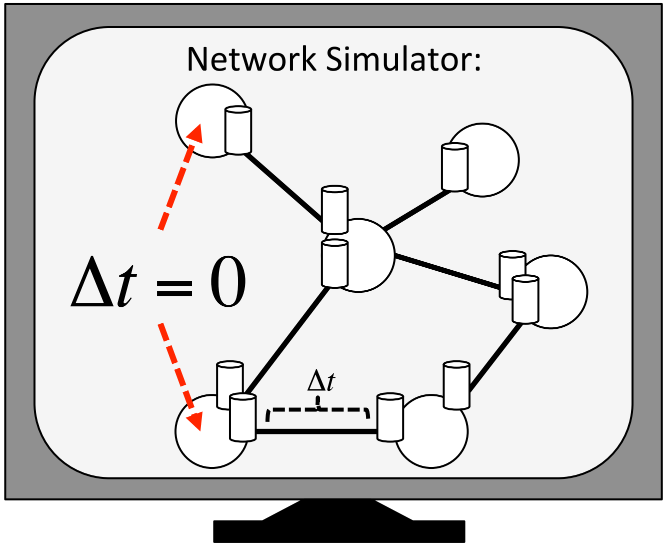
Network Simulation

- Computer systems are often very complex
  - How to test and evaluate?
- Solution: network simulation

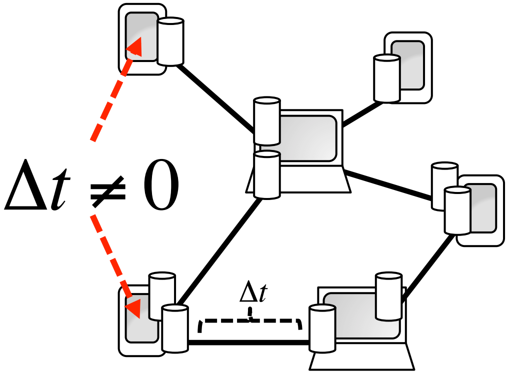


Network Simulation

- Network simulation
  - Impact of communication software execution ignored
  - **Can this always be ignored?**

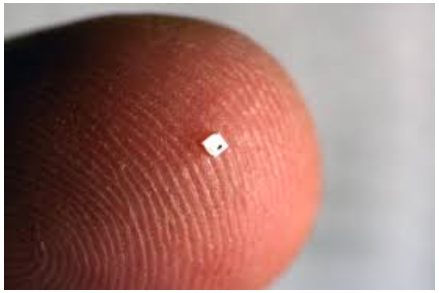


Real World:



New and emerging networks

- Heterogeneous sets of devices
- In all sizes (many very, very small!)
  - And thus **resource constrained!**



Network Simulation

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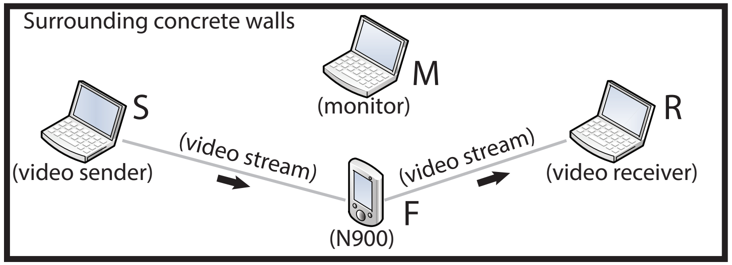
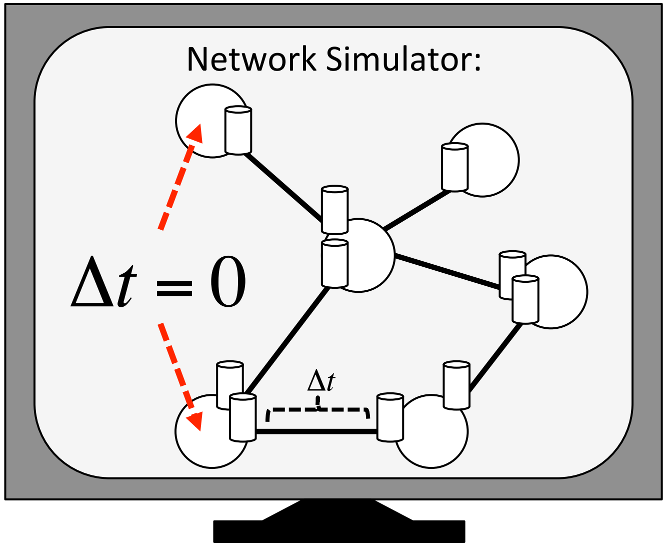
- Test:



- Throughput < 3.7 Mbps
  - WiFi-router: 15Mbps!
- 10-40 ms. already at 2 Mbps
  - Wifi-Router: a few milliseconds!



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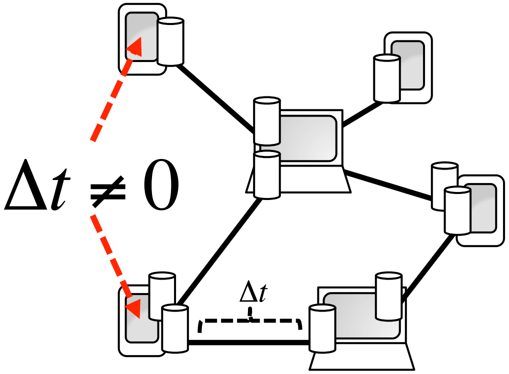

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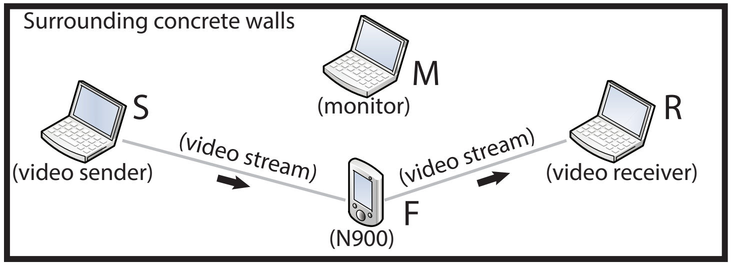

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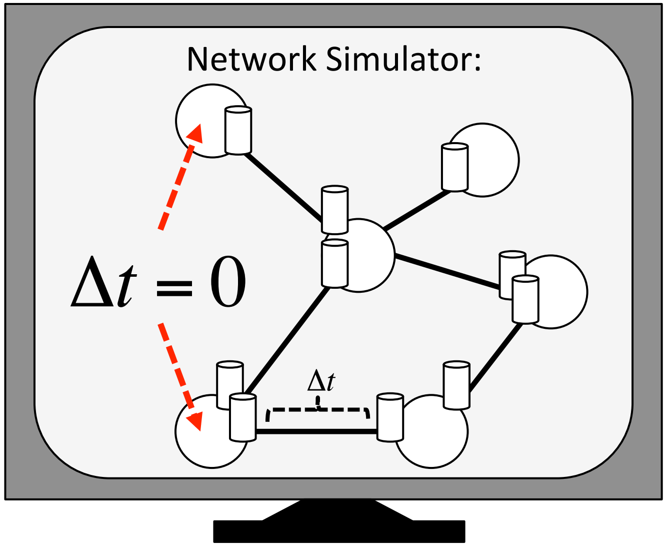

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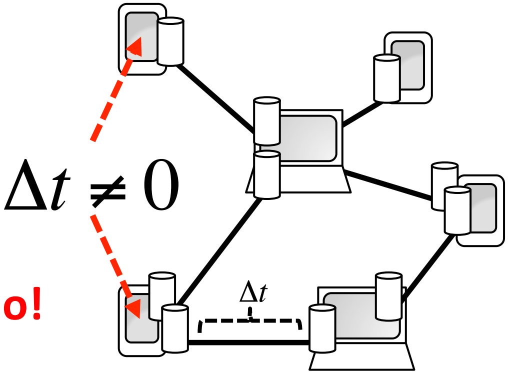
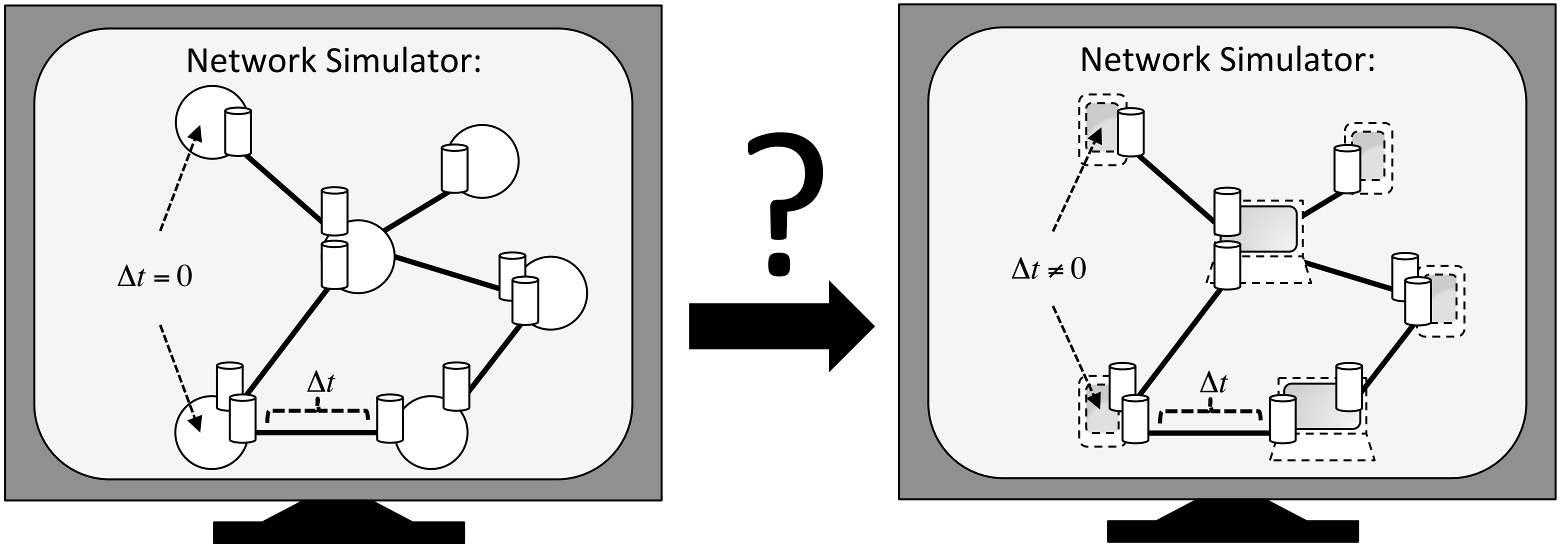


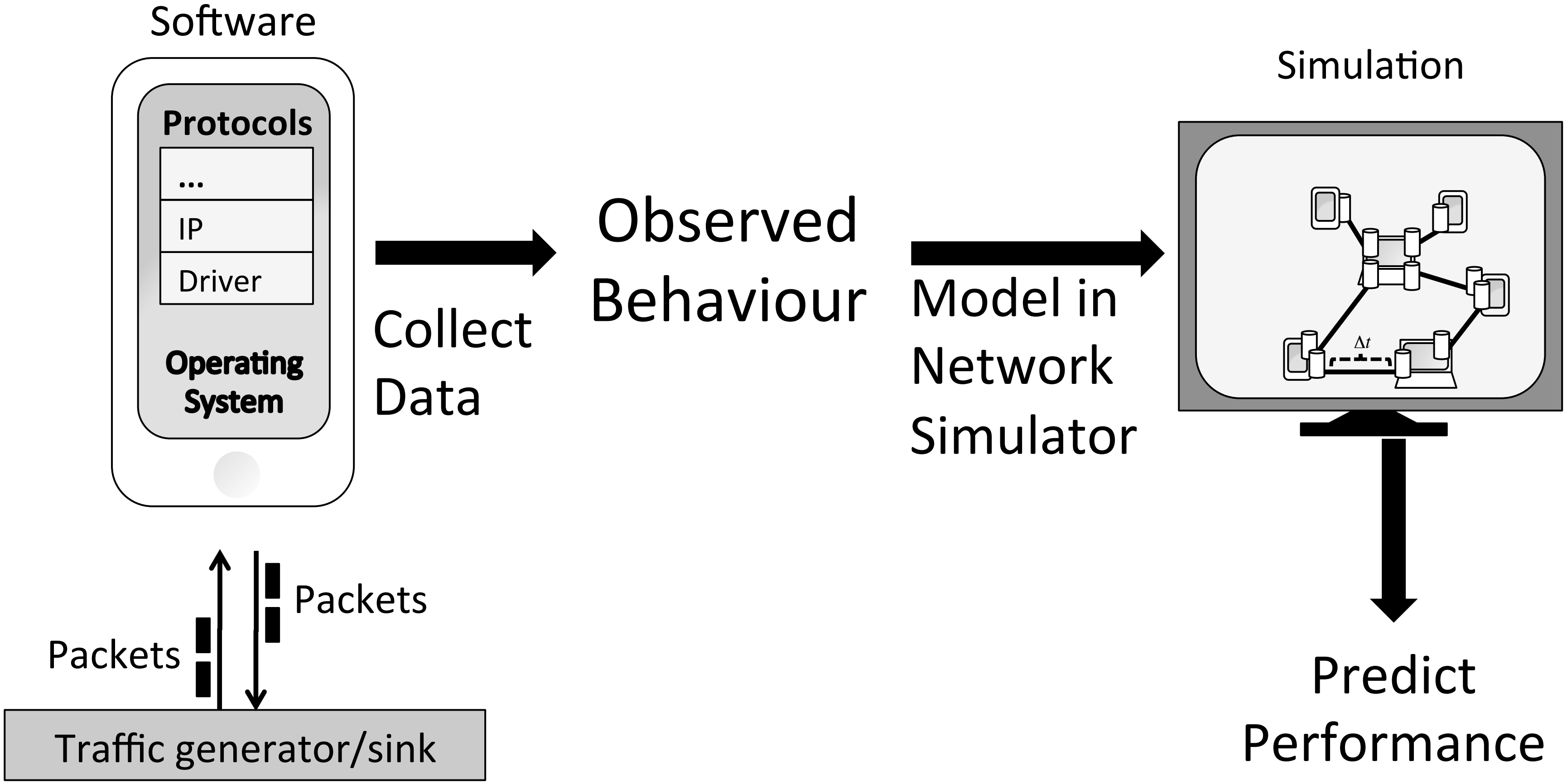
Answer: No!

Problem

How do we make network simulators account for the execution of communication software?



Core Idea



Software

Protocols

...

IP

Driver

Operating System

Packets

Packets

Traffic generator/sink

Collect Data

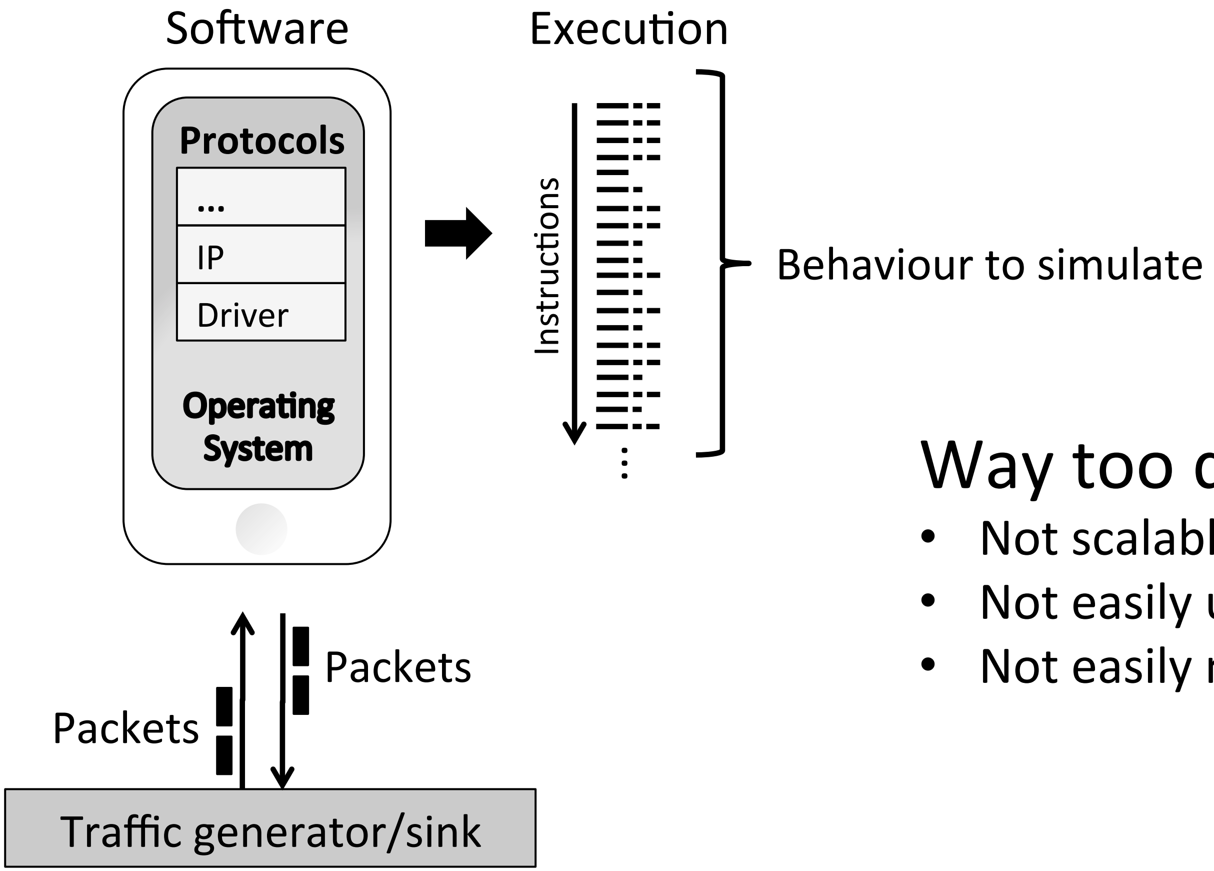
Observed Behaviour

Model in Network Simulator

Simulation

Predict Performance

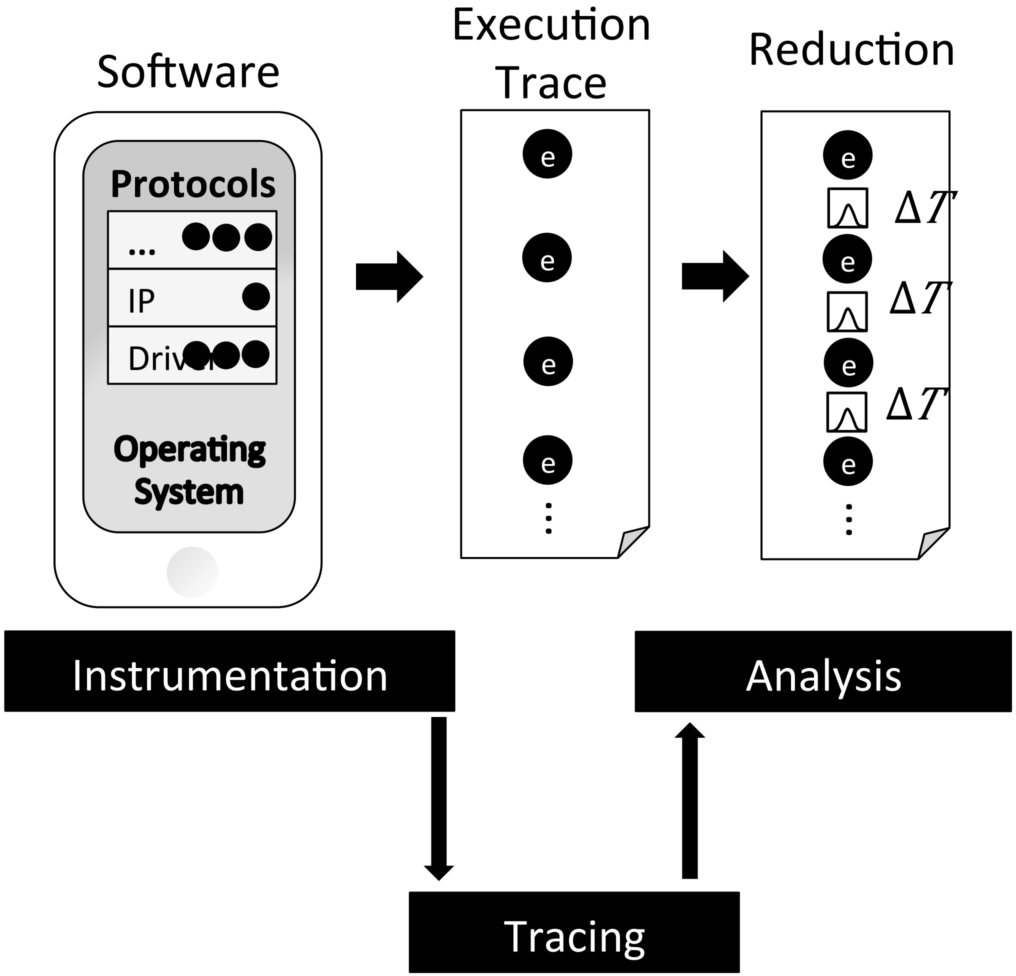
5-Step Approach



Way too detailed!

- Not scalable
- Not easily understandable
- Not easily modifiable

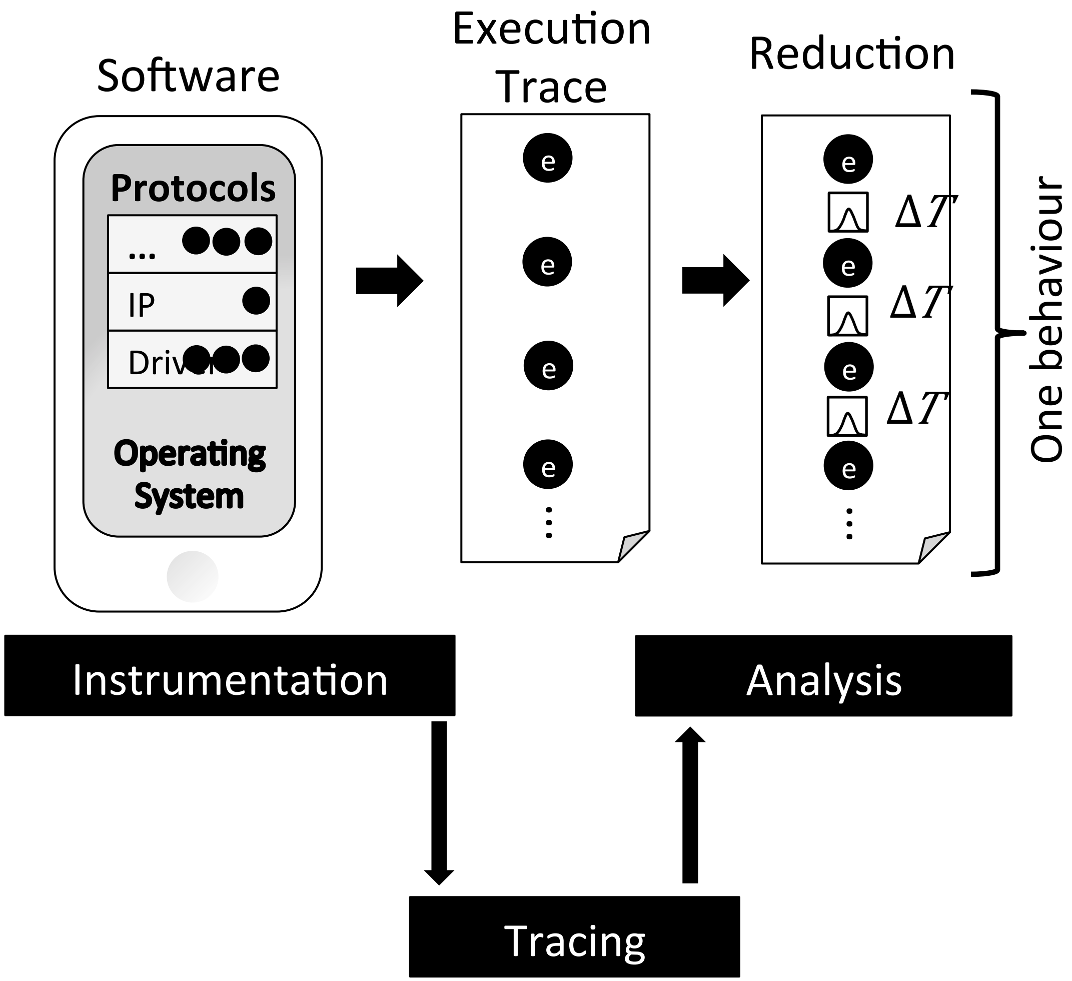
Simplification



Capture important events:

- Queuing
- Synchronization
- Loops
- Interactions with HW
- …

Capturing Change in Behaviour



Behaviour affected by input data,e.g.,:

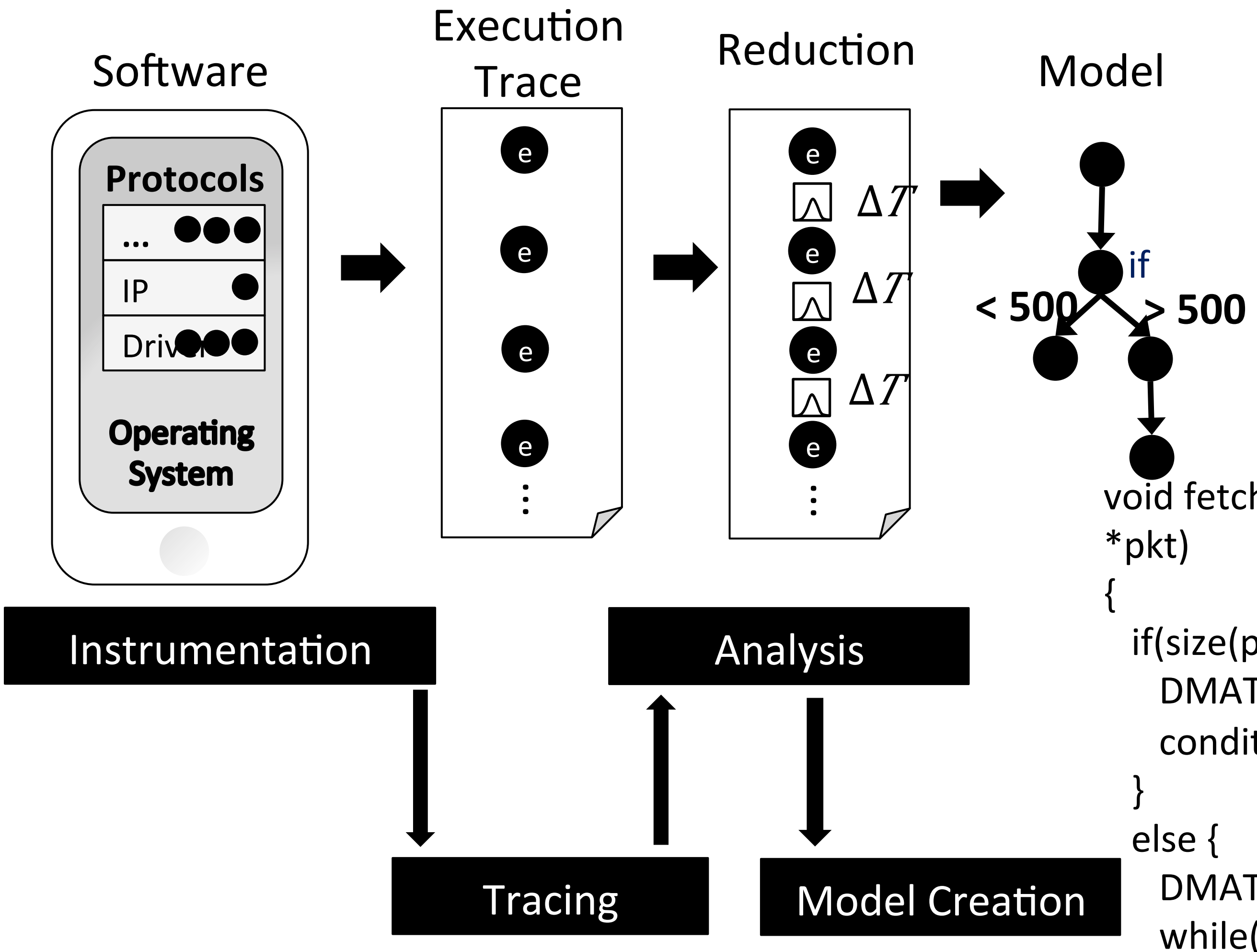
- Packet size, type, …
- Routing table size, …
- Bus state, …

-> Many behaviours!

Example:

```
void fetchFromNIC(Packet
*pkt)
{
  if(size(pkt) > 500) {
    DMATranferNIC(pkt);
    condition_wait(dma);
  }
  else {
    DMATranferNIC (pkt);
    while(!dma_done) {};
  }
}
```

Capturing Change in Behaviour



Software

Execution Trace

Reduction

Model

Instrumentation

Analysis

Tracing

Model Creation

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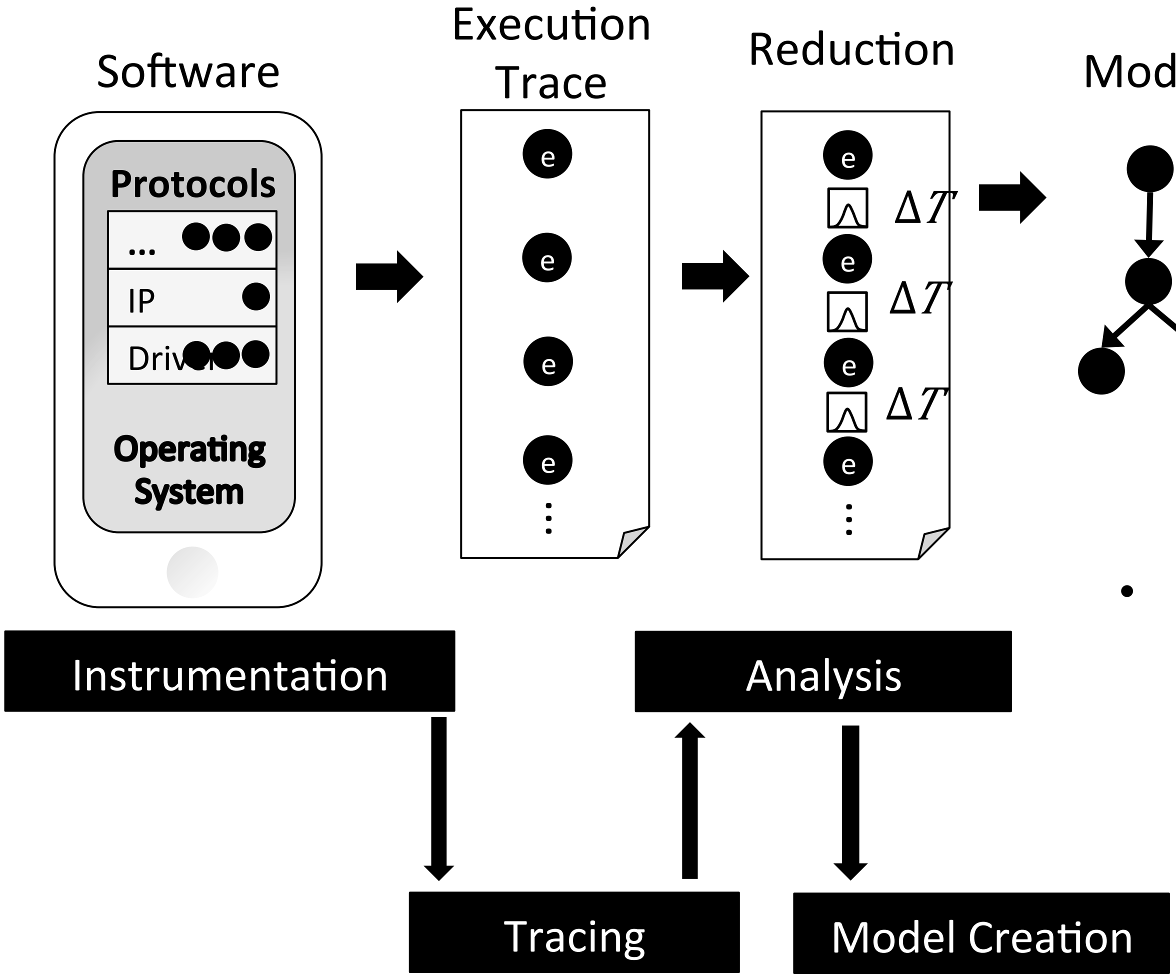
Capturing Impact of Multi-Threading



Software

Protocols

...

IP

Driver

Operating System

Execution Trace

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e

Reduction

e

ΔT

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ΔT

e

ΔT

e

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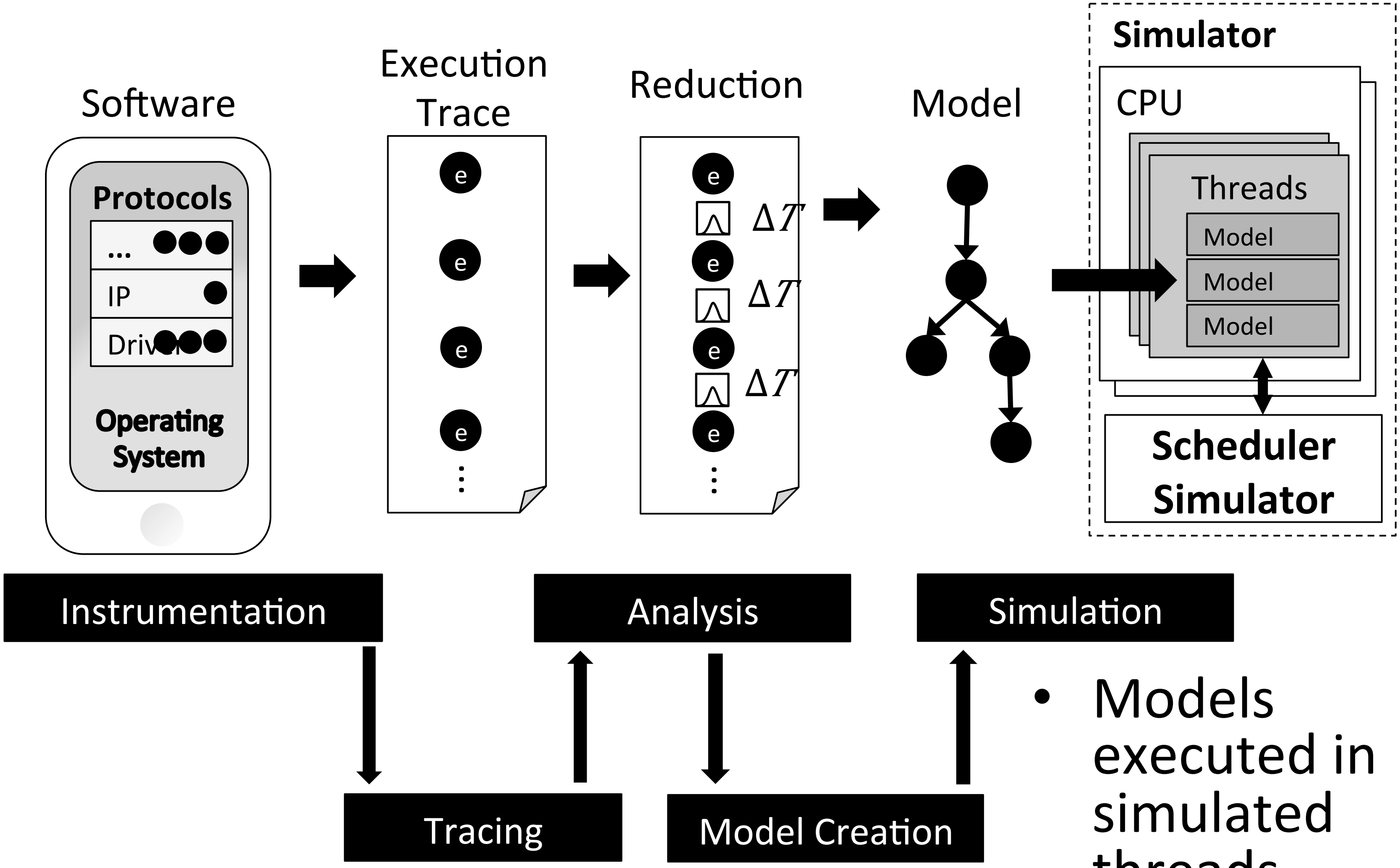
Model Creation

- Overall performance affected by multi-threading
  - Workload
  - Scheduling policy
  - Synchronization

Simulation



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Reduction

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ΔT

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Model

Simulator

CPU

Threads

Model

Model

Model

Scheduler Simulator

Instrumentation

Analysis

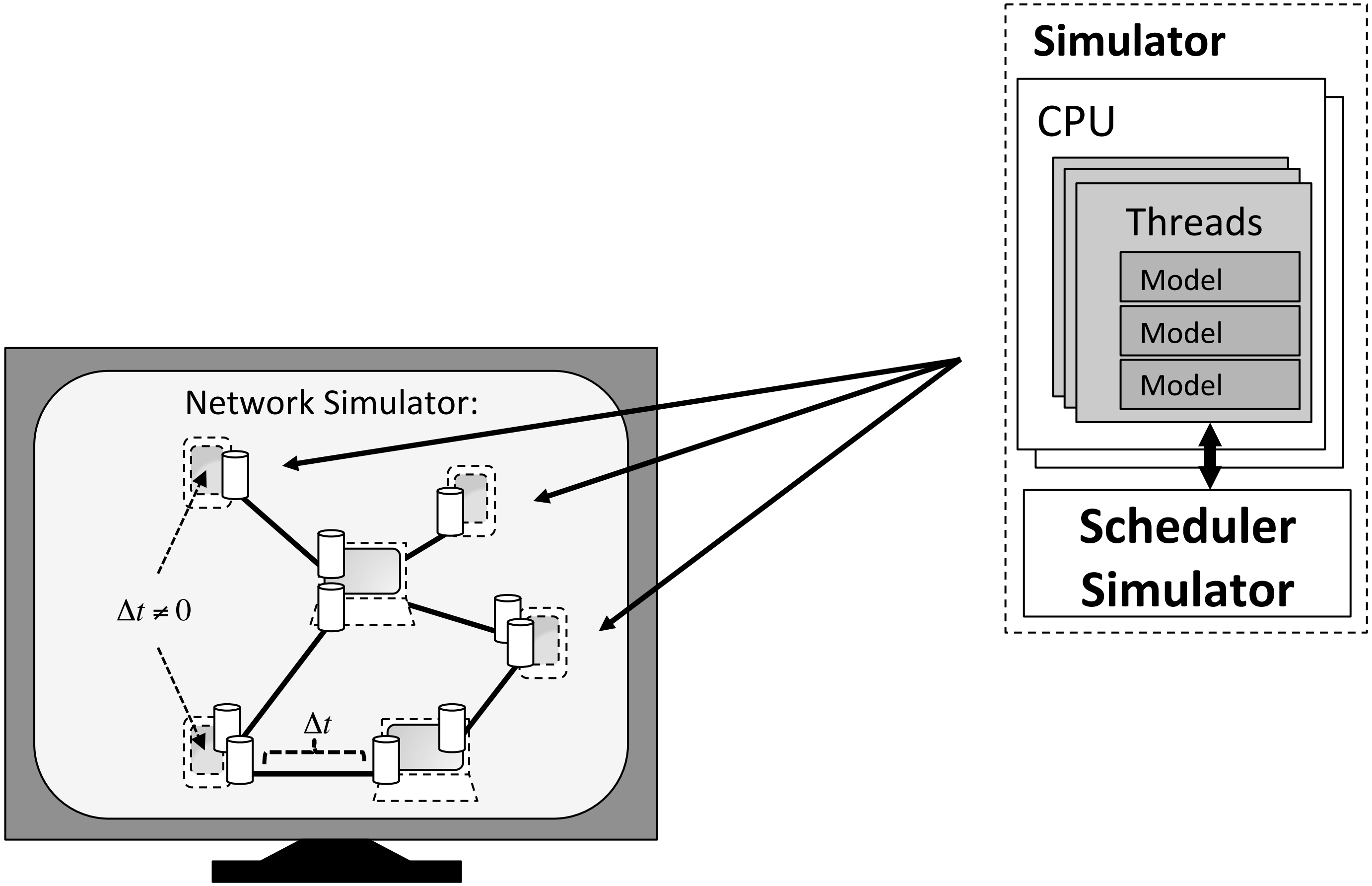
Simulation

Tracing

Model Creation

- Models executed in simulated threads

Simulation



Simulator

CPU

Threads

Model

Model

Model

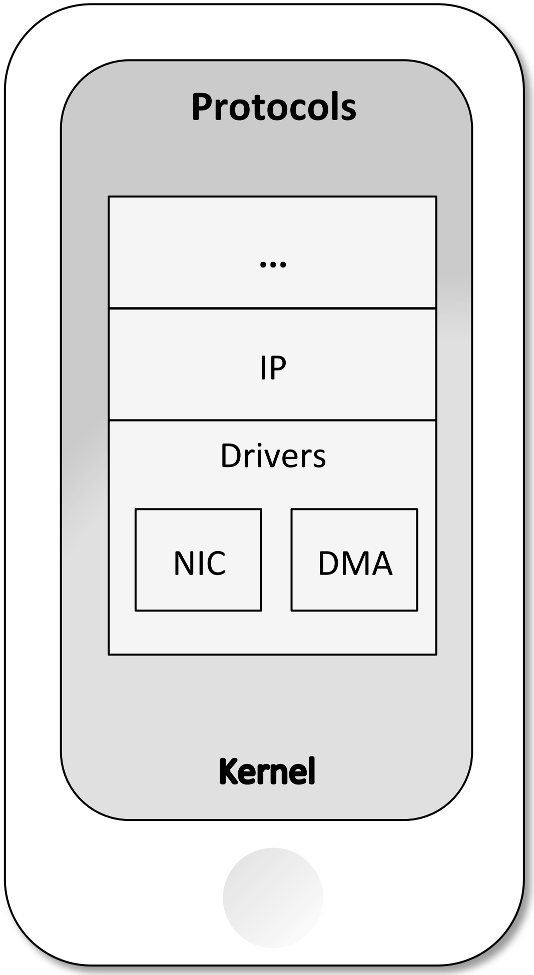
Scheduler Simulator

Network Simulator:

$\Delta t \neq 0$

Δt

Google Nexus One: Instrumentation



Instrumentation:

Networking sub-system, including IP
10 tracepoints

The rest of kernel
58 tracepoints

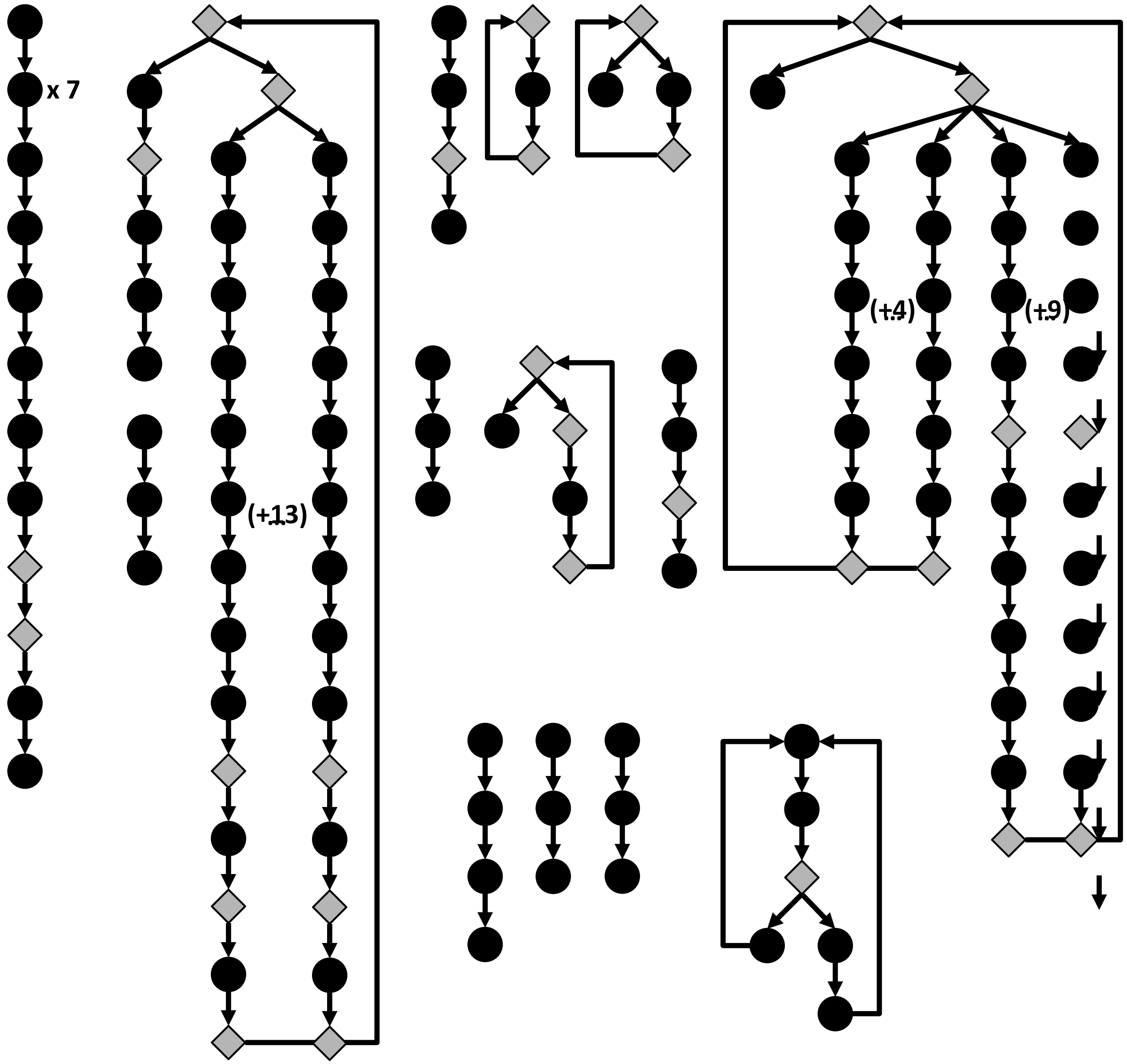
- Work scheduling
- Task scheduler and synchronization primitives
- Interrupts

NIC Driver
17 tracepoints

- NIC, IP and driver TX queues (4), receive and transmit services and loops (8), service context (5)

Parallel execution (DMA, …):
6 Tracepoints

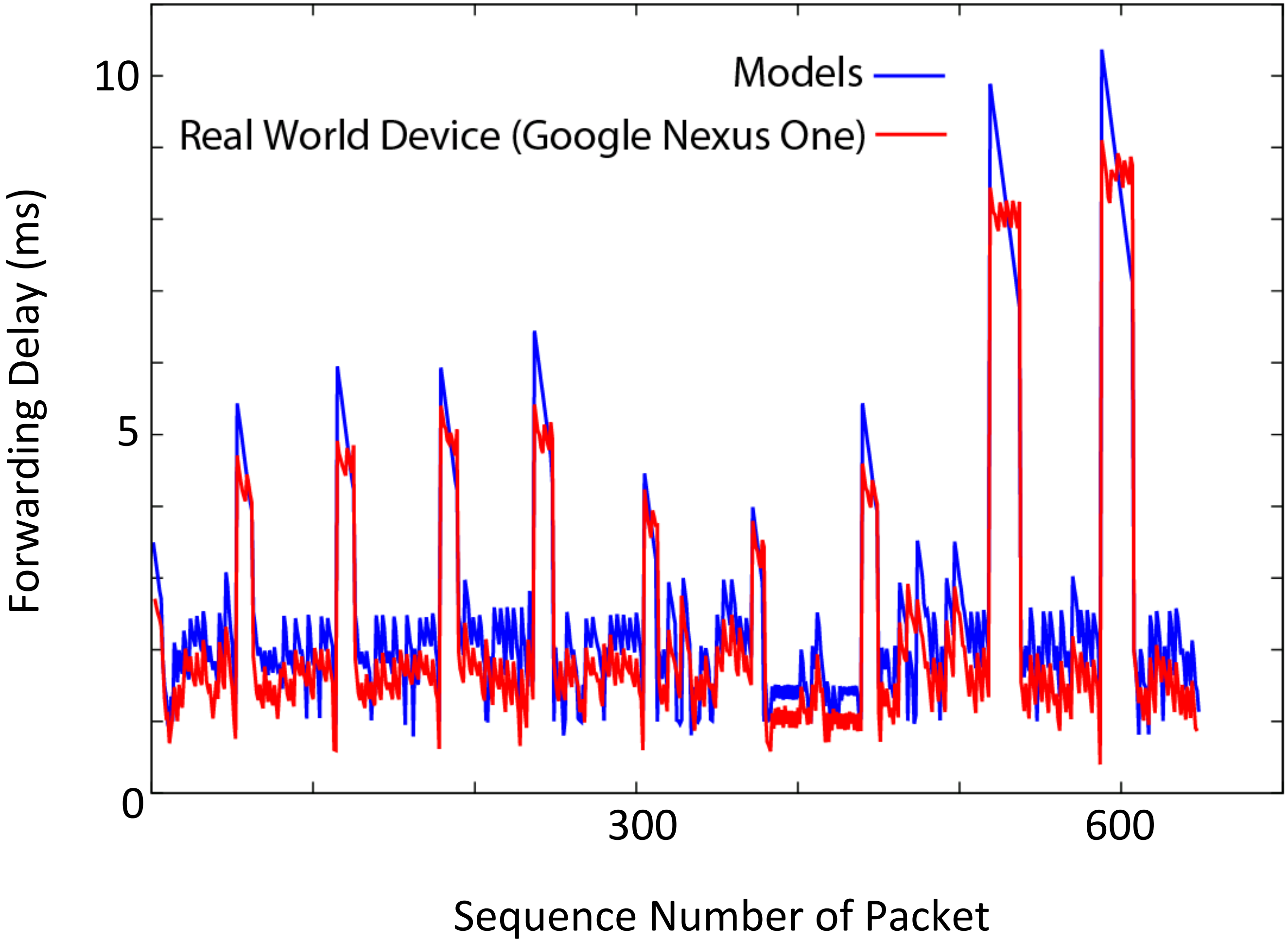
Google Nexus One: Final Models



2-300.000 instructions

about 100 statements

Google Nexus One: Key Result



Possible Master Theses

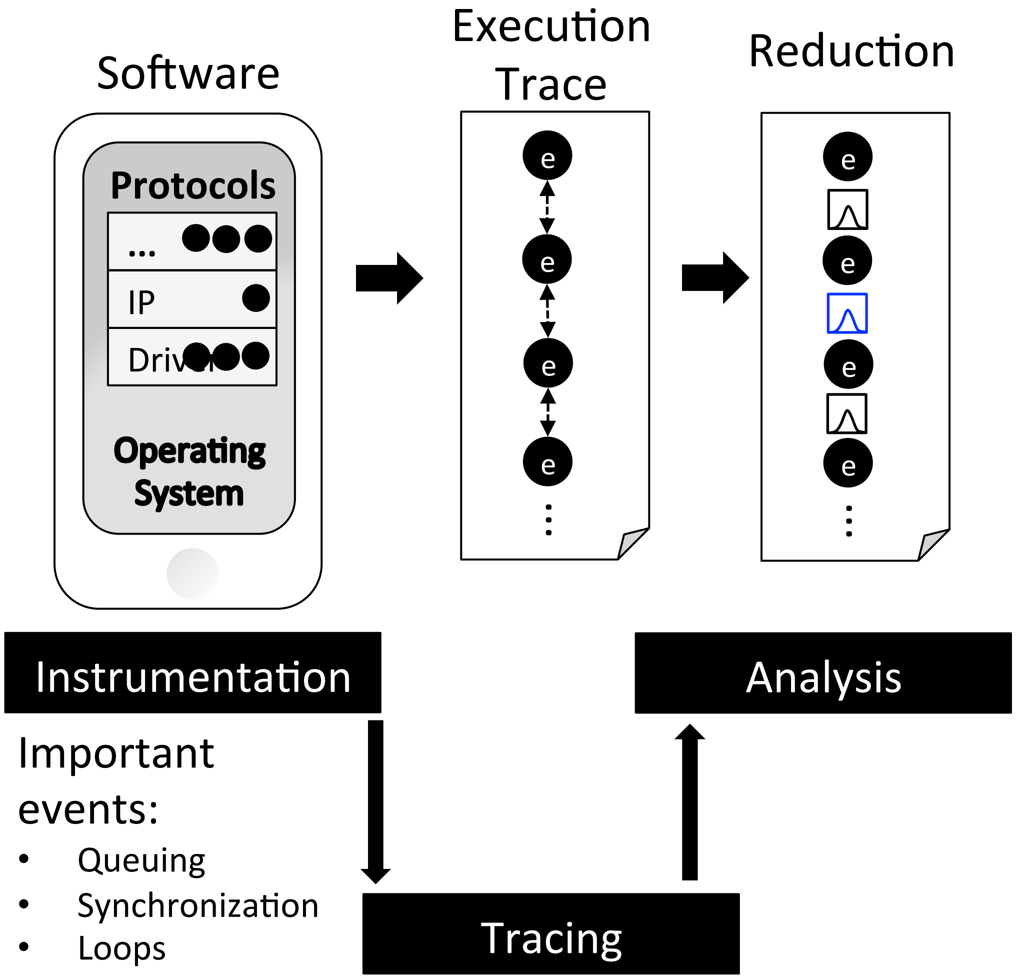
- Focus on programming:
  - Extend tracing framework for multi-core devices
  - Visualization
- Focus on modelling:
  - Additional protocols on the GN1
  - The N900
  - Sensors with TinyOS, Contiki, …
  - Software based routers
- Focus on experimentation:
  - Medium- to large-scale experiments
  - Replicate published experiments and compare results

Thank you for your Attention!

Questions?

(… or contact me for more information!)

Core Idea



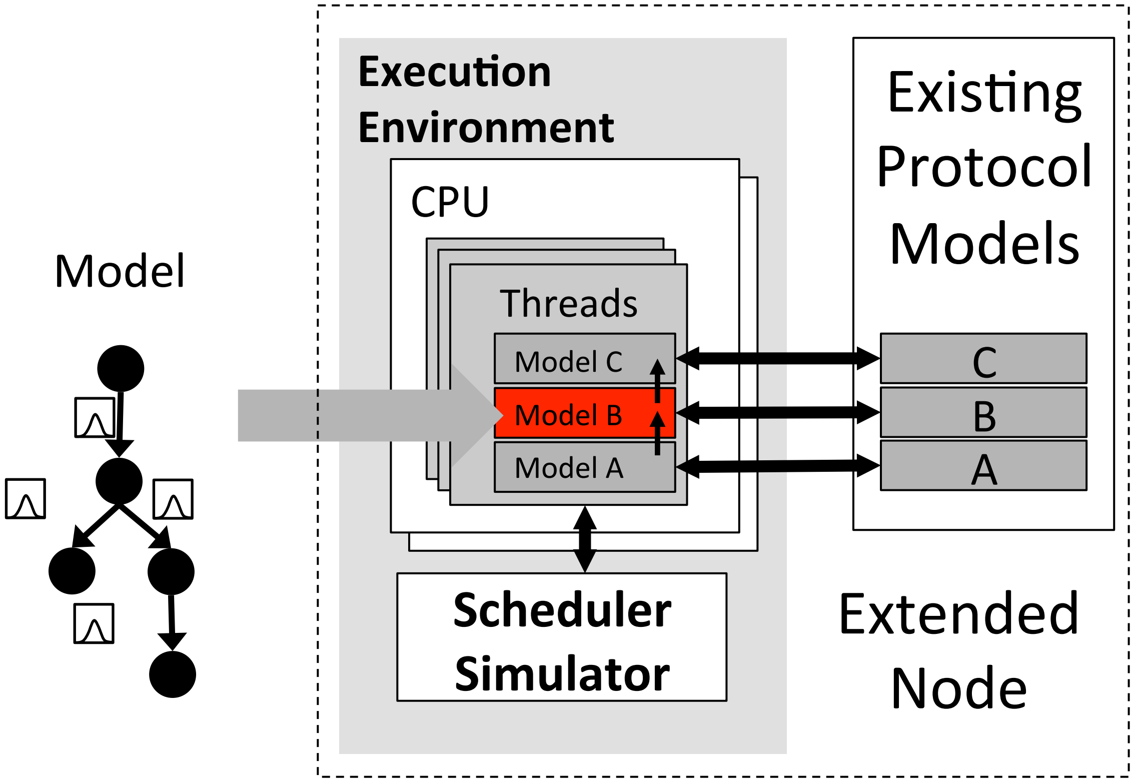
Important events:

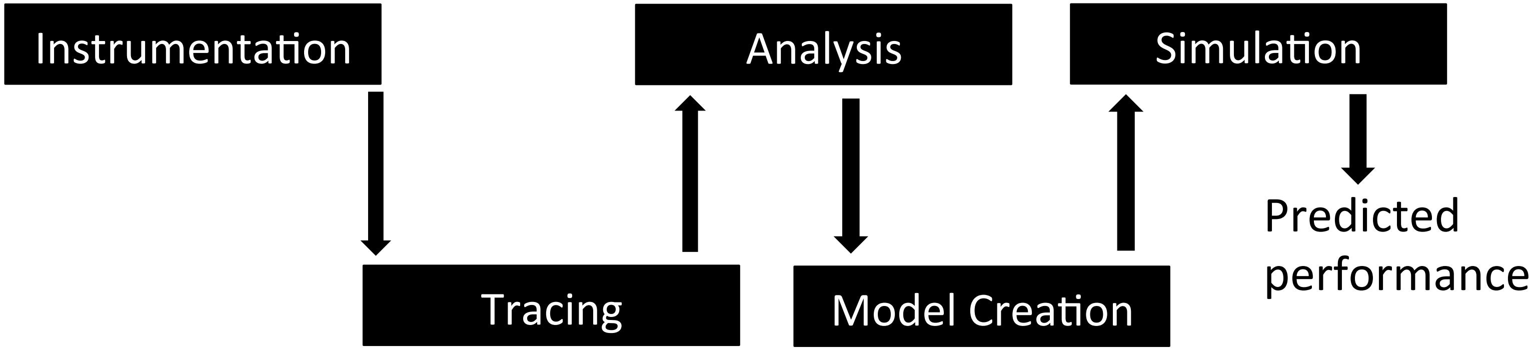
- Queuing
- Synchronization
- Loops
- Interactions with HW
- **Impact of Context**

Behaviour affected by execution context,e.g.,:

- Packet size, type, …
- Routing table size, …
- Bus state, …

Core Idea





Instrumentation

Tracing

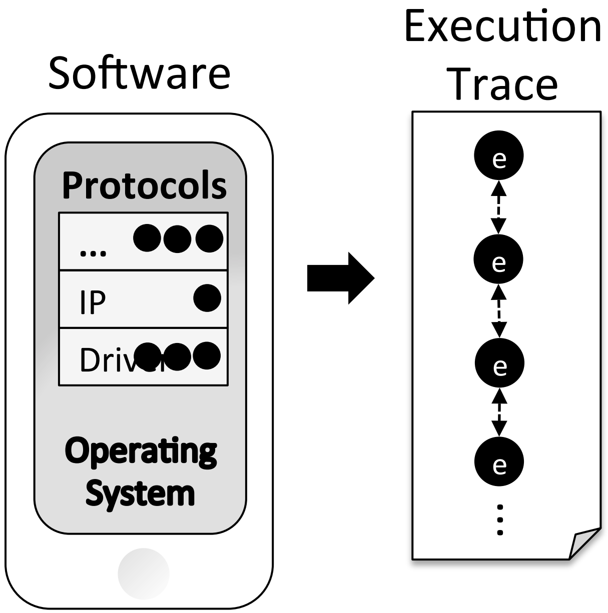
Analysis

Model Creation

Simulation

Predicted performance

Core Idea


Software
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IP
Driver
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Execution Trace
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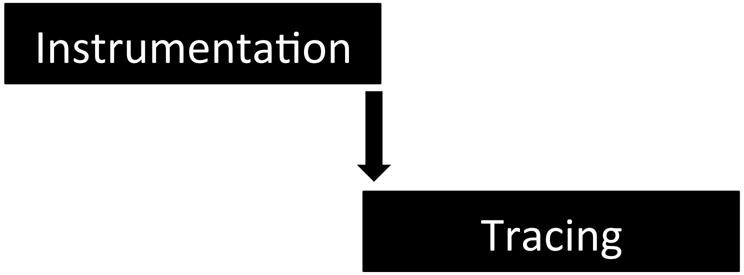
Instrumentation
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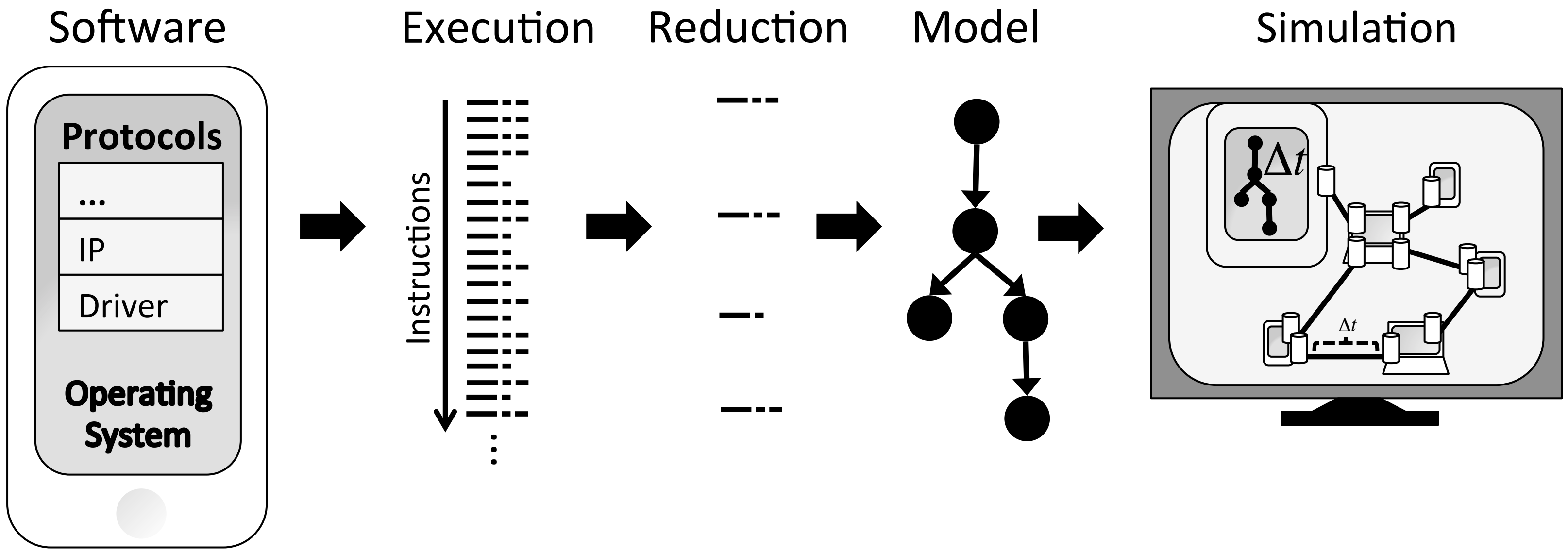

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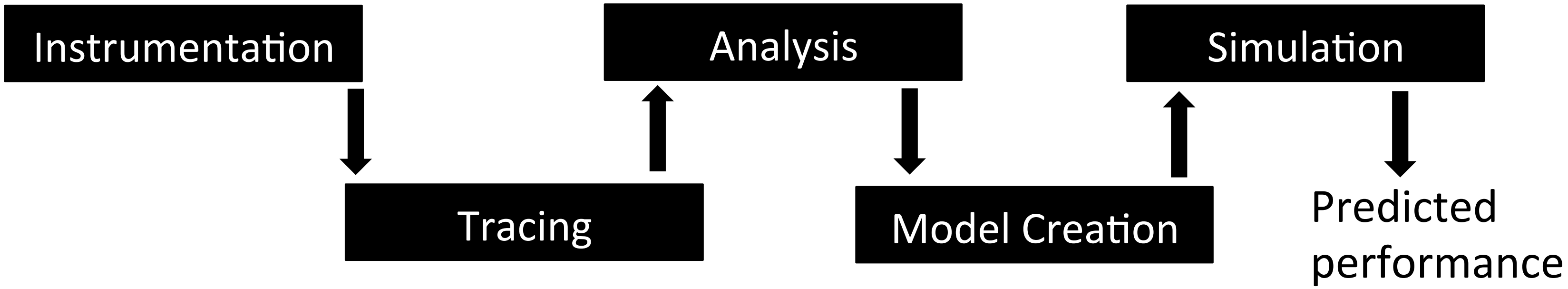
Δt



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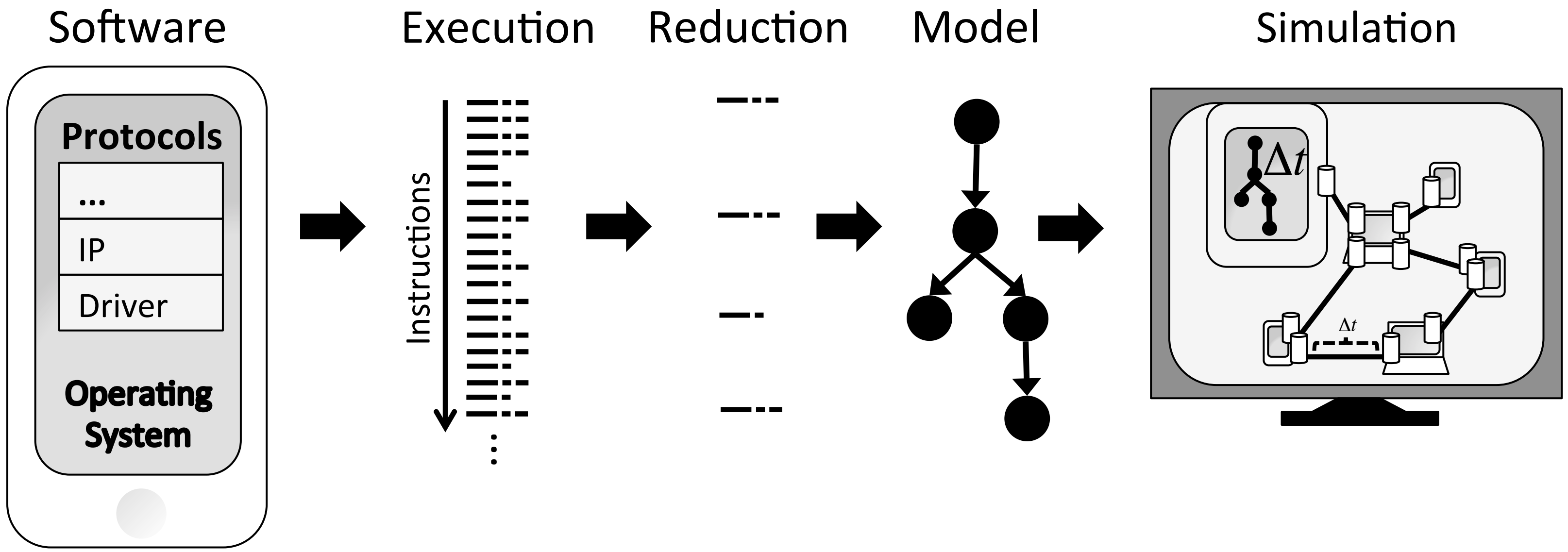

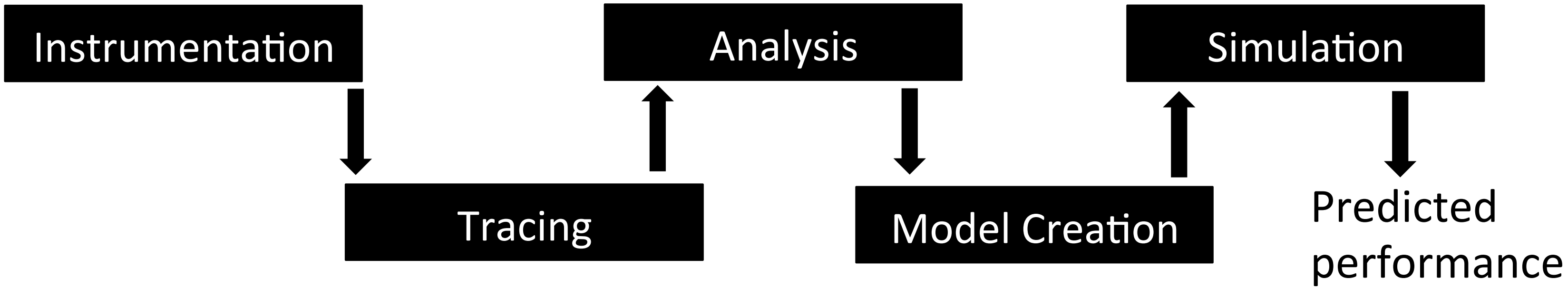

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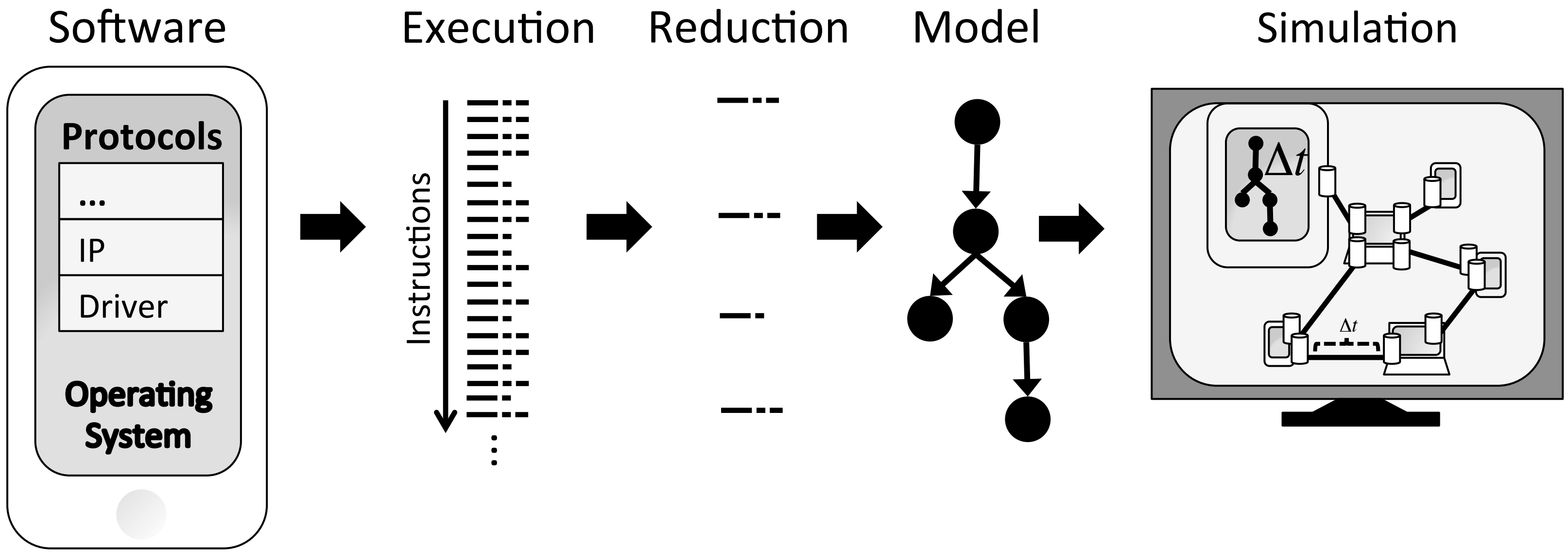

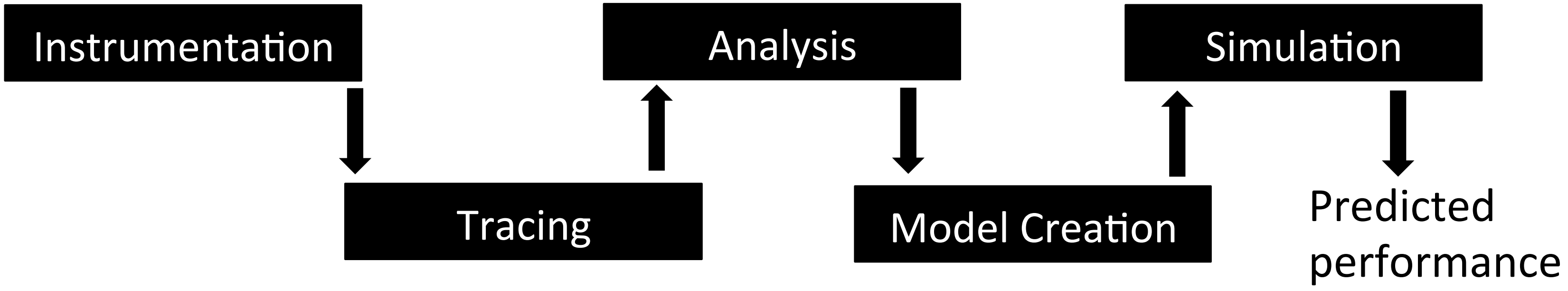

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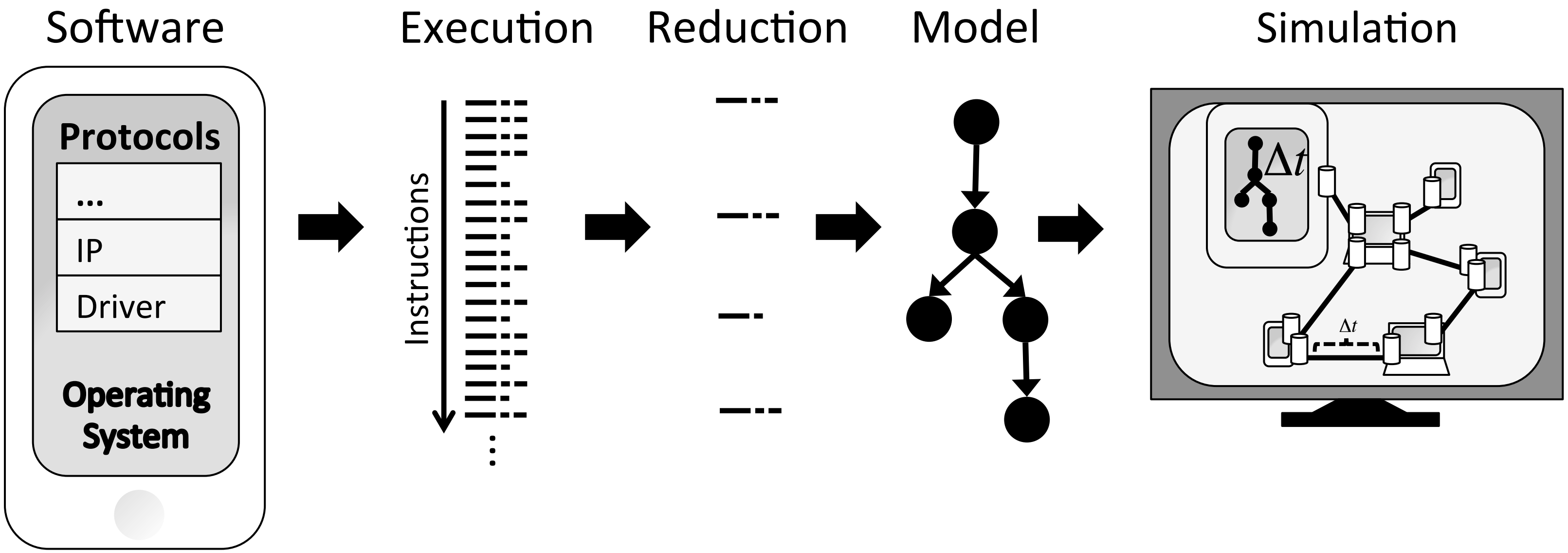

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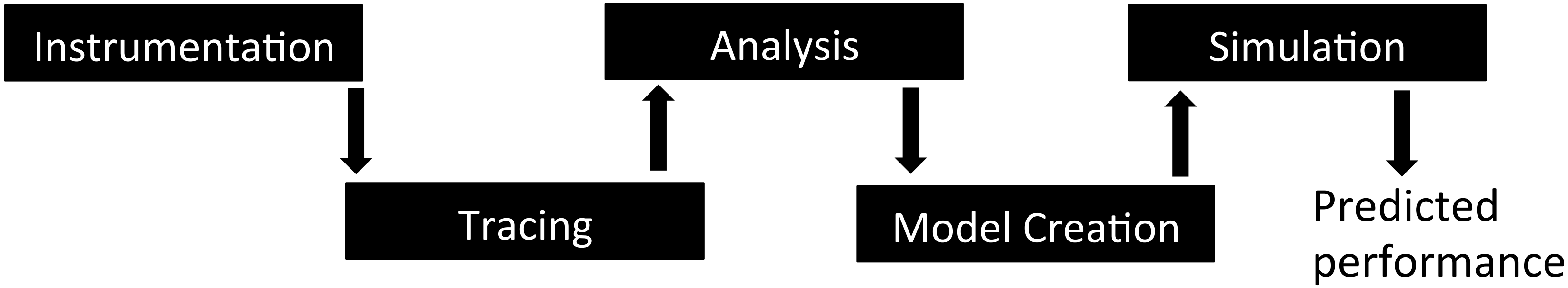

Instrumentation

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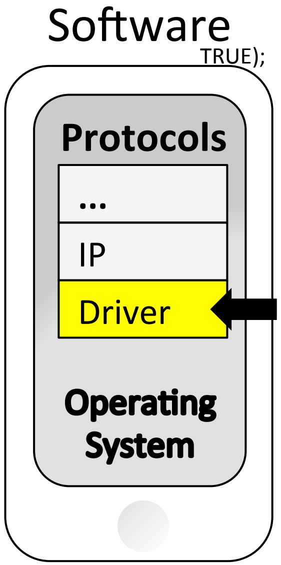
Important Events

Reason	Required Events
Separating services	**Class 1:** • SRVStart, SRVStop • CTXSwitch • HIRQStart, HIRQStop
CPU processing	**Class 2:** • CPU cycles • (and/or hardware performance counters)
Interactions with task scheduler	**Class 3:** • Awake • Sleep • Synch
Work scheduling in threads and interrupts	**Class 4:** • SRVStart, SRVStop • LoopStart, LoopRestart, LoopStop • Enqueue, Dequeue
Parallel processing	**Class 5:** • PEUStart • HIRQStart • Synch
Execution context	**Class 6:** • CondRead/Write • Dequeue • SRVEntry

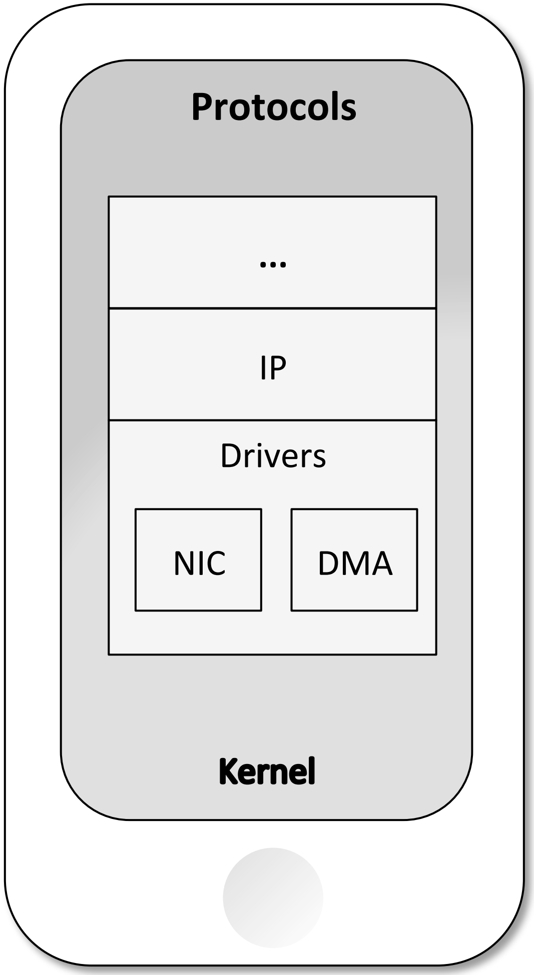
Example Instrumentation

```
uint
dhdsdio_sendfromq(dhd_bus_t *bus, uint maxframes, bool rxdone) {
    void *pkt;
    uint32 intstatus = 0;
    uint retries = 0;
    int ret = 0, prec_out;
    uint cnt = 0;
    uint datalen;
    uint8 tx_prec_map;

    dhd_pub_t *dhd = bus->dhd;
    sdpcmd_regs_t *regs = bus->regs;

    DHD_TRACE(("%s: Enter\n", __FUNCTION__));
    trace_sepext_queuecondition(rxdone, PKTQ_NIC, PKTQ_NIC);

    tx_prec_map = ~bus->flowcontrol;

    trace_sepext_loopstart(maxframes, 0, PKTQ_BCM4329_TXQ,
         PKTQ_BCM4329_TXQ);
    /* Send frames until the limit or some other event */
    for (cnt = 0; (cnt < maxframes) && DATAOK(bus); cnt++) {
        dhd_os_sdlock_txq(bus->dhd);

        trace_sepext_looprestart();

        if ((pkt = pktq_mdeq(&bus->txq, tx_prec_map, &prec_out)) == NULL) {
            dhd_os_sdunlock_txq(bus->dhd);
            break;
        }

        trace_sepext_pktqueue(((struct sk_buff *) pkt)->data,
         PKTQ_BCM4329_TXQ, 0, QUEUE_DEQUEUE);

        dhd_os_sdunlock_txq(bus->dhd);
        datalen = PKTLEN(bus->dhd->osh, pkt) - SDPCM_HDRLEN;
```


Software

```
#ifndef SDTEST
        ret = dhdsdio_txpkt(bus, pkt, SDPCM_DATA_CHANNEL, TRUE);
#else
        ret = dhdsdio_txpkt(bus, pkt,
            (bus->ext_loop ? SDPCM_TEST_CHANNEL : SDPCM_DATA_CHANNEL),
TRUE);


        if (ret)
            bus->dhd->tx_errors++;
        else
            bus->dhd->dstats.tx_bytes += datalen;

        /* In poll mode, need to check for other events */
        if (!bus->intr && cnt)
        {
            /* Check device status, signal pending interrupt */
            R_SDREG(intstatus, &regs->intstatus, retries);
            bus->f2txdata++;
            if (bcmsdh_regfail(bus->sdh)) {
             break;
            }
            if (intstatus & bus->hostintmask)
                bus->ipend = TRUE;
        }
    }
         trace_sepext_loopstop();

    /* Deflow-control stack if needed */
    if (dhd_doflow && dhd->up && (dhd->busstate == DHD_BUS_DATA) &&
      dhd->txoff && (pktq_len(&bus->txq) < FCLOW))
        dhd_txflowcontrol(dhd, 0, OFF);

         return cnt;
     }
```

Google Nexus One: Instrumentation



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Parallel execution (DMA, …):
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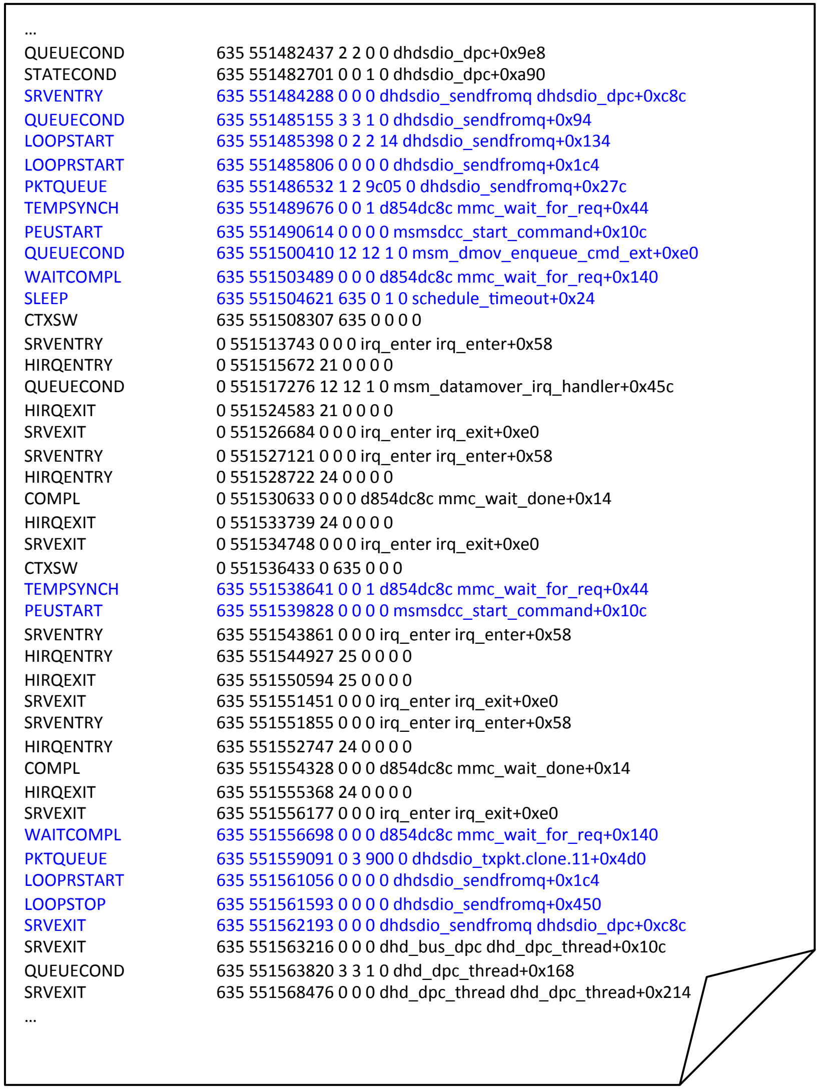
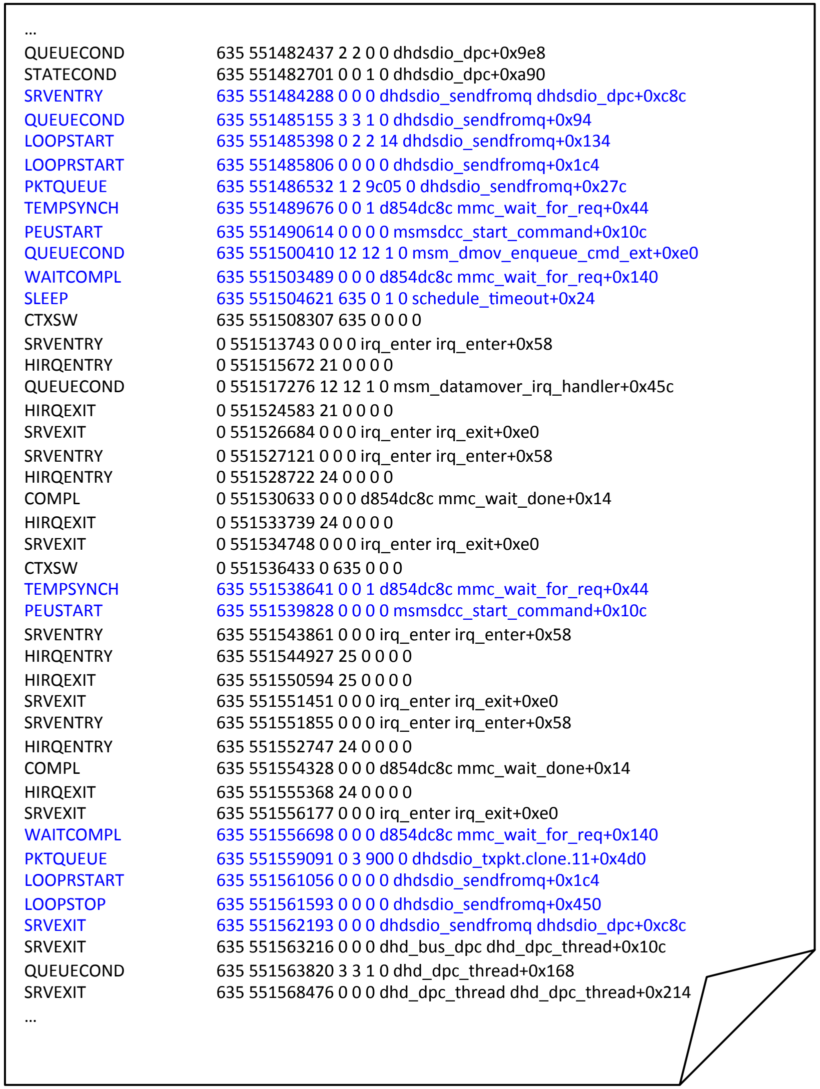
Resulting Trace File

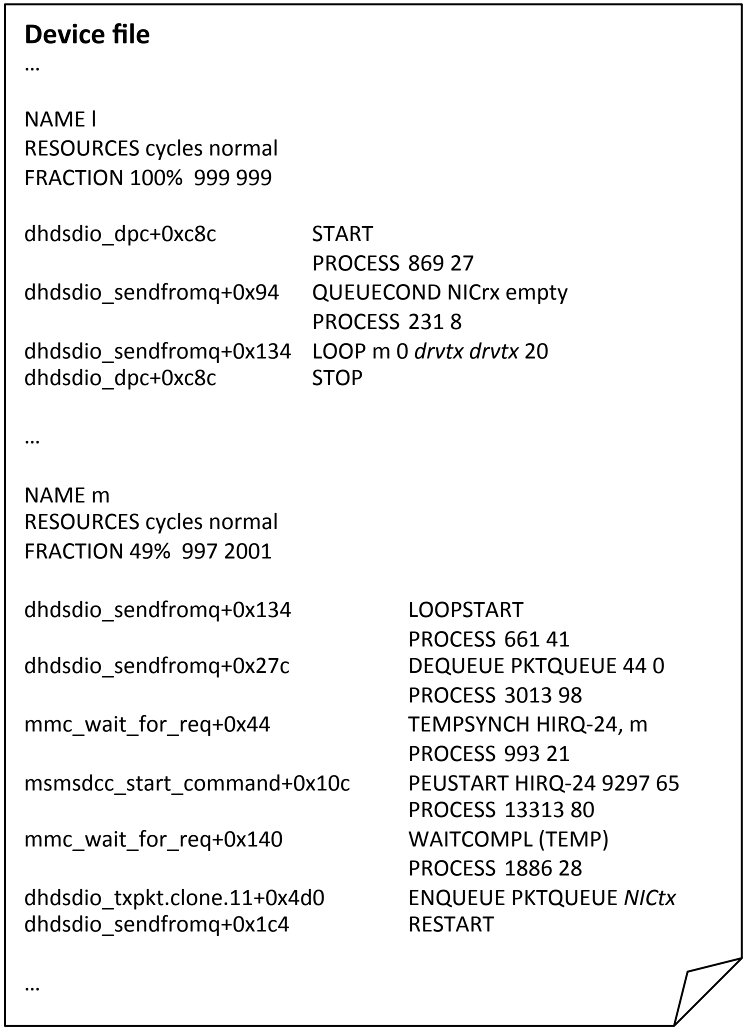


```
…
QUEUECOND        635 551482437 2 2 0 0 dhdsdio_dpc+0x9e8
STATECOND        635 551482701 0 0 1 0 dhdsdio_dpc+0xa90
SRVENTRY         635 551484288 0 0 0 dhdsdio_sendfromq dhdsdio_dpc+0xc8c
QUEUECOND        635 551485155 3 3 1 0 dhdsdio_sendfromq+0x94
LOOPSTART        635 551485398 0 2 2 14 dhdsdio_sendfromq+0x134
LOOPRSTART       635 551485806 0 0 0 0 dhdsdio_sendfromq+0x1c4
PKTQUEUE         635 551486532 1 2 9c05 0 dhdsdio_sendfromq+0x27c
TEMPSYNCH        635 551489676 0 0 1 d854dc8c mmc_wait_for_req+0x44
PEUSTART         635 551490614 0 0 0 0 msmsdcc_start_command+0x10c
QUEUECOND        635 551500410 12 12 1 0 msm_dmov_enqueue_cmd_ext+0xe0
WAITCOMPL        635 551503489 0 0 0 d854dc8c mmc_wait_for_req+0x140
SLEEP            635 551504621 635 0 1 0 schedule_timeout+0x24
CTXSW            635 551508307 635 0 0 0 0
SRVENTRY         0 551513743 0 0 0 irq_enter irq_enter+0x58
HIRQENTRY        0 551515672 21 0 0 0 0
QUEUECOND        0 551517276 12 12 1 0 msm_datamover_irq_handler+0x45c
HIRQEXIT         0 551524583 21 0 0 0 0
SRVEXIT          0 551526684 0 0 0 irq_enter irq_exit+0xe0
SRVENTRY         0 551527121 0 0 0 irq_enter irq_enter+0x58
HIRQENTRY        0 551528722 24 0 0 0 0
COMPL            0 551530633 0 0 0 d854dc8c mmc_wait_done+0x14
HIRQEXIT         0 551533739 24 0 0 0 0
SRVEXIT          0 551534748 0 0 0 irq_enter irq_exit+0xe0
CTXSW            0 551536433 0 635 0 0 0
TEMPSYNCH        635 551538641 0 0 1 d854dc8c mmc_wait_for_req+0x44
PEUSTART         635 551539828 0 0 0 0 msmsdcc_start_command+0x10c
SRVENTRY         635 551543861 0 0 0 irq_enter irq_enter+0x58
HIRQENTRY        635 551544927 25 0 0 0 0
HIRQEXIT         635 551550594 25 0 0 0 0
SRVEXIT          635 551551451 0 0 0 irq_enter irq_exit+0xe0
SRVENTRY         635 551551855 0 0 0 irq_enter irq_enter+0x58
HIRQENTRY        635 551552747 24 0 0 0 0
COMPL            635 551554328 0 0 0 d854dc8c mmc_wait_done+0x14
HIRQEXIT         635 551555368 24 0 0 0 0
SRVEXIT          635 551556177 0 0 0 irq_enter irq_exit+0xe0
WAITCOMPL        635 551556698 0 0 0 d854dc8c mmc_wait_for_req+0x140
PKTQUEUE         635 551559091 0 3 900 0 dhdsdio_txpkt.clone.11+0x4d0
LOOPRSTART       635 551561056 0 0 0 0 dhdsdio_sendfromq+0x1c4
LOOPSTOP         635 551561593 0 0 0 0 dhdsdio_sendfromq+0x450
SRVEXIT          635 551562193 0 0 0 dhdsdio_sendfromq dhdsdio_dpc+0xc8c
SRVEXIT          635 551563216 0 0 0 dhd_bus_dpc dhd_dpc_thread+0x10c
QUEUECOND        635 551563820 3 3 1 0 dhd_dpc_thread+0x168
SRVEXIT          635 551568476 0 0 0 dhd_dpc_thread dhd_dpc_thread+0x214
…
```

Resulting Reduction



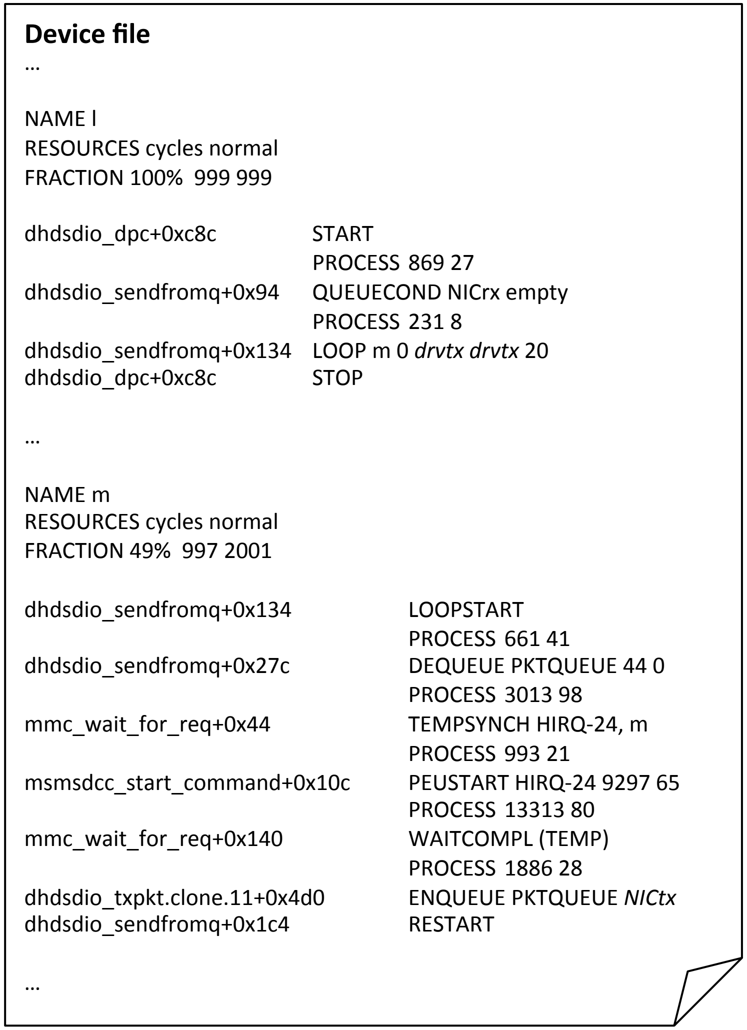
```
…
QUEUECOND      635 551482437 2 2 0 0 dhdsdio_dpc+0x9e8
STATECOND      635 551482701 0 0 1 0 dhdsdio_dpc+0xa90
SRVENTRY       635 551484288 0 0 0 dhdsdio_sendfromq dhdsdio_dpc+0xc8c
QUEUECOND      635 551485155 3 3 1 0 dhdsdio_sendfromq+0x94
LOOPSTART      635 551485398 0 2 2 14 dhdsdio_sendfromq+0x134
LOOPRSTART     635 551485806 0 0 0 0 dhdsdio_sendfromq+0x1c4
PKTQUEUE       635 551486532 1 2 9c05 0 dhdsdio_sendfromq+0x27c
TEMPSYNCH      635 551489676 0 0 1 d854dc8c mmc_wait_for_req+0x44
PEUSTART       635 551490614 0 0 0 0 msmsdcc_start_command+0x10c
QUEUECOND      635 551500410 12 12 1 0 msm_dmov_enqueue_cmd_ext+0xe0
WAITCOMPL      635 551503489 0 0 0 d854dc8c mmc_wait_for_req+0x140
SLEEP          635 551504621 635 0 1 0 schedule_timeout+0x24
CTXSW          635 551508307 635 0 0 0 0
SRVENTRY       0 551513743 0 0 0 irq_enter irq_enter+0x58
HIRQENTRY      0 551515672 21 0 0 0 0
QUEUECOND      0 551517276 12 12 1 0 msm_datamover_irq_handler+0x45c
HIRQEXIT       0 551524583 21 0 0 0 0
SRVEXIT        0 551526684 0 0 0 irq_enter irq_exit+0xe0
SRVENTRY       0 551527121 0 0 0 irq_enter irq_enter+0x58
HIRQENTRY      0 551528722 24 0 0 0 0
COMPL          0 551530633 0 0 0 d854dc8c mmc_wait_done+0x14
HIRQEXIT       0 551533739 24 0 0 0 0
SRVEXIT        0 551534748 0 0 0 irq_enter irq_exit+0xe0
CTXSW          0 551536433 0 635 0 0 0
TEMPSYNCH      635 551538641 0 0 1 d854dc8c mmc_wait_for_req+0x44
PEUSTART       635 551539828 0 0 0 0 msmsdcc_start_command+0x10c
SRVENTRY       635 551543861 0 0 0 irq_enter irq_enter+0x58
HIRQENTRY      635 551544927 25 0 0 0 0
HIRQEXIT       635 551550594 25 0 0 0 0
SRVEXIT        635 551551451 0 0 0 irq_enter irq_exit+0xe0
SRVENTRY       635 551551855 0 0 0 irq_enter irq_enter+0x58
HIRQENTRY      635 551552747 24 0 0 0 0
COMPL          635 551554328 0 0 0 d854dc8c mmc_wait_done+0x14
HIRQEXIT       635 551555368 24 0 0 0 0
SRVEXIT        635 551556177 0 0 0 irq_enter irq_exit+0xe0
WAITCOMPL      635 551556698 0 0 0 d854dc8c mmc_wait_for_req+0x140
PKTQUEUE       635 551559091 0 3 900 0 dhdsdio_txpkt.clone.11+0x4d0
LOOPRSTART     635 551561056 0 0 0 0 dhdsdio_sendfromq+0x1c4
LOOPSTOP       635 551561593 0 0 0 0 dhdsdio_sendfromq+0x450
SRVEXIT        635 551562193 0 0 0 dhdsdio_sendfromq dhdsdio_dpc+0xc8c
SRVEXIT        635 551563216 0 0 0 dhd_bus_dpc dhd_dpc_thread+0x10c
QUEUECOND      635 551563820 3 3 1 0 dhd_dpc_thread+0x168
SRVEXIT        635 551568476 0 0 0 dhd_dpc_thread dhd_dpc_thread+0x214
…
```



Device file

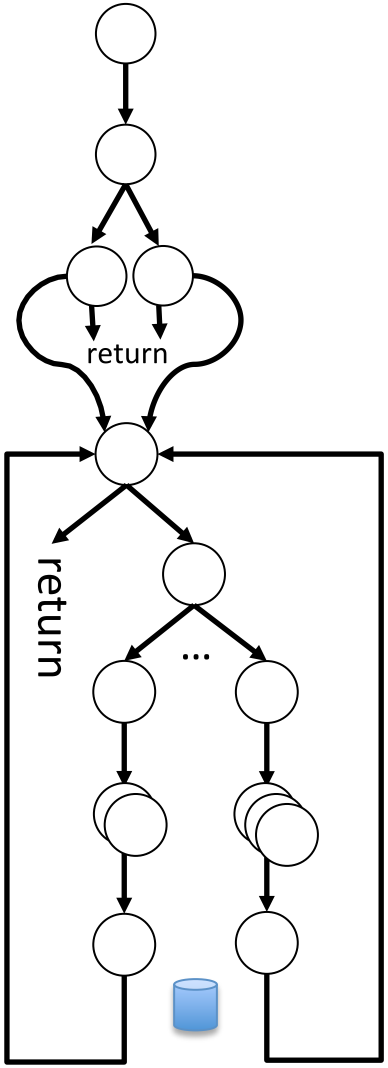
```
…

NAME l
RESOURCES cycles normal
FRACTION 100%  999 999

dhdsdio_dpc+0xc8c            START
                             PROCESS 869 27
dhdsdio_sendfromq+0x94       QUEUECOND NICrx empty
                             PROCESS 231 8
dhdsdio_sendfromq+0x134      LOOP m 0 drvtx drvtx 20
dhdsdio_dpc+0xc8c            STOP

…

NAME m
RESOURCES cycles normal
FRACTION 49%  997 2001

dhdsdio_sendfromq+0x134          LOOPSTART
                                 PROCESS 661 41
dhdsdio_sendfromq+0x27c          DEQUEUE PKTQUEUE 44 0
                                 PROCESS 3013 98
mmc_wait_for_req+0x44            TEMPSYNCH HIRQ-24, m
                                 PROCESS 993 21
msmsdcc_start_command+0x10c      PEUSTART HIRQ-24 9297 65
                                 PROCESS 13313 80
mmc_wait_for_req+0x140           WAITCOMPL (TEMP)
                                 PROCESS 1886 28
dhdsdio_txpkt.clone.11+0x4d0     ENQUEUE PKTQUEUE NICtx
dhdsdio_sendfromq+0x1c4          RESTART

…
```

Resulting Execution Model



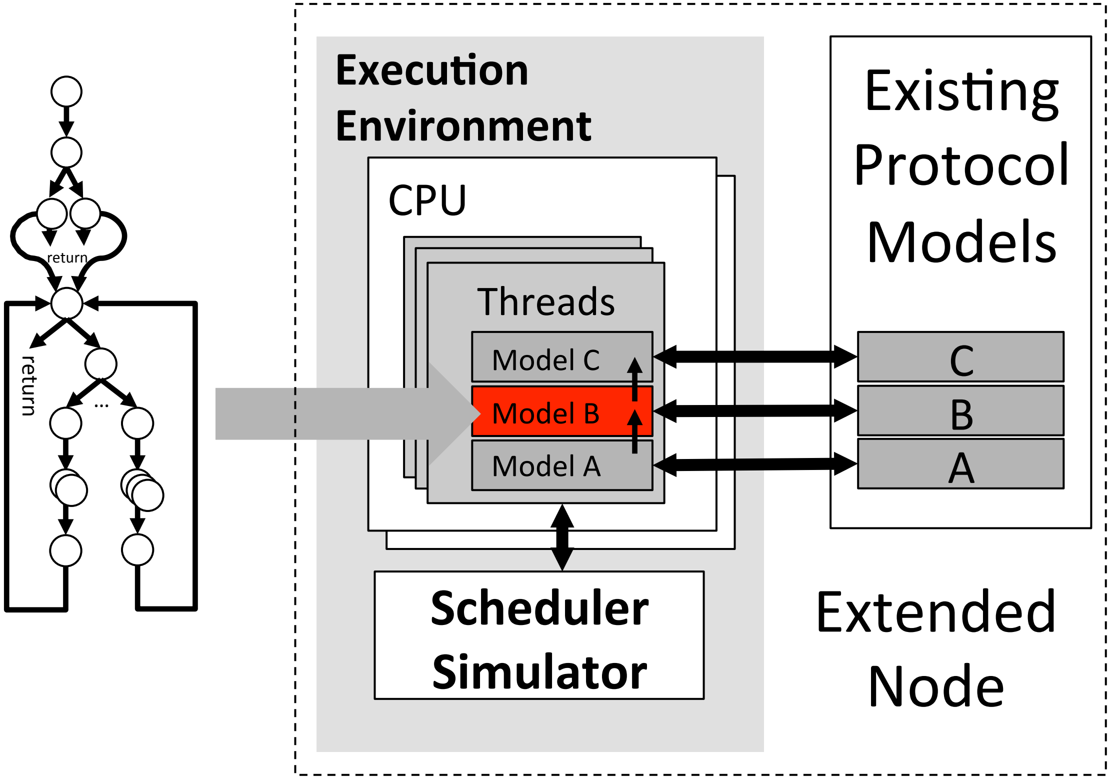
Device file

```
…

NAME l
RESOURCES cycles normal
FRACTION 100%  999 999

dhdsdio_dpc+0xc8c            START
                             PROCESS 869 27
dhdsdio_sendfromq+0x94       QUEUECOND NICrx empty
                             PROCESS 231 8
dhdsdio_sendfromq+0x134      LOOP m 0 drvtx drvtx 20
dhdsdio_dpc+0xc8c            STOP

…

NAME m
RESOURCES cycles normal
FRACTION 49%  997 2001

dhdsdio_sendfromq+0x134               LOOPSTART
                                      PROCESS 661 41
dhdsdio_sendfromq+0x27c               DEQUEUE PKTQUEUE 44 0
                                      PROCESS 3013 98
mmc_wait_for_req+0x44                 TEMPSYNCH HIRQ-24, m
                                      PROCESS 993 21
msmsdcc_start_command+0x10c           PEUSTART HIRQ-24 9297 65
                                      PROCESS 13313 80
mmc_wait_for_req+0x140                WAITCOMPL (TEMP)
                                      PROCESS 1886 28
dhdsdio_txpkt.clone.11+0x4d0          ENQUEUE PKTQUEUE NICtx
dhdsdio_sendfromq+0x1c4               RESTART

…
```

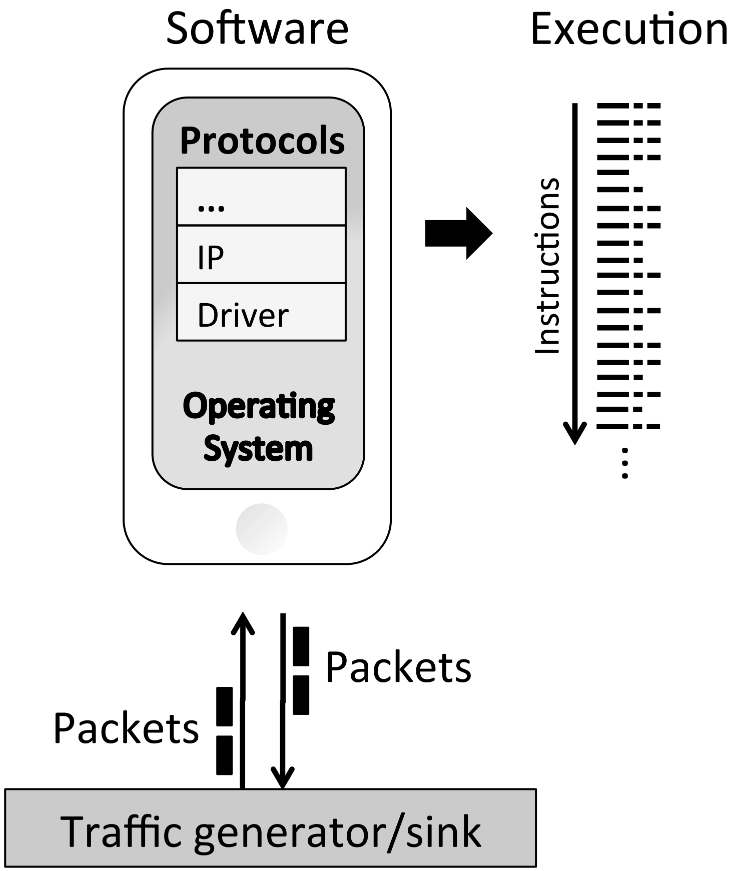


Extension of Simulator

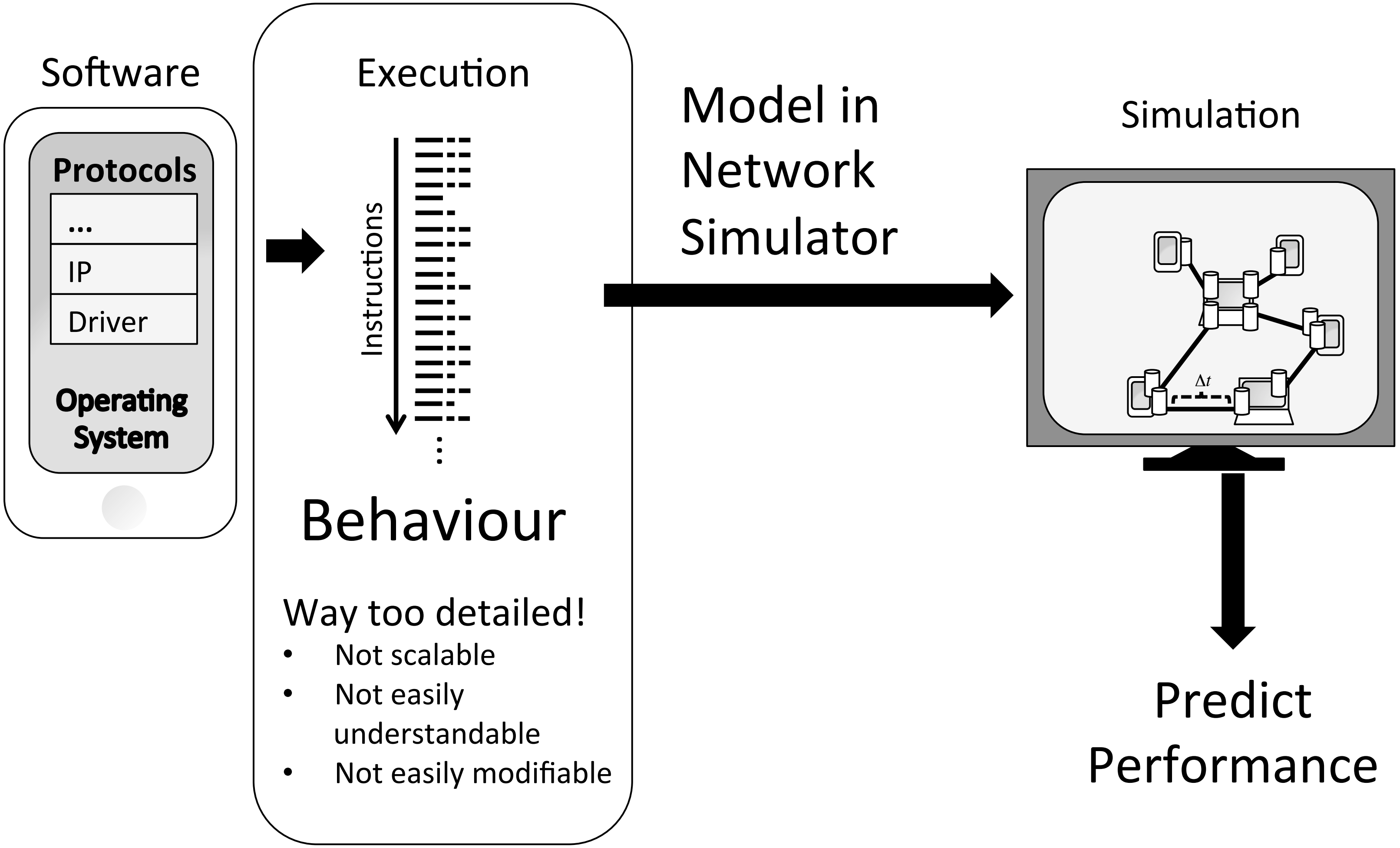
- Simulation:
  - Execute models in threads and interrupts
  - Uses scheduler simulator
  - Synchronize with existing protocol models



5-Step Approach



Core Idea



Software

Protocols

...

IP

Driver

Operating System

Execution

Instructions

Behaviour

Way too detailed!

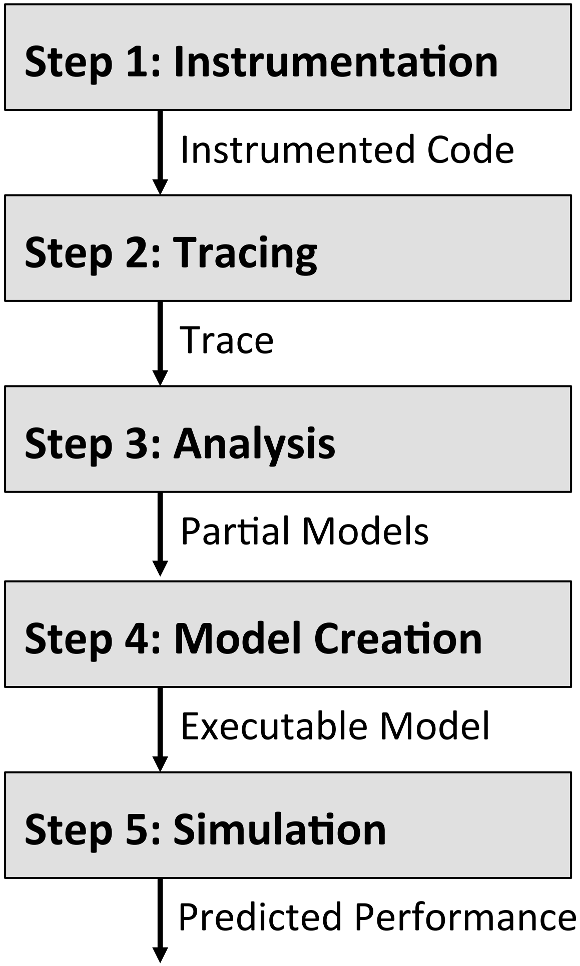
- Not scalable
- Not easily understandable
- Not easily modifiable

Model in Network Simulator

Simulation

Predict Performance

5-Step Appraoch to Simplify Models



Step 1: Instrumentation

Instrumented Code

Step 2: Tracing

Trace

Step 3: Analysis

Partial Models

Step 4: Model Creation

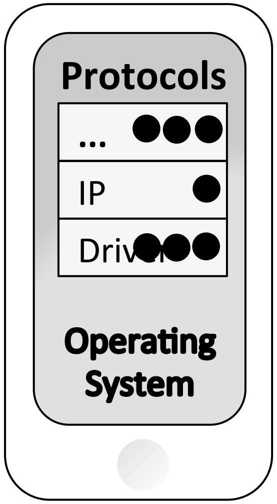
Executable Model

Step 5: Simulation

Predicted Performance

Step 1: Instrumentation

Software



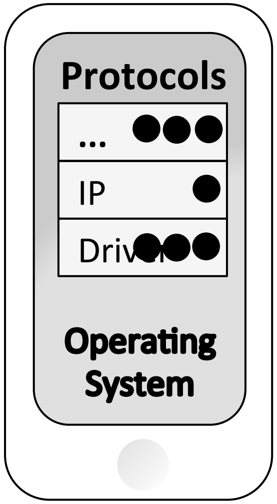
Instrumentation

Capture important events:

- Queuing
- Synchronization
- Loops
- Interactions with HW
- …

Step 1: Instrumentation

Software



Instrumentation

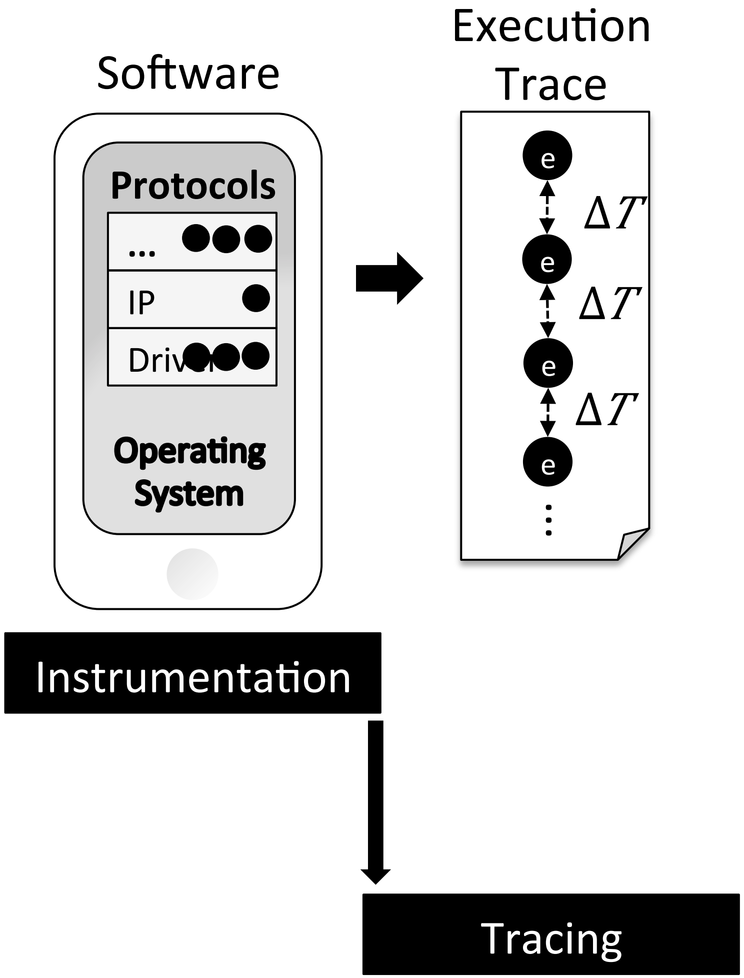
Capture important events:

- Queuing
- Synchronization
- Loops
- Interactions with HW
- …

Example:

```
…
pkt = pktq_mdeq(&bus->txq, tx_prec_map, &prec_out);



…
```

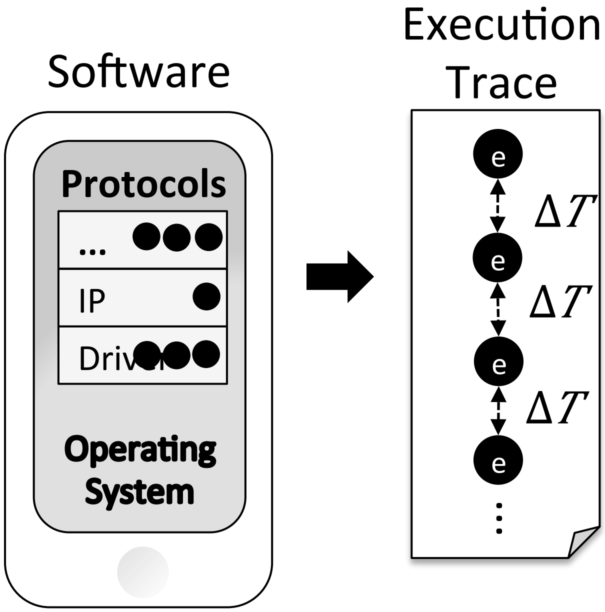
Step 2: Trace



Instrumentation

Tracing

Step 2: Trace



Example:

```
...
PKTQUEUE                ... 551486532 ...
SYNCH                   ... 551489676 ...
...
```

$\Delta T =$

551489676

$-$

551486532

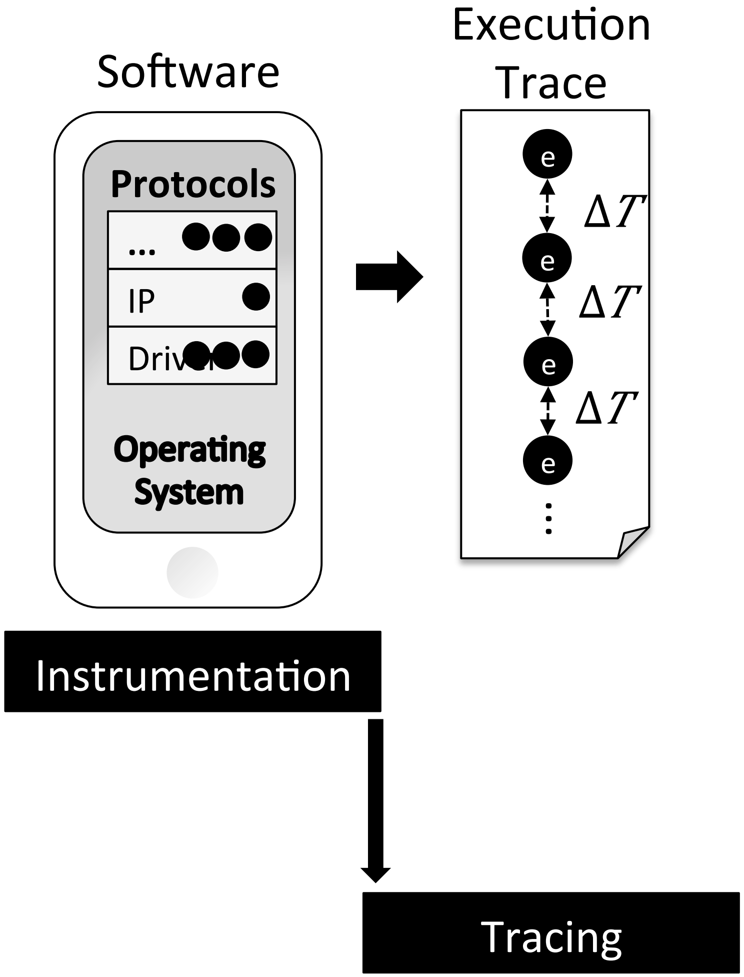
$=$

3144

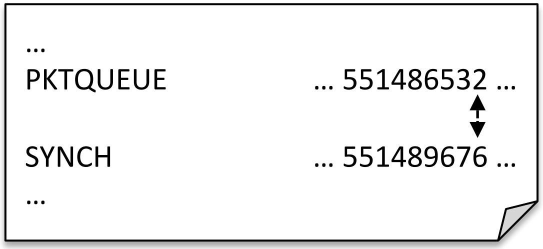
Instrumentation

Tracing

Step 2: Trace



Example:



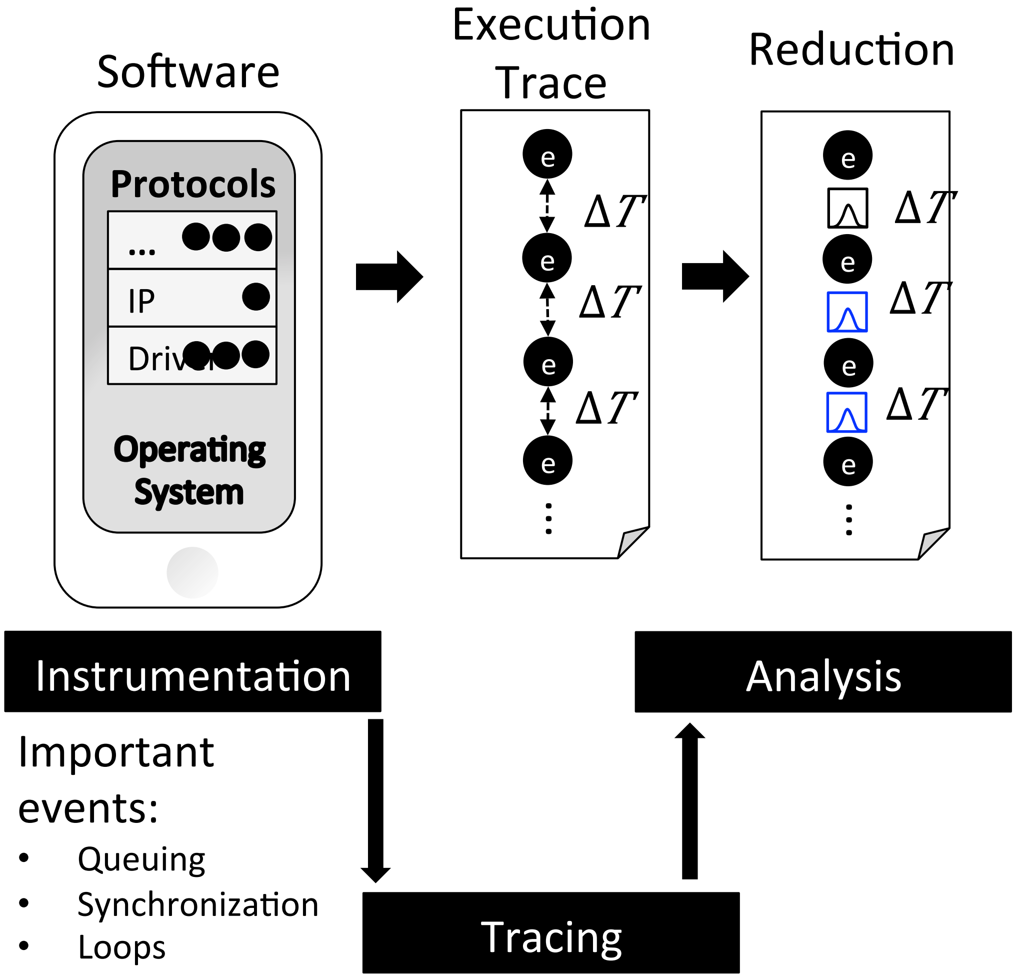
```
...
PKTQUEUE                 ... 551486532 ...

SYNCH                    ... 551489676 ...
...
```

ΔT=
551489676
–
551486532
=
3144

Small variations in consumed cycles

- Non-deterministic effects, e.g., memory caching

Step 3: Analyse



Example:

```
…
DEQUEUE PKTQUEUE …
PROCESS 3013 98
SYNCH …
PROCESS 993 21
…
```

Important events:

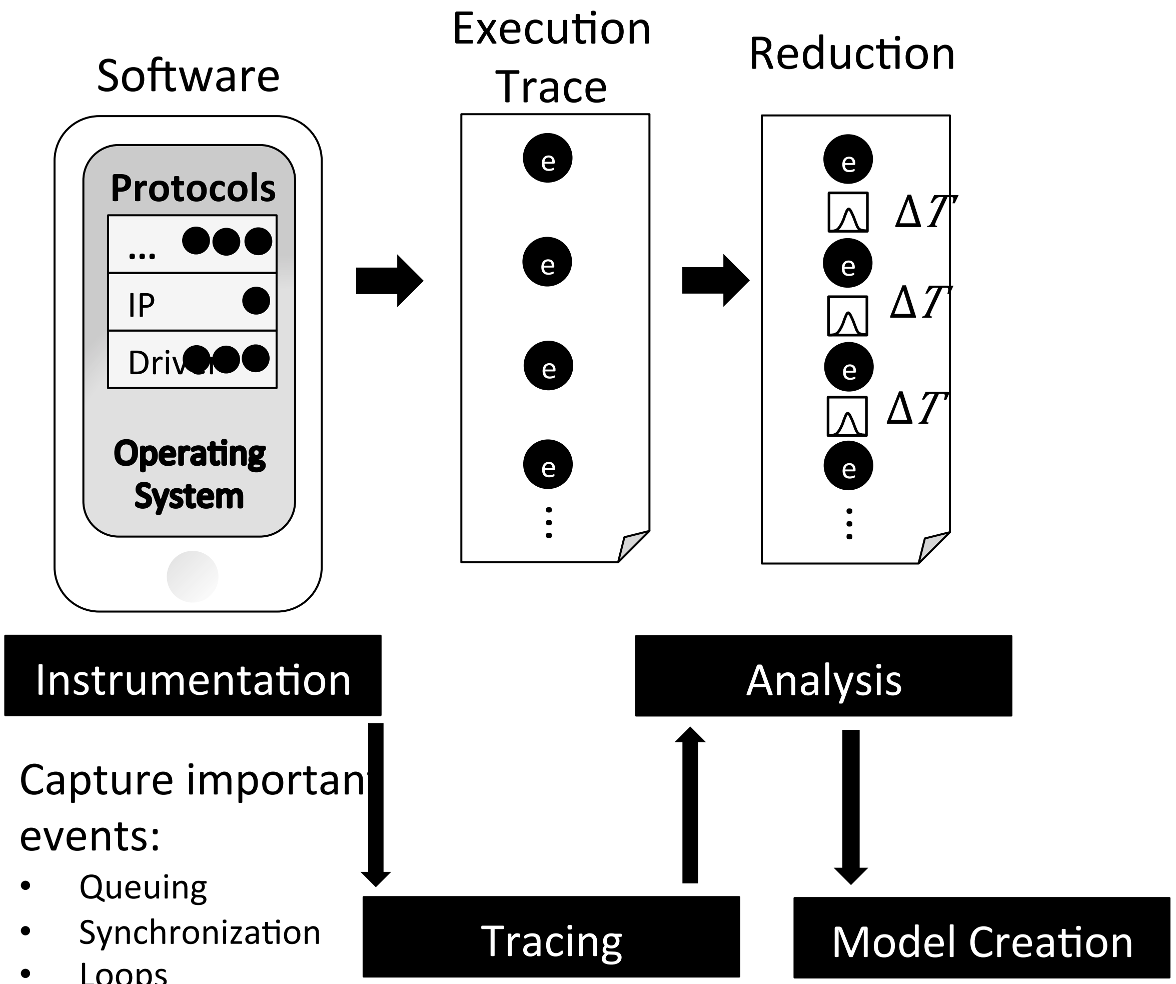
- Queuing
- Synchronization
- Loops
- Interactions with HW
- **Impact of Context**

Small variations in consumed cycles

- Non-deterministic effects, e.g., memory caching

Collect many traces and calculate statistics

Step 3: Analyse



Capture important events:

- Queuing
- Synchronization
- Loops
- Interactions with HW
- Impact of context

Example:

```
void fetchFromNIC(Packet *pkt)
{
  trace_semext_pktchar(*pkt);
  if(size(pkt) > 500) {
    DMATranferNIC(pkt);
    condition_wait(dma);
  }
  else {
    DMATranferNIC (pkt);
    while(!dma_done) {};
  }
}
```

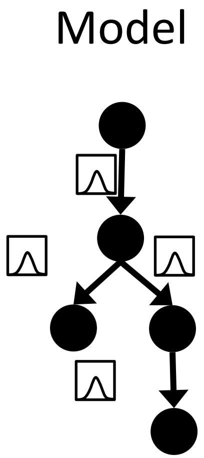
Behaviour affected by execution context,e.g.,:

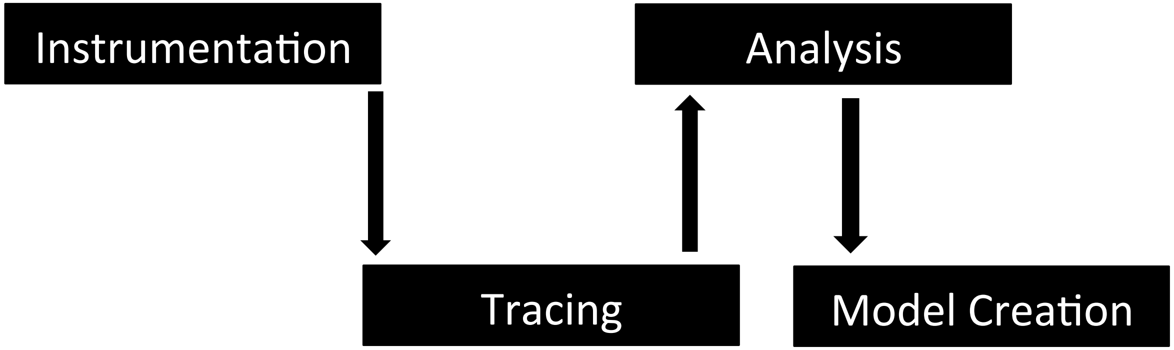
- Packet size, type, …
- Routing table size, …
- Bus state, …

Capture events for when and how behaviour changes

Step 4: Create Models

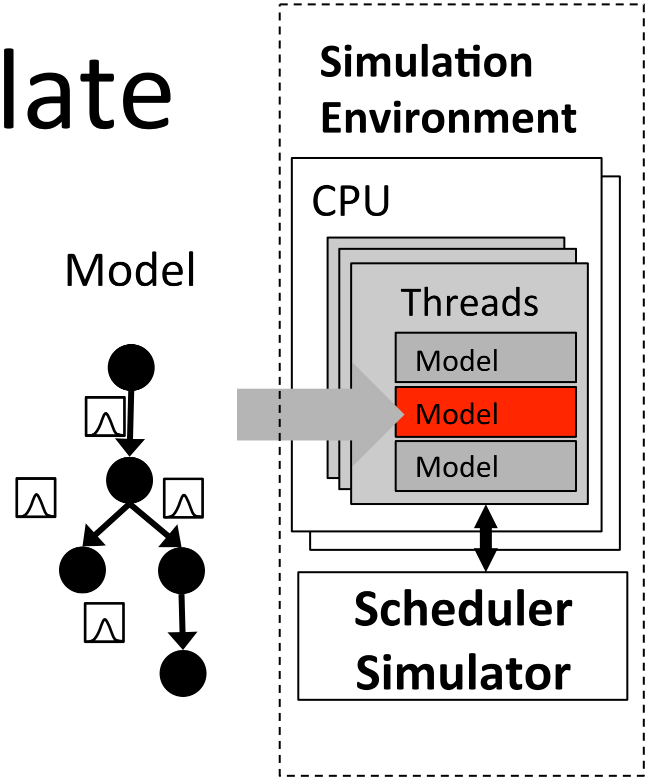
- Overall performance affected by multi-threading
  - Workload
  - Scheduling policy
  - Synchronization





Step 5: Simulate

- Overall performance affected by mutli-threading
  - Workload
  - Scheduling policy
  - Synchronization
- Simulation:
  - Execute models in threads and interrupts
  - Uses scheduler simulator



Model

Simulation Environment

CPU

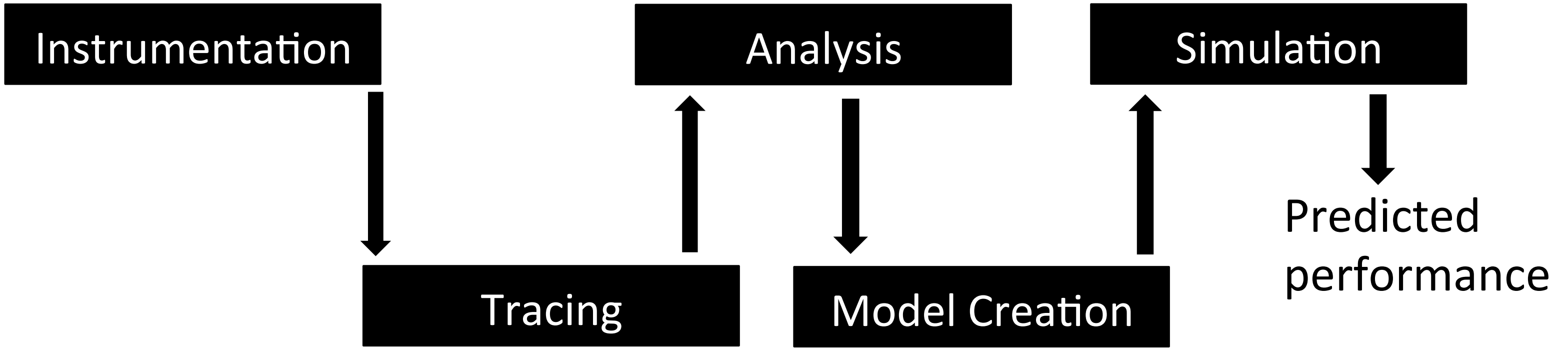
Threads

Model

Model

Model

Scheduler Simulator



Instrumentation

Tracing

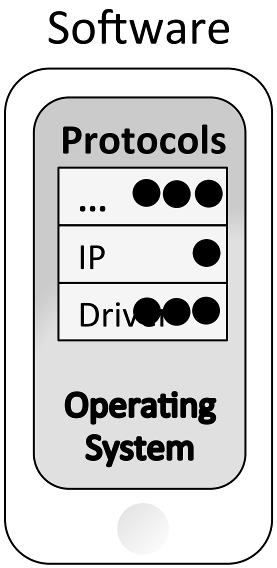
Analysis

Model Creation

Simulation

Predicted performance

Instrumentation



Instrumentation

Capture important events:

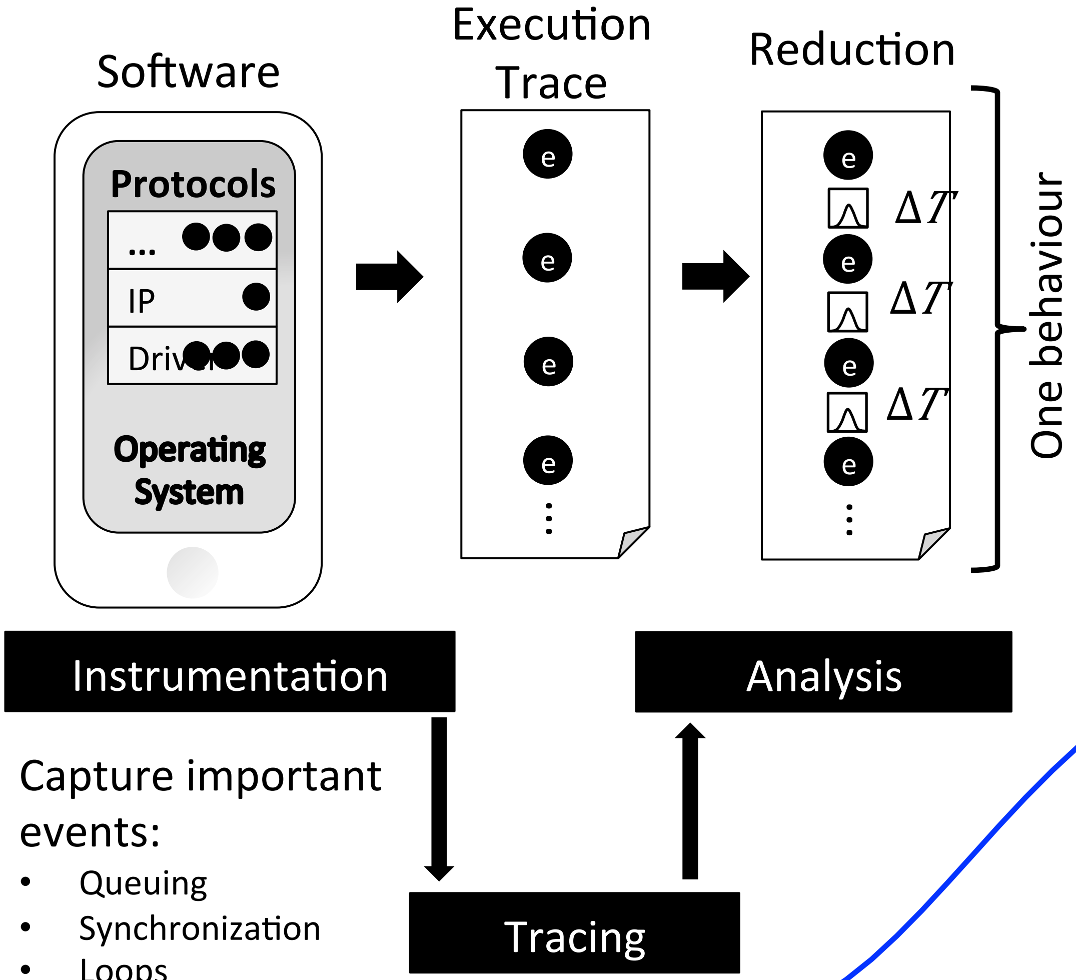
- Queuing
- Synchronization
- Loops
- Interactions with HW
- …

Example:

```
…
pkt = pktq_mdeq(&bus->txq, tx_prec_map, &prec_out);

trace(pkt, DRIVER_TXQ, QUEUE_DEQUEUE);
…
```

Store event in tracefile

Capturing Change in Behaviour



Capture important events:

- Queuing
- Synchronization
- Loops
- Interactions with HW
- **Impact of Context**

Behaviour affected by input data,e.g.,:

- Packet size, type, …
- Routing table size, …
- Bus state, …

= Many behaviours!

Example:

```
void fetchFromNIC(Packet *pkt)
{
  trace(size(pkt));
  if(size(pkt) > 500) {
    DMATranferNIC(pkt);
    condition_wait(dma);
  }
  else {
    DMATranferNIC (pkt);
    while(!dma_done) {};
  }
}
```