Pin: Intel's Dynamic Binary Instrumentation Engine

Pin Tutorial

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Which one of these people is the Pin Performance Guru?

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Agenda

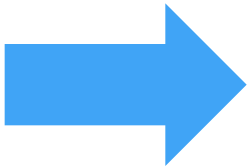
- Part 1: Introduction to Pin
- Part 2: Topics in Pin API
- Part 3: Advanced Pin
- Part 4: Performance – Optimizing your Pin tool

Part 1
Introduction to Pin

Instrumentation in a nutshell

- A technique that inserts code into a program to collect run-time information

```
movzx   ecx, [rax+0x2]
call    0x77ef7870
cmp     rax, rdx
jz      0x77f1eac9
```



```
 ..some code
 ..some code
movzx   ecx, [rax+0x2]
 ..some code
 ..some code
call    0x77ef7870
 ..some code
 ..some code
cmp     rax, rdx
 ..some code
 ..some code
jz      0x77f1eac9
```

Instrumentation types

- Different usages
  - Program analysis : performance profiling, error detection, capture & replay
  - Architectural study : processor and cache simulation, trace collection
  - Binary translation : Modify program behavior, emulate unsupported instructions
- Different types
  - Source code instrumentation
  - Static binary instrumentation
  - Dynamic binary instrumentation

Dynamic binary instrumentation

- Instrument binary code right before it runs
  - a.k.a. Just in time, or JIT

- Benefits
  - No need to recompile or re-link
  - Discover code at runtime
  - Handle dynamically generated code
  - Attach to running processes

Pin

- Dynamic binary instrumentation framework
- Developed at Intel

- What does "Pin" stand for?
  - **P**in **I**s **N**ot an acronym
  - Pin is based on the IPF post link optimizer iSpike
  - Pin is a small Spike
    - Spike is EOL
      http://www.cgo.org/cgo2004/papers/01_82_luk_ck.pdf

Advantages of Pin Instrumentation

- **Programmable Instrumentation:**
  - Write your own instrumentation tools, **called PinTools**
    - PinTools can be written in C, C++, assembly
  - APIs are designed to maximize ease of use
    - abstract away the underlying instruction set idiosyncrasies
- **Multiplatform:**
  - OS's: Windows, Linux, OSX, Android
  - Architectures: IA-32, Intel64, Intel® Xeon Phi™
- **Robust:**
  - Instruments real-life applications: Database, web browsers, …
  - Instruments multithreaded applications
  - Supports signals and exceptions, self modifying code…
- **Efficient:**
  - Applies compiler optimizations on instrumentation code

Pin can be used to instrument all the user level code in an application

PinTool Capabilities

- Replace application functions with your own
  - Call the original function from within your function
- Fully examine any application instruction, insert a call to your instrumenting function to be executed whenever that instruction executes
  - Pass parameters to your instrumenting function from a large set of supported parameters
    - Register values (including IP), also by reference (for modification)
    - Memory addresses read/written by the instruction
    - Full registers context
    - …
- Track function calls, including syscalls
  - Examine/change arguments
- Track application threads
- Intercept signals
- Instrument a process tree
- Many other capabilities…

Usage of Pin at Intel

- Profiling and analysis products
  - Intel® Parallel Studio XE
    - Intel® VTune™ Amplifier XE (performance analysis)
      - Locks and waits analysis
      - Concurrency analysis
    - Intel® Inspector XE (correctness analysis)
      - Threading error detection (data race and deadlock)
      - Memory error detection

- Architectural research and enabling
  - Emulating new instructions (Intel SDE)
  - Trace generation
  - Branch prediction and cache modeling

- Others
  - PinPlay, PinPoints.

Pin Usage Outside Intel

- **Popular and well supported**
  - 30,000+ downloads, 700+ citations
- **Free Download**
  - **www.pintool.org**
  - **Includes: D ode for 100s of Pin tools**
- **Pin User Gr**
  - **http://tec nheads/**
  - **Pin users a stions**
- **One user s**

Example Pin invocation

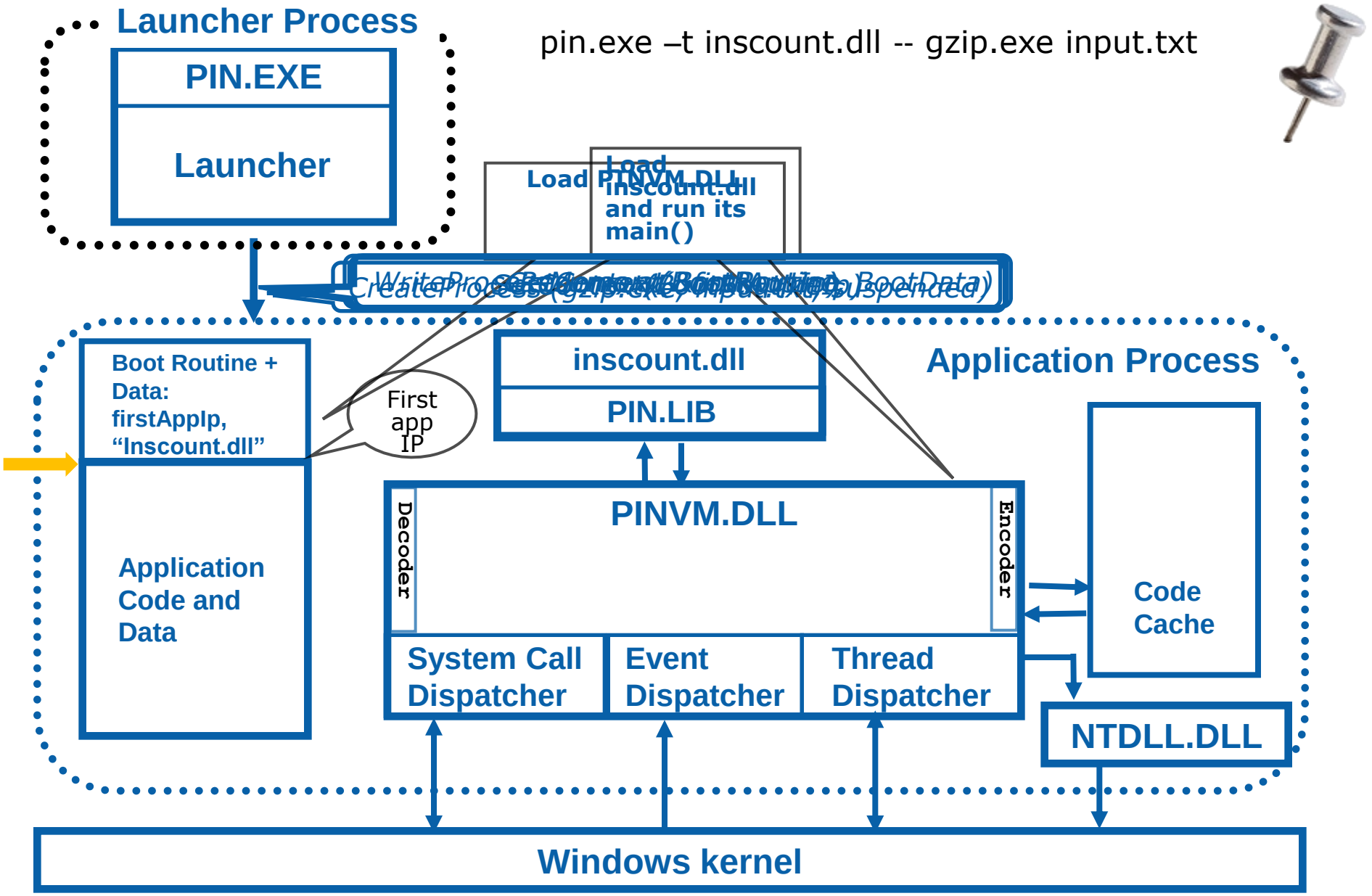
- Application:

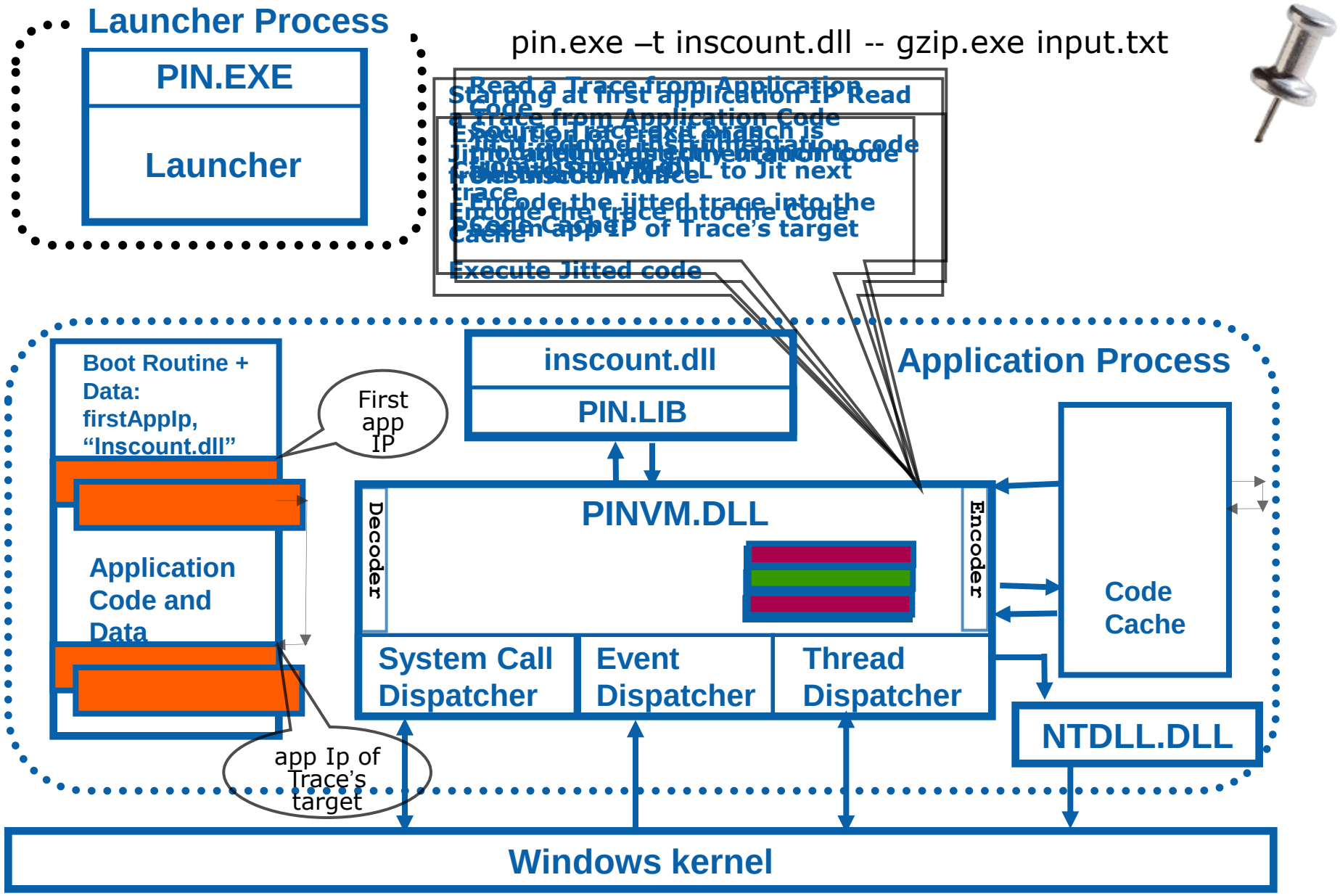
```
gzip.exe input.txt
```

- PinTool: inscount.dll
  - Count application instructions executed, print count at end

- Invocation:

```
> pin.exe -t inscount.dll -- gzip.exe input.txt
```





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Instruction Counting Tool (inscount.dll)

```
#include "pin.h"

UINT64 icount = 0;

void docount() { icount++; }

void Instruction(INS ins, void *v)
{
    INS_InsertCall(ins, IPOINT_BEFORE,
                   (AFUNPTR)docount, IARG_END);
}

void Fini(INT32 code, void *v)
{ std::cerr << "Count " << icount << endl; }

int main(int argc, char * argv[])
    PIN_Init(argc, argv);
    INS_AddInstrumentFunction(Instruction, 0);
    PIN_AddFiniFunction(Fini, 0);
    PIN_StartProgram();  // Never returns
    return 0;
}
```

Execution time routine

Jitting time routine: Pin CallBack

switch to pin stack
save registers
call docount
restore registers
switch to app stack

- `sub $0xff, %edx`

inc icount

- `cmp %esi, %edx`

save eflags
inc icount
restore eflags

- `jle <L1>`

inc icount

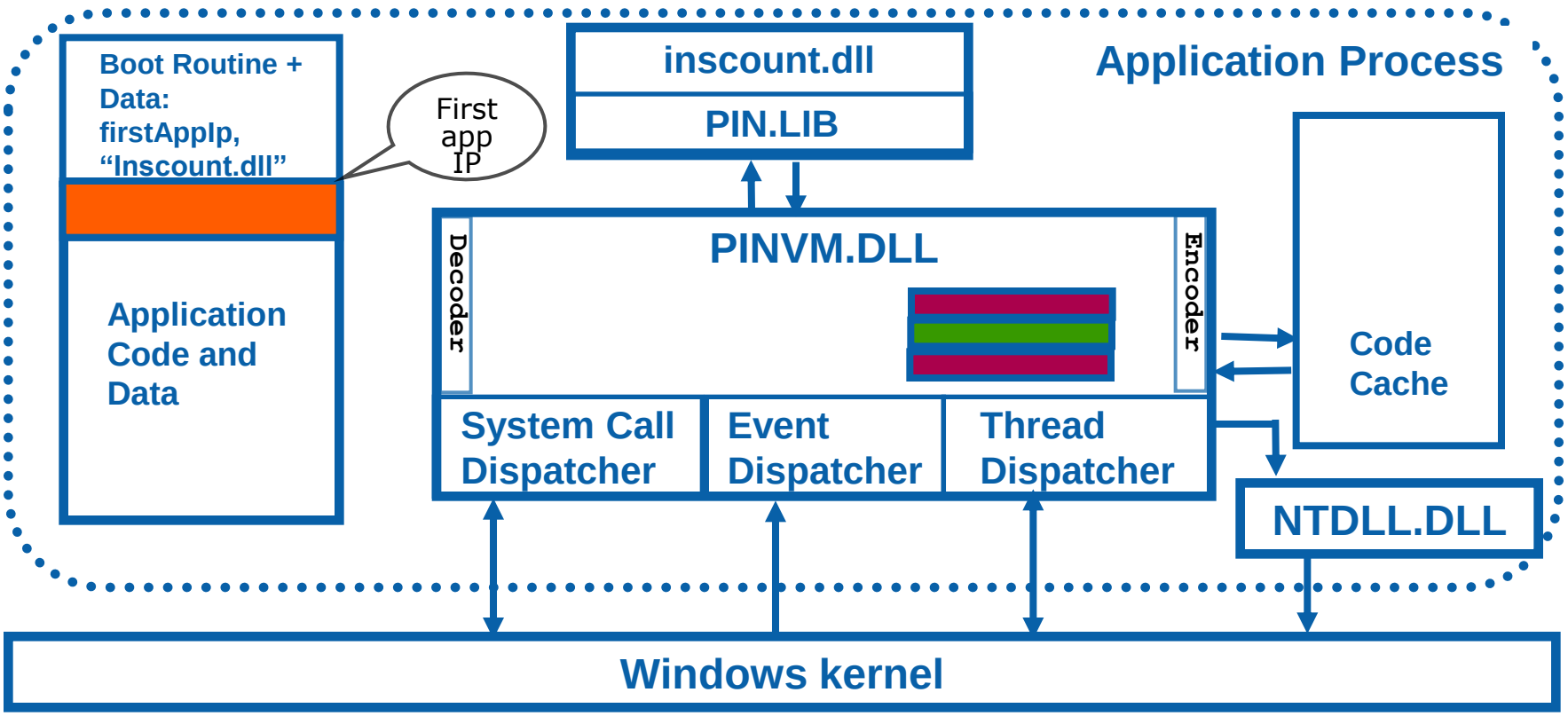
- `mov 0x1, %edi`

Instrumentation vs. Analysis

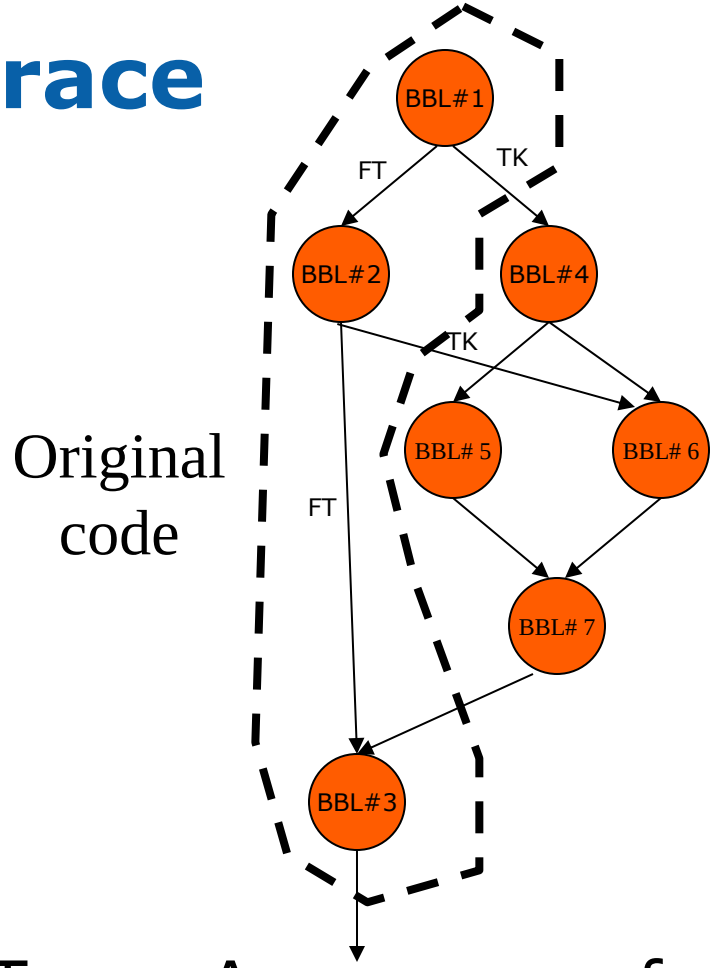
- Instrumentation routines define where instrumentation is inserted
  - e.g., before instruction
  - ☞ **Occurs *when* an instruction is being jitted**

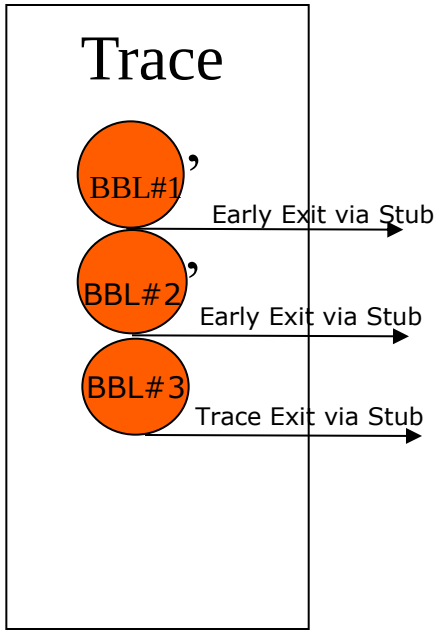
- Analysis routines define what to do when instrumentation is activated
  - e.g., increment counter
  - ☞ **Occurs *every time* an instruction is executed**

Instrumentation



Trace





- Trace: A sequence of continuous instructions, with one entry point
- BBL: has one entry point and ends at first control transfer instruction

ManualExamples/inscount2.cpp

```
#include "pin.H"

UINT64 icount = 0;

void PIN_FAST_ANALYSIS_CALL docount(INT32 c) { icount += c; }

void Trace(TRACE trace, void *v){// Pin Callback
  for(BBL bbl = TRACE_BblHead(trace);
      BBL_Valid(bbl);
      bbl = BBL_Next(bbl))
      BBL_InsertCall(bbl, IPOINT_ANYWHERE,
                     (AFUNPTR)docount, IARG_FAST_ANALYSIS_CALL,
                     IARG_UINT32, BBL_NumIns(bbl),
                     IARG_END);
}

void Fini(INT32 code, void *v) {// Pin Callback
  fprintf(stderr, "Count %lld\n", icount);
}

int main(int argc, char * argv[]) {
   PIN_Init(argc, argv);
   TRACE_AddInstrumentFunction(Trace, 0);
   PIN_AddFiniFunction(Fini, 0);
   PIN_StartProgram();
   return 0;
}
```

Multi-Threading

- Pin supports multi-threading
  - Application threads execute jitted code including instrumentation code (inlined and not inlined), without any serialization introduced by Pin
    - Instrumentation code can use Pin and/or OS synchronization constructs to introduce serialization if needed.
    - Pin provides APIs for thread local storage.
  - Pin callbacks are serialized
  - Jitting is serialized
    - Only one application thread can be jitting code at any time

SimpleExamples/inscount2_mt.cpp

```
#include "pin.H"
INT32 numThreads = 0;
const INT32 MaxNumThreads = 10000;
struct THREAD_DATA
{
    UINT64 _count;
    UINT8 _pad[56];  /* guess why? */  }icount[MaxNumThreads];
// Analysis routine
VOID PIN_FAST_ANALYSIS_CALL docount(ADDRINT c, THREADID tid) { icount[tid]._count += c;}
// Pin Callback
VOID ThreadStart(THREADID threadid, CONTEXT *ctxt, INT32 flags, VOID *v){numThreads++;}

VOID Trace(TRACE trace, VOID *v) { // Jitting time routine: Pin Callback
    for (BBL bbl = TRACE_BblHead(trace); BBL_Valid(bbl); bbl = BBL_Next(bbl))
        BBL_InsertCall(bbl, IPOINT_ANYWHERE, (AFUNPTR)docount, IARG_FAST_ANALYSIS_CALL,
                       IARG_UINT32, BBL_NumIns(bbl), IARG_THREAD_ID, IARG_END);   }

VOID Fini(INT32 code, VOID *v){// Pin Callback
    for (INT32 t=0; t<numThreads; t++)
        printf ("InsCount[of thread#%d]= %d\n",t,icount[t]._count);  }

int main(int argc, char * argv[])   {
    PIN_Init(argc, argv);
    for (INT32 t=0; t<MaxNumThreads; t++) {icount[t]._count = 0;}
    PIN_AddThreadStartFunction(ThreadStart, 0);
    TRACE_AddInstrumentFunction(Trace, 0);
    PIN_AddFiniFunction(Fini, 0);
    PIN_StartProgram(); return 0;   }
```

Why is there NO synchronization?

A couple more examples..

Memory Read Logger Tool

```
#include "pin.h"
#include <map>
std::map<ADDRINT, std::string> disAssemblyMap;
VOID ReadsMem (ADDRINT applicationIp,  ADDRINT memoryAddressRead,  UINT32 memoryReadSize)  {
    printf ("0x%x %s  reads %d bytes of memory at 0x%x\n",
            applicationIp, disAssemblyMap[applicationIp].c_str(),
            memoryReadSize, memoryAddressRead);}

VOID Instruction(INS ins, void * v)  {// Jitting time routine
    if (INS_IsMemoryRead(ins)) {
        disAssemblyMap[INS_Address(ins)] = INS_Disassemble(ins);
        INS_InsertCall(ins, IPOINT_BEFORE, (AFUNPTR) ReadsMem,
                       IARG_INST_PTR,// application IP
                       IARG_MEMORYREAD_EA,
                       IARG_ME     YREAD_SIZE,
                       IARG_E
    }
IARG_FUNCA

The value of AR                                                    ntation)

}
```

IARG_BRANCH_TAK

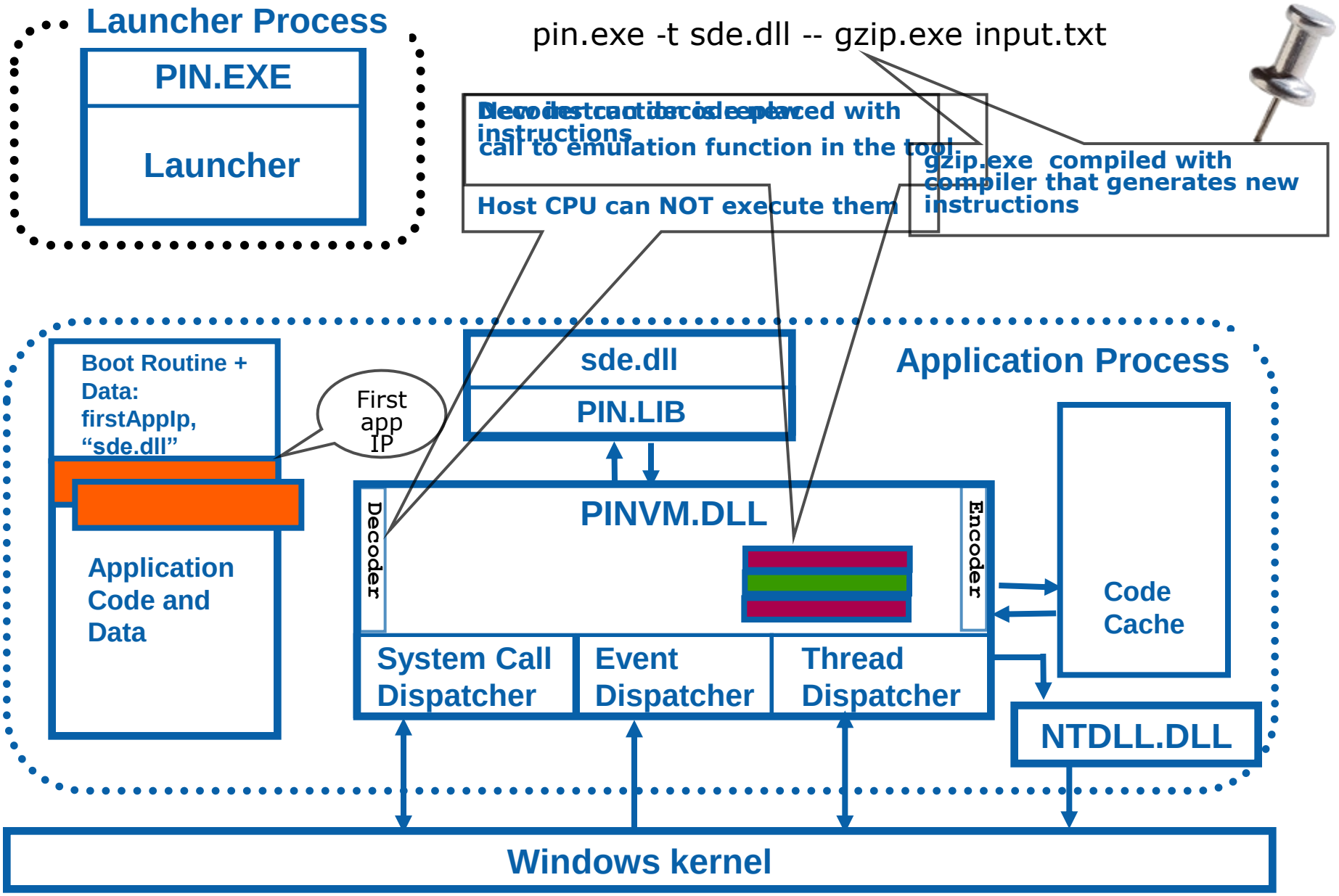
IARG_MAKE_ME_A_COFFEE

(Work in progress)

SDE

- SDE: A fast functional simulator for applications with new instructions
  - New instructions have been defined
  - Compiler generates code with new instructions
  - What can be used to run the apps with the new instructions?
    - Use PinTool that emulates new instructions.

- vmovdqu ymm?, mem256 vmovdqu mem256, ymm?
  - 16 new 256 bit ymm registers
  - Read/Write ymm register from/to memory.



sde_emul.dll Schema

```
#include "pin.H"

VOID EmVmovdquMem2Reg(unsigned int ymmDstRegNum, ADDRINT * ymmMemSrcPtr) {
    PIN_SafeCopy(ymmRegs[ymmDstRegNum], ymmMemSrcPtr, 32); }

VOID EmVmovdquReg2Mem(int ymmSrcRegNum, ADDRINT * ymmMemDstPtr) {
    PIN_SafeCopy(ymmMemDstPtr, ymmRegs[ymmRegNum], 32); }

VOID Instruction(INS ins, VOID *v)   {
   switch (INS_Opcode(ins)
   {
       :::::
       case XED_ICLASS_VMOVDQU:
       if (INS_IsMemoryRead(ins))        // vmovdqu ymm? <= mem256
            INS_InsertCall(ins, IPOINT_BEFORE,
                           (AFUNPTR)EmVmovdquMem2Reg,
                           IARG_UINT32, REG(INS_OperandReg(ins, 0)) - REG_YMM0,
                           IARG_MEMORYREAD_EA,
                           IARG_END);
       else if (INS_IsMemoryWrite(ins)) // vmovdqu mem256 <= ymm?
           INS_InsertCall(ins, IPOINT_BEFORE,
                           (AFUNPTR)EmVmovdquReg2Mem,
                           IARG_UINT32, REG(INS_OperandReg(ins, 1)) - REG_YMM0,
                           IARG_MEMORYWRITE_EA,
                           IARG_END);
       INS_DeleteIns(ins); //Processor does NOT execute this instruction
       break;
} }

int main(int argc, CHAR *argv[]) {
   PIN_Init(argc,argv));
   INS_AddInstrumentFunction(Instruction, 0);
   PIN_StartProgram();  }
```

Symbols

Probe-mode

The CONTEXT structure

Multi-threading

Instrumenting a process tree

Part 2

Topics in Pin API

Symbols

Symbols

- *PIN_InitSymbols()*
  - Pin will use whatever symbol information is available
    - Debug info in the app
    - Pdb files
    - Export Tables
    - On Windows uses dbghelp
  - See *PIN_InitSymbolsAlt()* for more control over which symbols will be used
- Use symbols to instrument/wrap/replace specific functions
- Access application debug information from a Pin tool
  - Use API function *PIN_GetSourceLocation()*

Instrument malloc and free

```
int main(int argc, char *argv[])
{
    // Initialize pin symbol manager
    PIN_InitSymbols();
    // See also PIN_InitSymbolsAlt() for more control over which symbols are read

    PIN_Init(argc,argv);

    // Register the function ImageLoad to be called each time an image is loaded in the process
    // This includes the process itself and all shared libraries it loads (implicitly or explicitly)
    IMG_AddInstrumentFunction(ImageLoad, 0);

    // Never returns
    PIN_StartProgram();
}
```

Instrument malloc and free

```
VOID ImageLoad(IMG img, VOID *v) // Pin Callback.
{
   // Instrument the malloc() and free() functions.  Print the input argument
   // of each malloc() or free(), and the return value of malloc().

   RTN mallocRtn = RTN_FindByName(img, "_malloc");  //  Find the malloc() function (decorated name).
   if (RTN_Valid(mallocRtn))
   {
      RTN_Open(mallocRtn);

      // Instrument malloc() to print the input argument value and the return value.
      RTN_InsertCall(mallocRtn, IPOINT_BEFORE,  (AFUNPTR)MallocBefore,
                     IARG_FUNCARG_ENTRYPOINT_VALUE, 0,
                     IARG_END);
      RTN_InsertCall(mallocRtn, IPOINT_AFTER, (AFUNPTR)MallocAfter,
                     IARG_FUNCRET_EXITPOINT_VALUE, IARG_END);

      RTN_Close(mallocRtn);
   }

   RTN freeRtn = RTN_FindByName(img, "_free"); // Find the free() function.
   if (RTN_Valid(freeRtn))
   {
      RTN_Open(freeRtn);
      // Instrument free() to print the input argument value.
      RTN_InsertCall(freeRtn, IPOINT_BEFORE, (AFUNPTR)FreeBefore,
                     IARG_FUNCARG_ENTRYPOINT_VALUE, 0,
                     IARG_END);
      RTN_Close(freeRtn);
   }
}
```

Alternative: Handling name-mangling and multiple symbols at same address

```
VOID Image(IMG img, VOID *v)
{
    // Walk through the symbols in the symbol table.
    for (SYM sym = IMG_RegsymHead(img); SYM_Valid(sym); sym = SYM_Next(sym))
    {
        string undFuncName = PIN_UndecorateSymbolName(SYM_Name(sym), UNDECORATION_NAME_ONLY);
```

From the pin manual:
Symbol name decorated according to Windows IA32 C calling conventions is undecorated as follows:

```
_foo     ->  foo    (__cdecl    convention)
_foo@4   ->  foo    (__stdcall  convention)
@foo@12  ->  foo    (__fastcall convention)
```

(http://pin.iil.intel.com/pin/Testing/Trees/trunk/Doc/Pin/html/group__SYM__BASIC__API.html#gd02e31773f5a8aef5e5a70be7f09dd17)

```
                                IARG_END);
            RTN_InsertCall(mallocRtn, IPOINT_AFTER, (AFUNPTR)MallocAfter,
                                IARG_FUNCRET_EXITPOINT_VALUE,
                                IARG_END);

            RTN_Close(mallocRtn);
        }
    }
    }
}
```

Accessing Application Debug Info from a Pin Tool: Catch a Memory Overwrite

```
VOID Instruction(INS ins, VOID *v) // INS_AddInstrumentFunction(Instruction, 0);
{
   UINT32 numMemOperands = INS_MemoryOperandCount(ins);

   // Iterate over each memory operand of the instruction.
   for (UINT32 memOp = 0; memOp < numMemOperands ; memOp++)
   {
      if (INS_MemoryOperandIsWritten(ins, memOp))
      { // Insert instrumentation code to catch a memory overwrite
          INS_InsertIfCall  (ins, IPOINT_BEFORE,
                                  AFUNPTR(AnalyzeMemWrite),
                                  IARG_FAST_ANALYSIS_CALL,
                                  IARG_MEMORYOP_EA, memop,
                                  IARG_MEMORYWRITE_SIZE,
                                  IARG_END);

           INS_InsertThenCall  (ins, IPOINT_BEFORE,
                                       AFUNPTR(MemoryOverWriteAt),
                                       IARG_FAST_ANALYSIS_CALL,
                                       IARG_INST_PTR,
                                       IARG_MEMORYOP_EA, memop,
                                       IARG_MEMORYWRITE_SIZE,
                                       IARG_END);

      }
   }
}
```

Accessing Application Debug Info from a Pin Tool: Catch a Memory Overwrite

```
KNOB<ADDRINT> KnobMemAddrBeingOverwritten(KNOB_MODE_WRITEONCE, "pintool",
                                          "mem_overwrite_addr", "256", "overwritten memaddr");

static ADDRINT PIN_FAST_ANALYSIS_CALL
AnalyzeMemWrite ( // Pin will inline this function, it is the IF part
                  ADDRINT memWriteAddr, UINT32 numBytesWritten)
{     // return 1 if this memory write overwrites the address specified by
      // KnobMemAddrBeingOverwritten
      return (memWriteAddr<= KnobMemAddrBeingOverwritten &&
              (memWriteAddr + numBytesWritten) > KnobMemAddrBeingOverwritten);
}



static VOID PIN_FAST_ANALYSIS_CALL
MemoryOverWriteAt ( // Pin will NOT inline this function, it is the THEN part
                    ADDRINT appIP, ADDRINT memWriteAddr, UINT32 numBytesWritten)
{
      INT32 column, lineNum;
      string fileName;

      PIN_GetSourceLocation (appIP,  &column, &line, &fileName);

      printf ("overwrite of %p  from instruction at %p  originating from file %s line %d col %d\n",
              KnobMemAddrBeingOverwritten, appIP, fileName.c_str(), lineNum, column);
      printf ("  writing %d bytes starting at %p\n", numBytesWritten, memWriteAddr);
}
```

Probe mode

Pin Probe-Mode

- Probe mode is a method of using Pin to instrument at the function level only. Wrap, Replace, call Analysis function before/after.
- Replacement or Wrapping function can call the replaced (original) function.
- The application and the replacement routine are run natively (not Jitted).
  - Faster than Jit-mode
  - Puts more responsibility on the tool writer.
  - Probes can only be placed on RTN boundaries
  - Must be inserted within the Image load callback.
  - Pin will automatically remove the probes when an image is unloaded.
- Many of the PIN APIs that are available in JIT mode are not available in Probe mode.

JIT Mode vs Probe Mode

- JIT Mode
  - Pin creates a modified copy of the application on-the-fly
  - Original code never executes

    ➢More flexible, more common approach

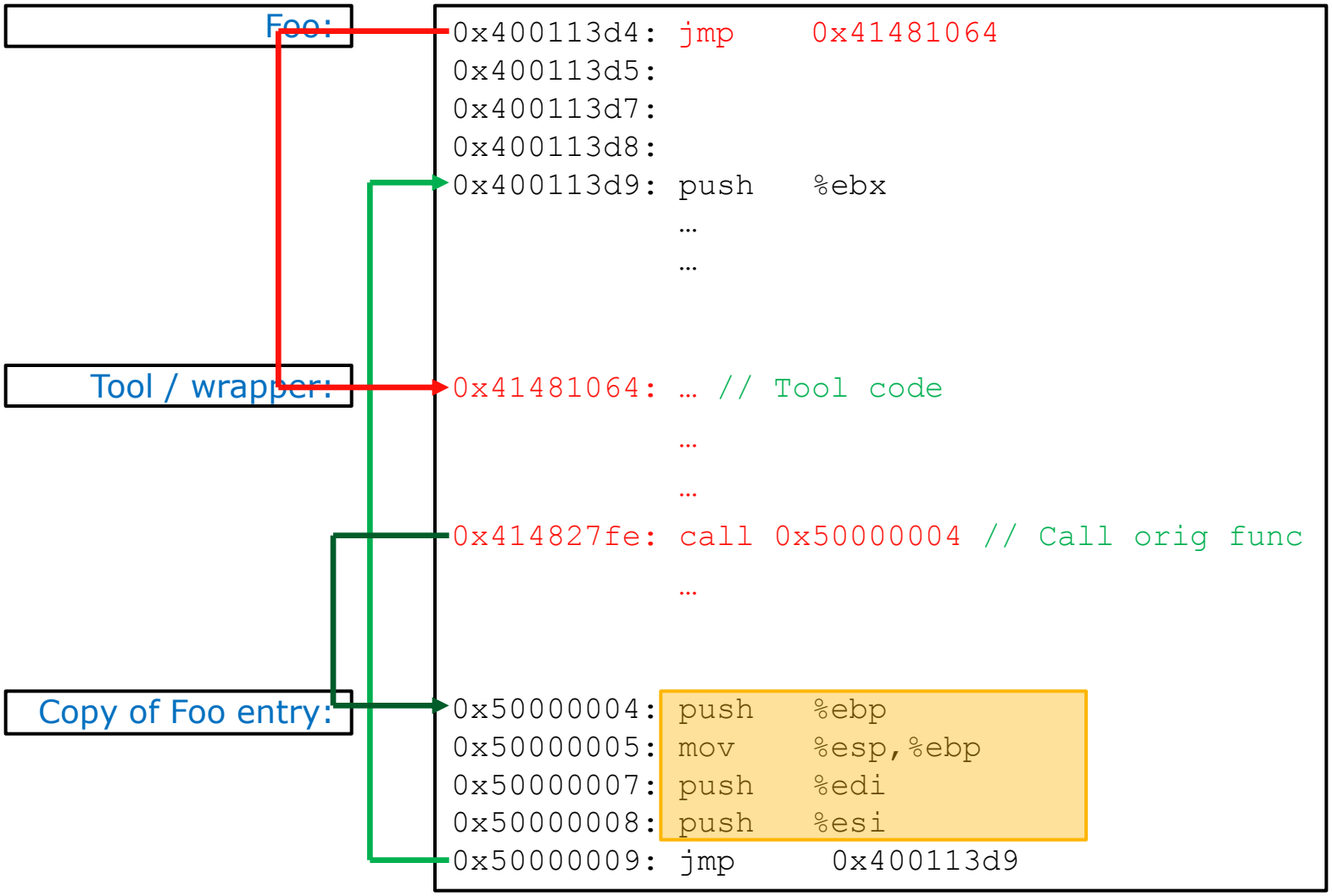
- Probe Mode
  - Pin modifies the original application instructions
  - Inserts jumps to instrumentation code (trampolines)

    ➢Lower overhead (less flexible) approach

A Sample Probe

- A probe is a jump instruction that overwrites original instruction(s) in the application
  - Instrumentation invoked with probes
  - Pin copies/translates original bytes so probed (replaced) functions can be called from the replacement function

A Sample Probe



PinProbes Instrumentation

- Advantages:
  - Low overhead – few percent
  - Less intrusive – execute original code
  - Leverages Pin:
    - API
    - Instrumentation engine
- Disadvantages:
  - More tool writer responsibility
  - Routine-level granularity (RTN)

Using Probes to Replace/Wrap a Function

- *RTN_ReplaceSignatureProbed()* **redirects all calls to application routine** `rtn` **to the specified replacementFunction**
  - Can add IARG_* types to be passed to the replacement routine, including pointer to original function and IARG_CONTEXT.
  - Replacement function can call original function.

- To use:
  - Must use *PIN_StartProgramProbed()*
  - Function prototype is required

Malloc Wrapping – Jit Mode

```
#include "pin.H"
void * MallocWrapper( CONTEXT * ctxt, AFUNPTR pf_malloc, size_t size)
{  // Simulate out-of-memory every so often
   void * res;
   if (TimeForOutOfMem())
      return (NULL);
   PIN_CallApplicationFunction(ctxt, PIN_ThreadId(),
                               CALLINGSTD_DEFAULT,  pf_malloc,
                              PIN_PARG(void *),  &res, PIN_PARG(size_t), size);
   return res;
}
VOID ImageLoad(IMG img, VOI  *v) { // Pin callback. Registered by IMG_AddInstrumentFunction
    if (strstr(IMG_Name(img).c_str(),  "libc.so") ||
       strstr(IMG_Name(img),
   {
       RTN mallocRtn = RTN_FindByName(img,

       PROTO protoMalloc = PROTO_Allocate( PIN_PAR
                                          "malloc", PIN_

       RTN_ReplaceSignature(mallocRtn, AFUNPTR(MallocW
                            IARG_PROTOTYPE, protoMallo
                            IARG_CONST_CONTEXT,
                            IARG_ORIG_FUNCPTR,
                            IARG_FUNCARG_ENTRYPOINT_VALUE, 0,
                            IARG_END);
   }
}
int main(int argc, CHAR *argv[]) {
   PIN_InitSymbols();
   PIN_Init(argc,argv));
   IMG_AddInstrumentFunction(ImageLoad, 0);
   PIN_StartProgram();
}
```

The ImageLoad callback is called for each image (exe, shared library) loaded into the process

It is called before any code in the loaded image is executed

This is referred to ahead-of-time-instrumentation

This is rather expensive

Also has 2 synchronization points

Malloc Wrapping – Probe Mode

```
#include "pin.H"
void * MallocWrapper(AFUNPTR pf_malloc, size_t size)
{  // Simulate out-of-memory every so often
   void * res;
   if (TimeForOutOfMem())
       return (NULL);
   res = pf_malloc(size);
   return res;
}

VOID ImageLoad (IMG img, VOID *v) {
    if (strstr(IMG_Name(img).c_str(), "libc.so") ||
       strstr(IMG_Name(img).c_str(), "MSVCR80") || strstr(IMG_Name(img).c_str(), "MSVCR90"))
   {
       RTN mallocRtn = RTN_FindByName(img, "malloc");

       if ( RTN_Valid(mallocRtn) &&
           RTN_IsSafeForProbedReplacement(mallocRtn) )
      {
         PROTO proto_malloc  = PROTO_Allocate(PIN_PARG(void *), CALLINGSTD_DEFAULT, "malloc",
                                              PIN_PARG(size_t), PIN_PARG_END() );

         RTN_ReplaceSignatureProbed (mallocRtn,
                                     AFUNPTR(MallocWrapper),
                                     IARG_PROTOTYPE, proto_malloc,
                                     IARG_ORIG_FUNCPTR,
                                     IARG_FUNCARG_ENTRYPOINT_VALUE, 0,
                                     IARG_END);
} }}

int main(int argc, CHAR *argv[]) {
   PIN_InitSymbols();    PIN_Init(argc,argv));
   IMG_AddInstrumentFunction(ImageLoad, 0);
   PIN_StartProgramProbed();            }
```

Using Probes to Call Analysis Functions

- *RTN_InsertCallProbed()* invokes the analysis routine before or after the specified `rtn`
  - Use **`IPOINT_BEFORE`** or **`IPOINT_AFTER`**
    - **`Pin may NOT be able to find all AFTER points on the function when it is running in Probe-Mode`**
  - PIN IARG_TYPEs are used for arguments

- To use:
  - Must use *PIN_StartProgramProbed()*

Tool Writer Responsibilities

- No control flow into the instruction space where probe is placed
  - 5 bytes on IA-32, 7 bytes on Intel64
  - Branch into “replaced” instructions will fail
  - Probes at function entry point only
- Thread safety for insertion and deletion of probes
  - During image load callback is safe
  - Only loading thread has a handle to the image
- Replacement function has same behavior as original

The CONTEXT structure

CONTEXT*

- CONTEXT* is a ***Handle*** to the full register context of the application at a particular point in the execution
  - It can NOT be dereferenced.
  - It can only be passed to Pin API functions

- CONTEXT* is passed by default to a number of Pin Callback functions: e.g.
  - ThreadStart
    - Registered by *PIN_AddThreadStartFunction*
  - BufferFull
    - Registered by *PIN_DefineTraceBuffer*
  - OnContextChange
    - Registered by *PIN_AddContextChangeFunction*

CONTEXT*,
IARG_CONST_CONTEXT, IARG_CONTEXT

- Pin provides API to Get and Set registers within the CONTEXT
- Can request CONTEXT* be passed to an analysis function by requesting IARG_(CONST)_CONTEXT
- Requesting IARG_CONTEXT
  - The analysis function will NOT be inlined
  - The passing of the CONTEXT* is time consuming
- Passing IARG_CONST_CONTEXT is ~4X faster than IARG_CONTEXT
  - Contents of CONTEXT* passed for IARG_CONST_CONTEXT can NOT be

From the pin manual:
Tools that need a CONTEXT* and only read from it should use IARG_CONST_CONTEXT. Tools that need a CONTEXT* and only occasionally write into it should also use IARG_CONST_CONTEXT. … PIN_SaveContext can be used by the tool to get a writable copy of the CONTEXT*.

CONTEXT* …

- Changes made to the contents of a CONTEXT*
  - IARG_CONTEXT (Analysis routines)
    - Changes made will be visible in subsequent PIN API calls made from within the nesting of the analysis function
    - Changes made will NOT be visible in the application context after return from the analysis function.
    - If you want to change register values, use IARG_REG_REFERENCE, IARG_RETURN_REGS, or PIN_ExecuteAt().
  - Passed to PIN Callbacks
    - Changes made will be visible also after callback returns

Function Replacement with register change

```
#include "pin.H"
void *FunctionReplacer (
                        CONTEXT * ctxt,
                        AFUNPTR pf_malloc, size_t size)
{
   void * res;
   CONTEXT writableContext, * context = ctxt;

   if (TimeForRegChange())  {
      PIN_SaveContext(ctxt, &writableContext); // need to copy the ctxt into a writable context
      context = & writableContext;
      PIN_SetContextReg(context , REG_GAX, 1);
   }
   PIN_CallApplicationFunction(context , PIN_ThreadId(), CALLINGSTD_DEFAULT,  pf_malloc,
                               PIN_PARG(void *),  &res, PIN_PARG(size_t), size);
   return res;
}
VOID ImageLoad(IMG img, VOID *v) { // Pin callback. Registered by IMG_AddInstrumentFunction
   RTN rtn = RTN_FindByName(img, "Function");

    PROTO proto = PROTO_Allocate( PIN_PARG(void *), CALLINGSTD_DEFAULT,
                                  "proto", PIN_PARG(size_t), PIN_PARG_END() );

    RTN_ReplaceSignature (rtn, AFUNPTR(FunctionReplacer), IARG_PROTOTYPE, proto,
                          IARG_CONST_CONTEXT,
                          IARG_ORIG_FUNCPTR, IARG_FUNCARG_ENTRYPOINT_VALUE, 0, IARG_END);
}

int main(int argc, CHAR *argv[]) {
   PIN_InitSymbols();
   PIN_Init(argc,argv));
   IMG_AddInstrumentFunction(ImageLoad, 0);
   PIN_StartProgram();
}
```

Multi - Threading

Multi-Threading

- Pin fully supports multi-threading
  - Pin does not serialize application threads executing jitted code (including analysis code)
    - Pin provides synchronization constructs to introduce serialization if needed.
  - Pin does NOT create any threads of it's own
  - System calls require serialized entry to the VM before and after execution – BUT actual execution is NOT serialized
  - Pin callbacks are serialized
  - *Jitting* is serialized
    - Only one application thread can be jitting code at any time

Multi-Threading services

- Pin Tools can:
  - Track Threads
    - ThreadStart, ThreadFini callbacks
    - IARG_THREAD_ID (Not available in probe mode)
  - Use Pin Virtual registers and TLS for thread-specific data
  - Use Pin Locks to synchronize threads
  - Create dedicated threads to do Pin Tool work

Using the TLS

- Pin tools can allocate TLS slots, by using the *PIN_CreateThreadDataKey()* function
  - Deallocate with *PIN_DeleteThreadDataKey()*
- Each thread can use *PIN_SetThreadData()* and *PIN_GetThreadData()* to access the TLS slots
  - Initial per-thread value is NULL
- Allocating a TLS slot receives an optional callback function
  - Callback will be invoked per thread upon thread exit, if the thread has a non-NULL value in the corresponding slot

Virtual registers

- Pin's context structure includes several scratch general purpose registers
  - Do not map to actual architecture registers
- Can be accessed and modified same as physical registers
- Preferred to use the *PIN_ClaimToolRegister()* API
  - Claims a free scratch register to be used by the tool
  - Can help avoid contention when tool has several components which all require scratch registers

Pin Tool threads

- Pin tools may create their own threads
  - These threads will not be instrumented
- Use Pin API *PIN_SpawnInternalThread()*
  - System services, like *clone()* or *CreateThread(),* must not be used.
- Tool threads can only be created in the tool's main(), or from within another tool thread

Locking Guidelines

- **Basic Rules**
  - Any locks acquired in a Pin callback, must be released before returning from that callback.
  - Any locks acquired in an analysis routine, must be released before returning from the analysis routine.
  - If the tool calls a Pin API from a callback, it should not hold any tool locks when calling the API.
  - If the tool calls a Pin API from an analysis routine, it should not hold any tool locks when calling the API
    - For some Pin API calls, the tool may need to acquire the Pin client lock first (see documentation of the API)

Locking Guidelines

- **Advanced Rules**
  - Some rules may be partially relaxed, in specific cases
  - If the tool acquires lock L in an analysis routine, it may continue holding L after the analysis routine completes:
    - Lock L must be released before leaving the trace that contains the analysis routine.
      - A trace may have multiple exit points
      - The tool must establish a callback which, in case of exception, releases the lock L. Tools can use *PIN_AddContextChangeFunction()* to establish this call-back.
      - Lock L may not be acquired by any Pin callback
  - The tool may hold a lock L while calling a Pin API, if that lock obeys the following sub-rule:
      - The tool does not acquire lock L from any call-back.
      - The Pin API invoked does not cause Application code to execute

Instrumenting a process tree

Instrumenting a Process Tree

- Process A creates Process B
  - Process B creates Process C and D
    - And so forth
- Pin can instrument all or part of the process tree
  - Use the *–follow_exevc* Pin invocation switch to turn this on
  - Can use different Pin modes (Jit or Probe) on the different processes in the process tree.
  - Can use different Pin Tools on the different processes of a process tree.
- Architecture of processes in the process tree may be intermixed
  - e.g. Process A is 32bit, Process B is 64 bit, Process C is 64 bit, Process D is 32 bit…

Instrumenting a Process Tree

```
// If this Pin Callback returns FALSE, then the child process will run Natively
BOOL FollowChild(CHILD_PROCESS childProcess, VOID * userData)          {
   BOOL res;
   INT appArgc;
   CHAR const * const * appArgv;

   OS_PROCESS_ID pid = CHILD_PROCESS_GetId(childProcess);

   // Get the command line that child process will be Pinned with, these are the Pin invocation switches
   // that were specified when this (parent) process was Pinned
   CHILD_PROCESS_GetCommandLine(childProcess, &appArgc, &appArgv);

   INT childArgc = 0;
   CHAR const * childArgv[20];
   [...] // :::: Create the Child's Argc and Argv :::

   CHILD_PROCESS_SetPinCommandLine(childProcess, childArgc, childArgv);

   return TRUE;  /* Specify Child process is to be Pinned */
}

int main(INT32 argc, CHAR **argv)  {
   PIN_Init(argc, argv);
   cout << " Process is running on Pin in " << PIN_IsProbeMode() ? " Probe " : " Jit " << " mode "

   // The FollowChild Callback will be called when the application is about to spawn a child process
   PIN_AddFollowChildProcessFunction (FollowChild, 0);

   if ( PIN_IsProbeMode() )
      PIN_StartProgramProbed(); // Never returns
   else
      PIN_StartProgram();
}
```

OS Specifics: Linux

Managing exceptions

Managing signals

Code Cache API

OS Specifics: Windows

Debugging & Pin

Part 3
Advanced Pin

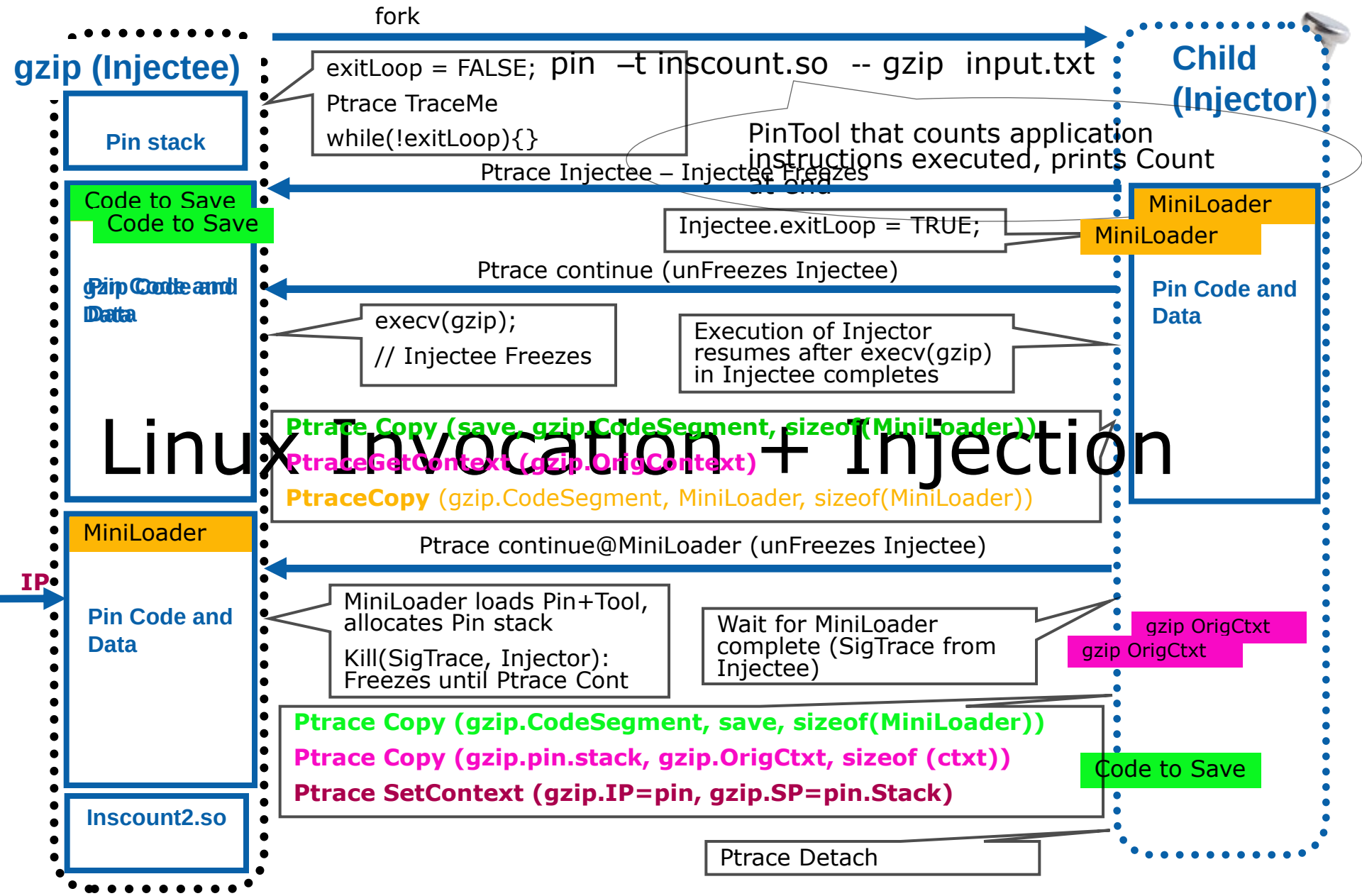
OS Specifics - Linux

Linux Challenges (1/2)

- **Handling system calls**
  - Pin must intercept system calls to regain control of the application on return from the system
  - Pin must monitor system calls to notify instrumentation when DLLs are loaded/unloaded, threads are created/terminated, etc.
  - **Some system calls may behave differently on different Linux distributions.**
- **Signal handling**
  - Pin must identify whether the signal originated from the application, the tool or Pin itself.
  - **Pin cannot seem to interfere with the applications signal mask.**

Linux Challenges (2/2)

- **Injection**
  - Pin relies on the ptrace system call for injection.
  - Some platforms do not allow tracing a parent application by a child. In such cases the application is run on the child.
- **Isolation of instrumentation from the application**
  - Instrumentation runs in the same process as the application it is observing.
  - Pin must emulate several libc services.



Handling System Calls

- **Pin must manage the execution of system calls**
  - Pin must maintain control all the time
  - System calls are executed inside pin and return to the application
  - In most cases the system call is executed without the pin VM lock
  - Certain system calls are emulated by pin (see below)
- **System call emulation**
  - Pin detects if a system call needs emulation.
  - Pin needs to know the attributes of each memory page for SMC support
    - Therefore all system calls related to memory are emulated by pin
  - Signal related system calls are emulated
  - Creating of new threads and new child processes
  - Setting/getting of the TLS segment registers
  - Thread and process termination

Signal Handling

- Pin registers its own signal handlers for all signals, and saves the application's handlers.
- Pin must handle both synchronous and asynchronous signals.
- Asynchronous signals:
  - These signals may be delivered "at will" so Pin waits for safe point to deliver them.
  - When such a signal arrives, Pin's internal handler registers this signal, unlinks the current trace and resumes execution from the code cache.
  - At the trace's exit point, the executing thread jumps to the VM, thus transferring control over to Pin. The VM checks if there are pending signals and calls the application's original signal handlers for these signals (jitting them).
- Synchronous signals:
  - These signals must be delivered immediately.
  - They may originate from the application, the tool or Pin itself.
  - Pin's internal handler is called, it determines the origin of the signal and propagates the signal delivery to the tool and application if necessary.
  - If signal is delivered to the application, the application's signal handler is jitted.

Multithreading Support

- **Pin instruments and runs all threads of the application from the first to the last user-mode instruction**
  - Attaches to the thread upon the first user-space instruction
  - Maintains control until the thread exits
- **Pin's threading activities are transparent to the application**
  - The Pin VM serializes some of its operations (e.g. JIT compilation), but never executes code of the application under Pin locks
  - Each thread has a shadow stack that is used by the Pin VM and the Pintool
  - Pin and pintools are prohibited from using the pthread library due to conflicts with some internal structures. Therefore Pin provides its own APIs for thread creation and control.

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Thread-Local Storage

- Segment virtualization
  - TLS is accessed via the fs (64 bit) or gs (32 bit) segment register.
  - Both the application and Pin share this register, but expect different values.
  - Pin emulates the application's usage of the fs/gs register thus isolating the application's TLS for Pin's.

Isolation (1/2)

- Pin is injected in to address space and has its own copy of the dynamic loader and runtime libraries (GLIBC, etc).
- Pin uses a small library of CRT for direct calls to system calls.
- The process has a single signals table (shared among all threads), pin manages an internal signal table and emulate all the system calls related to signals.

Isolation (2/2)

- pthread functions cannot be called from an analysis or replacement routine

- Pintools on Linux need to take care when calling standard C or C++ library routines from analysis or replacement functions
  - because the C and C++ libraries linked into Pintools are **not** thread-safe

Managing Exceptions

Exceptions

- Catch Exceptions that occur in Pin Tool code
  - Global exception handler
    - *PIN_AddInternalExceptionHandler()*
  - Guard code section with exception handler
    - *PIN_TryStart()*
    - *PIN_TryEnd()*

Exceptions example (1/3)

```
VOID InstrumentDivide(INS ins, VOID* v)
{
   if ((INS_Mnemonic(ins) == "DIV") &&
      (INS_OperandIsReg(ins, 0)))
   {  // Will Emulate div instruction with register operand
      INS_InsertCall(ins,
                     IPOINT_BEFORE,
                     AFUNPTR(EmulateIntDivide),
                     IARG_REG_REFERENCE, REG_GDX,
                     IARG_REG_REFERENCE, REG_GAX,
                     IARG_REG_VALUE, REG(INS_OperandReg(ins, 0)),
                     IARG_CONST_CONTEXT,
                     IARG_THREAD_ID,
                     IARG_END);
      INS_Delete(ins); // Delete the div instruction
   }
}
```

```
int main(int argc, char * argv[])
{
   PIN_Init(argc, argv);
   INS_AddInstrumentFunction (InstrumentDivide, 0);
   PIN_AddInternalExceptionHandler (GlobalHandler, NULL); // Registers a Global Exception Handler
   PIN_StartProgram();    // Never returns
   return 0;
}
```

Exceptions example (2/3)

```
VOID EmulateIntDivide(ADDRINT * pGdx, ADDRINT * pGax, ADDRINT divisor, CONTEXT * ctxt,
    THREADID tid)
{

    PIN_TryStart(tid, DivideHandler, ctxt);  // Register a Guard Code Section  Exception Handler

    UINT64 dividend = *pGdx;
    dividend <<= 32;
    dividend += *pGax;
    *pGax = dividend / divisor;
    *pGdx = dividend % divisor;

    PIN_TryEnd(tid);                          /* Guarded Code Section ends  */
}
```

Exceptions example (3/3)

```
EXCEPT_HANDLING_RESULT
DivideHandler (THREADID tid, EXCEPTION_INFO * pExceptInfo,
               PHYSICAL_CONTEXT * pPhysCtxt, // The context when the exception occurred
               VOID *appContextArg )         // The application context when the exception occurred
{
   if(PIN_GetExceptionCode(pExceptInfo) == EXCEPTCODE_INT_DIVIDE_BY_ZERO)
   {  // Divide by zero occurred in the code emulating the divide, use PIN_RaiseException to raise this
      // exception at the appIP – for handling by the application
      cout << " DivideHandler : Caught divide by zero." << PIN_ExceptionToString(pExceptInfo) <<  endl;

      // Get the application IP where the exception occurred from the application context
      CONTEXT * appCtxt = (CONTEXT *)appContextArg;
      ADDRINT faultIp = PIN_GetContextReg (appCtxt, REG_INST_PTR);

      // raise the exception at the application IP, so the application can handle it as it wants to
      PIN_SetExceptionAddress (pExceptInfo, faultIp);
      PIN_RaiseException (appCtxt, tid, pExceptInfo);  // never returns
   }
   return EHR_CONTINUE_SEARCH;
}


EXCEPT_HANDLING_RESULT
GlobalHandler(THREADID threadIndex, EXCEPTION_INFO * pExceptInfo,
              PHYSICAL_CONTEXT * pPhysCtxt, VOID *v)
{
   cout << "GlobalHandler: Caught unexpected exception. " << PIN_ExceptionToString(pExceptInfo) << endl;
   return EHR_UNHANDLED;
}
```

Monitoring Application Exceptions

- *PIN_AddContextChangeFunction()*
  - Can monitor and change the application state at application exceptions

```
int main(int argc, char **argv)
{
   PIN_Init(argc, argv);

   PIN_AddContextChangeFunction(OnContextChange, 0);

   PIN_StartProgram();
}
```

Monitoring Application Exceptions

```
static void OnContextChange (THREADID tid,
                             CONTEXT_CHANGE_REASON reason,
                             const CONTEXT *ctxtFrom  // Application's register state at exception point
                             CONTEXT *ctxtTo,         // Application's register state delivered to handler
                             INT32 info,
                             VOID *v)
{
   if (CONTEXT_CHANGE_REASON_SIGRETURN == reason
      || CONTEXT_CHANGE_REASON_APC == reason
      || CONTEXT_CHANGE_REASON_CALLBACK == reason
      || CONTEXT_CHANGE_REASON_FATALSIGNAL == reason
      || ctxtTo == NULL)
   { // don't want to handle these
      return;
   }

   // CONTEXT_CHANGE_REASON_EXCEPTION
   // change some register values in the context that the application will see at the handler
   FPSTATE fpContextFromPin;
   // change the bottom 4 bytes of xmm0
   PIN_GetContextFPState (ctxtFrom, &fpContextFromPin);
   fpContextFromPin.fxsave_legacy._xmm[3] = 'de';
   fpContextFromPin.fxsave_legacy._xmm[2] = 'ad';
   fpContextFromPin.fxsave_legacy._xmm[1] = 'be';
   fpContextFromPin.fxsave_legacy._xmm[0] = 'ef';
   PIN_SetContextFPState (ctxtTo,     &fpContextFromPin);

   // change eax
   PIN_SetContextReg(ctxtTo, REG_RAX, 0xbaadf00d);
}
```

Managing Signals

Signals

- Tools can establish an interceptor function for signals delivered to the application
  - Tools should never call sigaction() directly to handle signals.
  - Interceptor function is called whenever the application receives the requested signal, regardless of whether the application has a handler for that signal.
  - Interceptor function can then decide whether the signal should be forwarded to the application

Signals

- A tool can take over ownership of a signal in order to:
  - use the signal as an asynchronous communication mechanism to the outside world.
    - For example, if a tool intercepts SIGUSR1, a user of the tool could send this signal and tell the tool to do something. In this usage model, the tool may call PIN_UnblockSignal() so that it will receive the signal even if the application attempts to block it.
  - "squash" certain signals that the application generates.
    - a tool that forces speculative execution in the application may want to intercept and squash exceptions generated in the speculative code.
- A tool can set only one "intercept" handler for a particular signal, so a new handler overwrites any previous handler for the same signal. To disable a handler, pass a NULL function pointer.

Signals

```
BOOL EnableInstrumentation = FALSE;

BOOL SignalHandler(THREADID, INT32, CONTEXT *, BOOL, const EXCEPTION_INFO *, void *)
{
    // When tool receives the signal, enable instrumentation.  Tool calls
    // PIN_RemoveInstrumentation() to remove any existing instrumentation from Pin's code cache.
    EnableInstrumentation = TRUE;
    PIN_RemoveInstrumentation();

    return FALSE; /* Tell Pin NOT to pass the signal to the application. */
}

VOID Trace(TRACE trace, VOID *)
{
    if (!EnableInstrumentation)
        return;

    for (BBL bbl = TRACE_BblHead(trace);  BBL_Valid(bbl);  bbl = BBL_Next(bbl))
        BBL_InsertCall(bbl, IPOINT_BEFORE, AFUNPTR(AnalysisFunc), IARG_INST_PTR, IARG_END);
}
int main(int argc, char * argv[])
{
    PIN_Init(argc, argv);

    PIN_InterceptSignal(SIGUSR1, SignalHandler, 0); // Tool should really determine which signal is NOT in
                                                    // use by application
    PIN_UnblockSignal(SIGUSR1, TRUE);
    TRACE_AddInstrumentFunction(Trace, 0);

    PIN_StartProgram();
}
```

Code-Cache API

Pin Code-Cache API

- The Code-Cache API allows a Pin Tool to:
  - Inspect Pin's code cache and/or alter the code cache replacement policy
  - Assume full control of the code cache
  - Remove all or selected traces from the code cache
  - Monitor code cache activity, including start/end of execution of code in the code cache

Pin Code-Cache API

```
VOID DoSmcCheck(VOID * traceAddr, VOID * traceCopyAddr,  USIZE traceSize, CONTEXT * ctxP) {
   if (memcmp(traceAddr, traceCopyAddr, traceSize) != 0)  /* application code changed */     {
      // the jitted trace is no longer valid
      free(traceCopyAddr);
      CODECACHE_InvalidateTraceAtProgramAddress((ADDRINT)traceAddr);
      PIN_ExecuteAt(ctxP); /* Continue jited execution at this application trace */
   }
}
VOID InstrumentTrace(TRACE trace, VOID *v)                  {
   VOID *  traceAddr;    VOID *  traceCopyAddr;    USIZE traceSize;

   traceAddr = (VOID *)TRACE_Address(trace);  // The appIP of the start of the trace

   traceSize = TRACE_Size(trace);                    // The size of the original application trace in bytes
   traceCopyAddr = malloc(traceSize);

   if (traceCopyAddr != 0)                                    {
      memcpy(traceCopyAddr, traceAddr, traceSize);        // Copy of original application code in trace
      // Insert a call to DoSmcCheck before every trace
      TRACE_InsertCall(trace, IPOINT_BEFORE, (AFUNPTR)DoSmcCheck,
                       IARG_PTR, traceAddr,
                       IARG_PTR, traceCopyAddr,
                       IARG_UINT32 , traceSize,
                       IARG_CONTEXT,
                       IARG_END);

   }
}
int main(int argc, char * argv[])  {
   PIN_Init(argc, argv);
   TRACE_AddInstrumentFunction(InstrumentTrace, 0);
   PIN_StartProgram();
}
```

OS Specifics: Windows

Pin for Android

Debugging & Pin

Part 3 - continue

Advanced Pin

OS Specifics - Windows

Windows Challenges (1/2)

- **Handling system calls**
  - Pin must intercept system calls to regain control of the application on return from the system
  - Pin must monitor system calls to notify instrumentation when DLLs are loaded/unloaded, threads are created/terminated, etc.
  - **System call interface is undocumented**
  - **System call numbers potentially change with each system build**
- **Handling exceptions and asynchronous interruptions**
  - To maintain control and notify instrumentation about control flow changes Pin must intercept all transitions from kernel to user mode
  - **Windows is not designed to have an independent agent interposed between the kernel and application**
    - **The kernel dispatches interruptions via (undocumented) entry points in ntdll.dll**

The main obstacle: direct interface between user-level code and Windows kernel is undocumented

Windows Challenges (2/2)

- **Injection**
  - PIN VMM is a DLL that must be loaded into the address space of the application to get initial control of the process
  - **Windows is not designed for proprietary loader**
  - Common practice: intercept control at the entry point of the application
    - **Instrumentation can not observe initialization procedures in statically linked application DLLs**
    - **Injection presented in the introduction is referred to as Late Injection**
      - **It misses the initialization procedures in statically linked application DLLs**
  - **Early injection is not trivial**
- **Isolation of instrumentation from the application**
  - Instrumentation runs in the same process as the application it is observing
  - Enabling C run-time in the instrumentation causes sharing of system libraries (e.g. kernel32.dll) and their state with the application
  - To be transparent, Pin must
    - **Preserve original state of system resources**
    - **Avoid reentrant use of shared libraries**

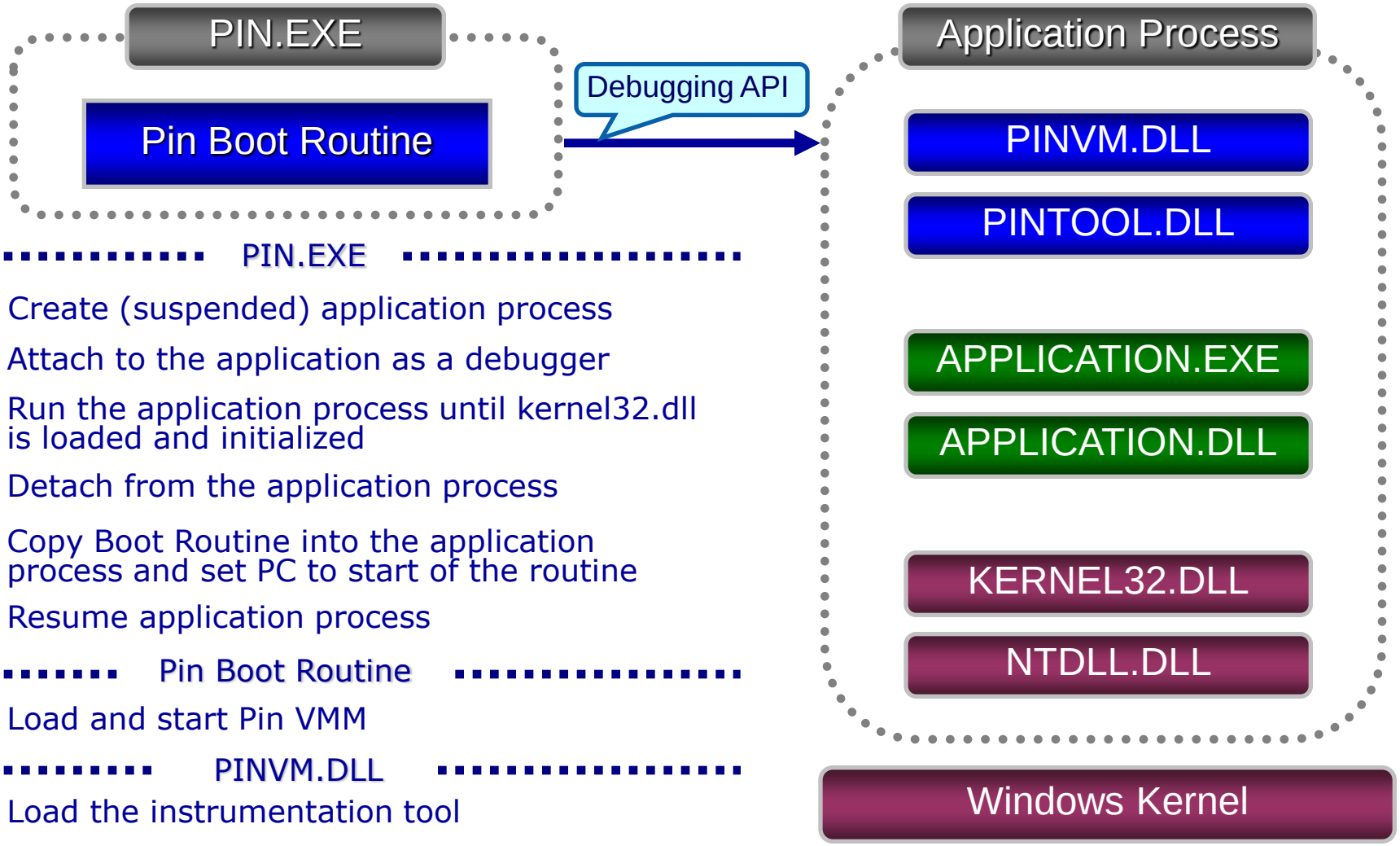
Pin minimizes its dependence on Windows system services in order to maximize observability and achieve better isolation

Injection

- Injection is the procedure for loading the PINVM.DLL into the address space of an application and gaining control of execution
- Other systems hook the entry point of the application
  - Too late: initialization procedures in application DLLs can not be instrumented
- For maximum observability, Pin should inject itself into a new process as early as possible, however…
- Pin depends on some basic system services so it is not possible to load PINVM.DLL until the loader and kernel32.dll have initialized
- **The optimal injection point: just after initialization of kernel32.dll**
  - **Injection presented in the introduction is referred to as Late Injection**
    - **It misses the initialization procedures in staticly linked application DLLs**

Early Injection step by step

pin –t pintool.dll -- application.exe



PIN.EXE

- ✓ Create (suspended) application process
- ✓ Attach to the application as a debugger
- ✓ Run the application process until kernel32.dll is loaded and initialized
- ✓ Detach from the application process
- ✓ Copy Boot Routine into the application process and set PC to start of the routine
- ✓ Resume application process

Pin Boot Routine

- ✓ Load and start Pin VMM

PINVM.DLL

- ✓ Load the instrumentation tool
- ✓ Instrument and execute the application

All application instructions are executed under Pin control

Handling System Calls

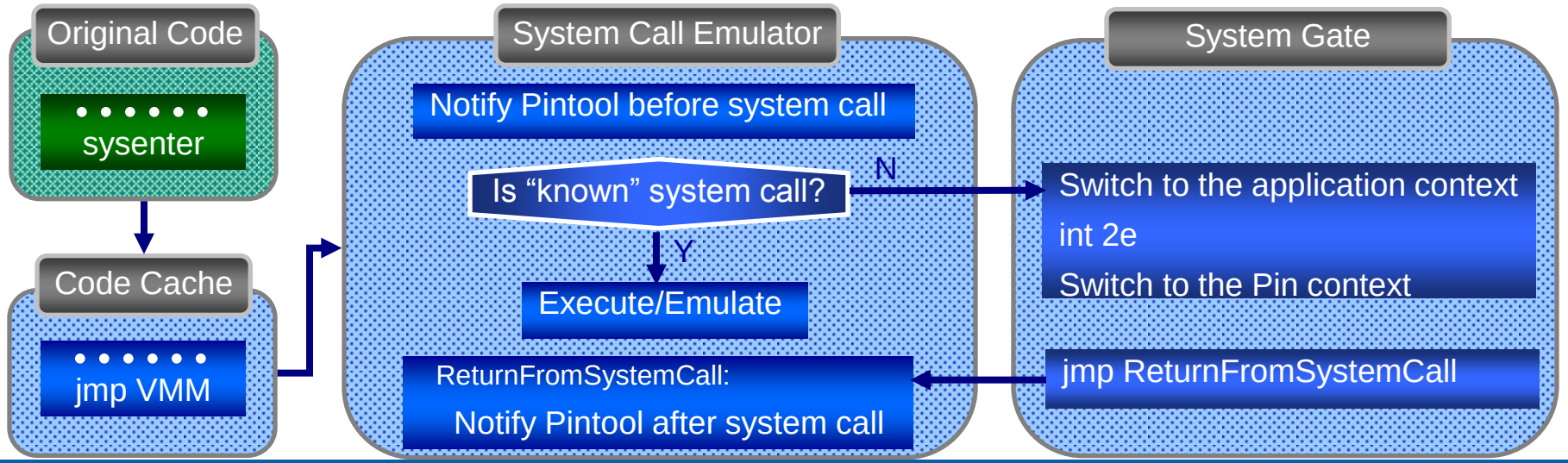
- **Pin must manage the execution of system calls**
  - To regain control when the system returns to user mode with a modified thread context
  - To monitor and handle some important system events
    - Loading DLLs, creation and termination of threads and processes, etc.
- **Pin intercepts system call instructions, not Win32 APIs**
  - Pin instruments all modules in the user space, including system libraries
  - Some applications use native API (NTDLL interface) directly, bypassing Win32 API
  - Win32 API layer is very wide, while system call instructions are easy to discover
- **Three steps in managing system calls:**
  - Detect a system call and redirect control to VMM
  - Execute the system call on behalf of the application
  - Regain control when the kernel returns to user with a new context
    - The system may interrupt system call execution by asynchronous calls to application procedures

System Call Interception

- **Pin detects system call instructions when it generates traces in the code cache**
  - IA-32: ***sysenter*** and ***int 2E***; Intel64: ***syscall***; etc.
  - This is a static analysis, so the overhead is low
- **Pin executes system calls in VMM, not in the code cache** - emits jump to VMM instead of the system call instruction
  - Enables flushing the code cache while a system call blocks in the kernel
  - VM lock is NOT held during the actual syscall
- **Some system calls may affect Pin's internal state. To handle them properly, Pin must know the corresponding system call numbers**
  - Windows system call numbers are unpublished and potentially change with each system build
  - Pin discovers system call numbers dynamically, on the early stage of the injection process
    - *We trace the corresponding NTDLL functions until a system call instruction is reached and then read the system call number from the EAX/RAX register*

System Call Execution

- The ***System Call Emulator*** executes all "known" system calls that may affect the VMM state, e.g. memory mappings, creation and termination of threads and processes, etc.
- The remaining, unknown system calls are forwarded to the ***System Gate***
  - Per-thread procedure that transparently executes system calls and regains control upon return or interruption
  - Fills/spills original context before/after system calls
  - Recovers original context (PC) when a system call is interrupted



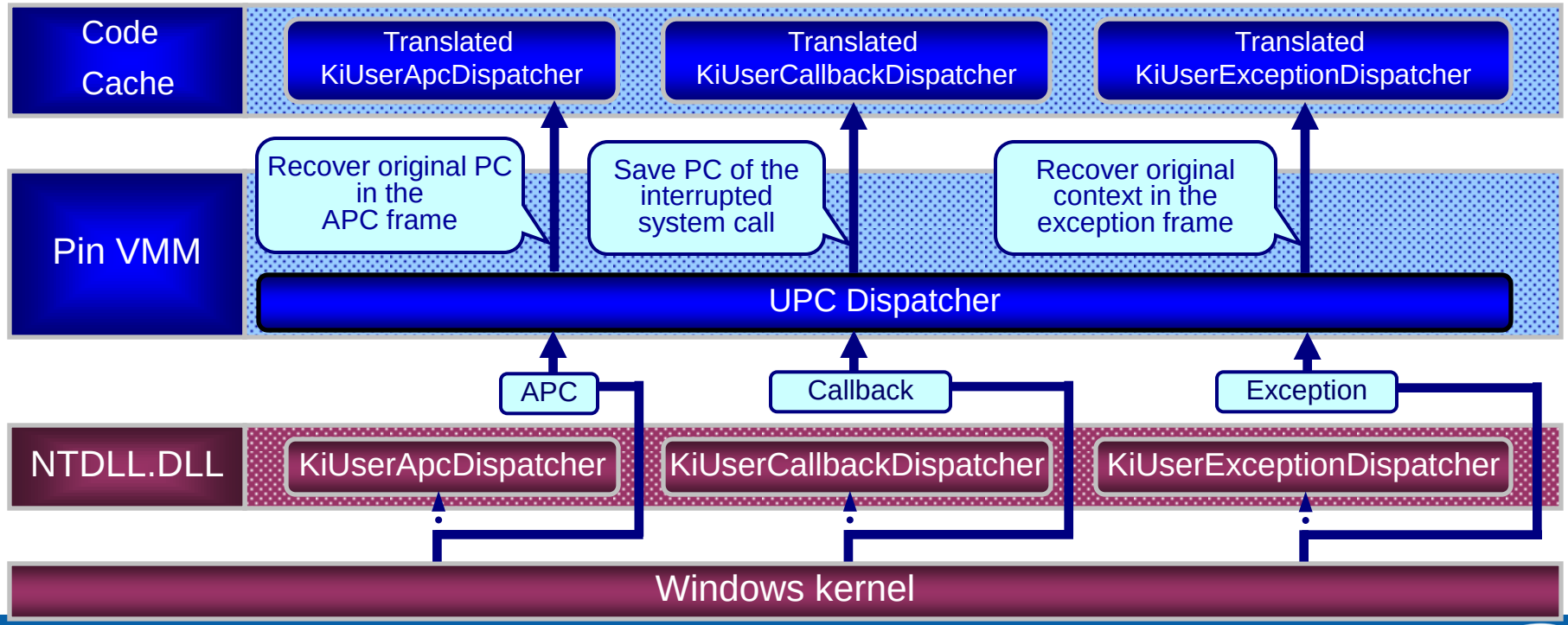
System Gate executes system calls "blindly", assuming that each of them can arbitrarily modify context and control flow (if interrupted)

User Procedure Calls (UPC)

- UPC is a control transfer from the kernel to a user-level procedure
- ***Asynchronous procedure call (APC)***
  - Asynchronous events: file I/O completion, timer expiration
  - Thread initialization APC signals start of a new thread
- ***Callback***
  - Asynchronous Windows GUI message
- ***Exception***
  - Access violation, illegal instruction, divide by zero, etc.
- Asynchronous events are not delivered immediately, but wait in queue until the application invokes an i*nterruptible (alertable)* system call
- **Pin must intercept UPCs to maintain control of the application and recover the original interruption context (visible to the application)**

UPC Interception

- The kernel dispatches UPCs through entry points in NTDLL.DLL
- To intercept UPCs, Pin overwrites the NTDLL entry points with trampolines that jump to the ***Event Dispatcher*** in Pin
- When a UPC is intercepted, Pin recovers original interruption context in the UPC frame prepared by the kernel
  - *JIT Compiler* recovers context of exceptions that occurred in the code cache
  - *System Call Emulator* recovers context of interrupted system calls



Pin intercepts all control transfers from the kernel to the user mode

Exceptions (1/2)

- Unlike *APCs* and *callbacks* that are queued and delivered at the next alertable system call, exceptions are synchronous events
- Exceptions do not necessarily cause abnormal termination of the process – the application may expect and handle exceptions
- Pin must provide exception handlers with the same exception information that accompanies exceptions in the native application
  - Exception context, code and exception-specific parameters
- From Pin's perspective, there are three kinds (sources) of exceptions in Windows applications:
  - An attempt to **fetch** an invalid or inaccessible instruction
  - An attempt to **execute** a faulting instruction
  - **Software exceptions** generated by the application

Exceptions (2/2)

- Decoder (**fetcher**) of instructions raises an exception if it encounters an invalid or inaccessible instruction
  - When the kernel delivers this exception back to the user mode, Pin skips the context translation because it sees original PC in the exception context
- Other **hardware exceptions** that occur in the code cache
  - Recovery of the original exception context is nontrivial due to register allocation
  - Pin retranslates the interrupted trace to get the virtual-physical register bindings at the faulting point
  - Optimization: small cache of register bindings for frequent exceptions
- Other **hardware** exceptions that occur in the tool code
  - Pin APIs for tool to manage it's exceptions
- Application can generate **software exceptions** using Win32 API
  - The exception context represents an original application state
  - Context translation is not needed

Pin delivers precise exceptions to applications handlers

Multithreading Support

- **Pin instruments and runs all threads of the application from the first to the last user-mode instruction**
  - Attaches to a new thread when the system delivers the thread initialization APC
  - Maintains control until the thread exits
  - Intercepts threads created by remote processes
- **Pin's threading activities are transparent to the application**
  - Pin VMM serializes some of its operations (e.g. JIT compilation), but never executes code of the application under Pin locks
  - Except for initialization phase, Pin never acquires windows locks in system libraries, e.g. loader lock or process heap lock
  - Each thread has a shadow stack that is used by Pin VMM and Pintool

Thread-Local State

- Key elements of Pin's thread-local state:
  - **Spill area** keeps values of spilled virtual registers
    - JIT-compiled traces need fast access to spilled register values
    - Pin "steals" one physical register to point to the spilling area
  - **TEB (Thread Environment Block) state**
    - Keeps original thread-local state of system libraries, e.g. last Win32 error value, stack limit
    - C run-time routines may access/modify these values
    - Need to preserve the original state while running in Pin VMM or PinTool
  - **System call state**
    - Contains information about active and interrupted system calls in the thread
    - The information is used to restore the original context on return from the system
- Pin steals one TLS slot from the application to enable fast access to the thread-local data in Pin VMM

Isolation (1/2)

- Pin Tools are compiled to use the static CRT
- Pin on Windows does not separate DLLs loaded by the tool from the application DLLs - it uses the same system loader.
  - The tool should not load any DLL that can be shared with the application.
  - The tool should avoid static links to any common DLL, except for those listed in PIN_COMMON_LIBS (see source\tools\ms.flags file).

Isolation (2/2)

- Pin on Windows guarantees safe usage of C/C++ run-time services in Pin tools, including indirect calls to Windows API through C run-time library.
  - Any other use of Windows API in Pin tool is not guaranteed to be safe
- Pin uses some base types that conflict with Windows types. If you use "windows.h", you may see compilation errors. So do:

```
namespace WINDOWS { #include <windows.h> }
```

Pindroid (Pin for Android)

itrace.out (~/nmo.../Charm/Source) - VIM

File Edit View Search Terminal Help

```
13 0x4001da60: jb 0x4001da70
14 0x4001da70: pop esi
15 0x4001da71: pop edx
16 0x4001da72: pop ecx
17 0x4001da73: pop ebx
18 0x4001da74: ret
19 0x40141877: mov esi, dword ptr [ebp+0x8]
20 0x4014187a: mov dword ptr [ebp-0x108], eax
21 0x40141880: add esi, 0x14
22 0x40141883: mov dword ptr [ebp-0x100], esi
23 0x40141889: mov dword ptr [esp], esi
24 0x4014188c: call 0x401153a0
25 0x401153a0: jmp dword ptr [ebx+0x1c0]
26 0x40014000: push ebp
27 0x40014001: mov ebp, esp
28 0x40014003: push edi
29 0x40014004: push esi
30 0x40014005: push ebx
31 0x40014006: sub esp, 0x2c
32 0x40014009: mov esi, dword ptr [ebp+0x8]
33 0x4001400c: call 0x40012701
34 0x40012701: nop
35 0x40012702: nop
                                13,1          1%
```

Pindroid (Pin for Android)

Features:

- Runs on Intel-based Phones and Tablets.
- Support latest Android OS versions.
- Instrument apps with Pin:
  - Attach to running apps.
  - Spawned apps from Zygote.
  - Spawned apps from scratch (app_process).
- Instrument Native and Jitted code.

A Step-by-step tutorial is available!

Pindroid (Pin for Android)

Usages:

- Investigate DalvikVM behavior.
- Profile user level services (libc, webkit, etc...)
- Create cache modeling for Android apps
- Analyze Native <-> Jit transitions
- Perform security profiling.

Debugging & Pin

Transparent debugging, and extending the debugger

- Transparently debug the application while it is running on Pin + Pin Tool
  - **PinADX**: Customizable Debugging with Dynamic Instrumentation (Presented at CGO 2012)

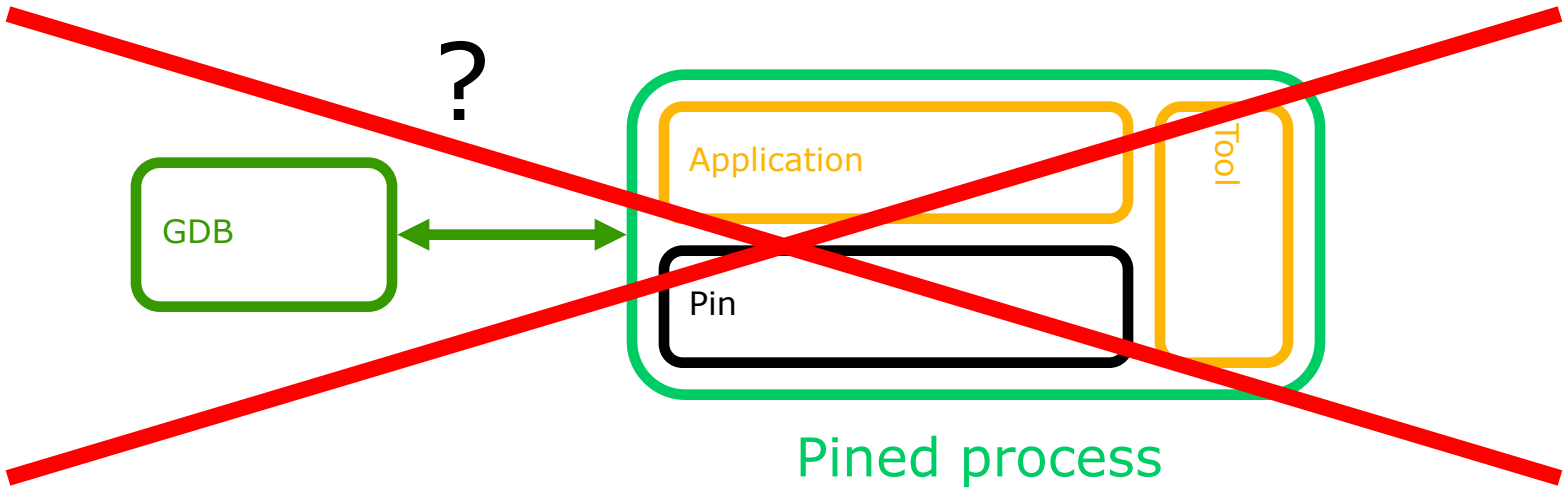
- Use Pin Tool to enhance/extend the debugger capabilities
  - Watchpoint: Is order of magnitude faster when implemented using Pin Tool
  - Which branch is branching to address 0
    - Easy to write a Pin Tool that implements this

Debug Application while Running Pin

- Useful for Pin-based emulators
  - User can debug application while emulating

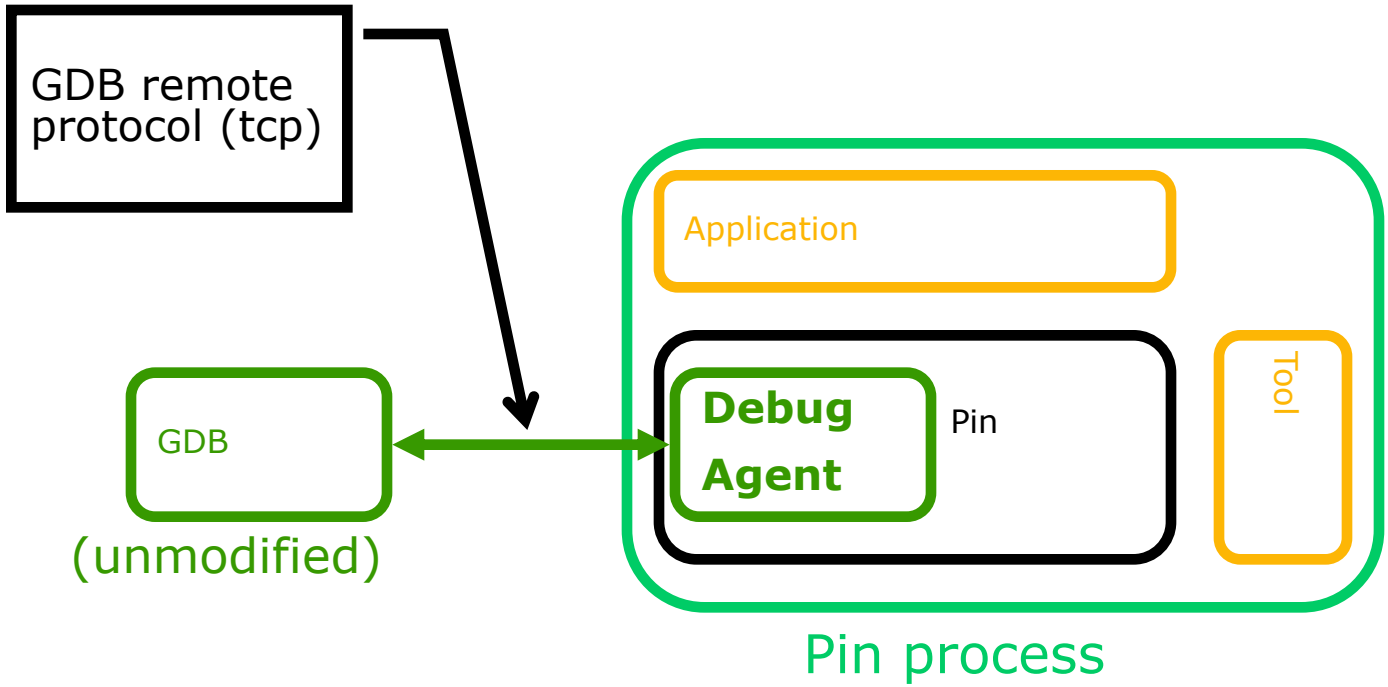
- Provide advanced debugging features with Pin:
  - Stack monitoring features
  - Buffer overrun detection
  - Write your own debugger extension via Pin

Naïve Solution Won't Work



- Why can't we just debug normally?
  - Debugger sees Pin state, not application state
  - Pin recompiles application code
  - Instructions wrong, registers wrong, PC wrong, …

Pin Debugger Interface



- GDB debugs application (not Pin itself)
- Leverage GDB remote protocol ABI

Debug the Application with Pin - GDB

1. Run Pin with -appdebug

```
$ pin -appdebug -t tool.so -- ./application
Application stopped until continued from debugger.
Start GDB, then issue this command at the (gdb) prompt:
  target remote :1234
```

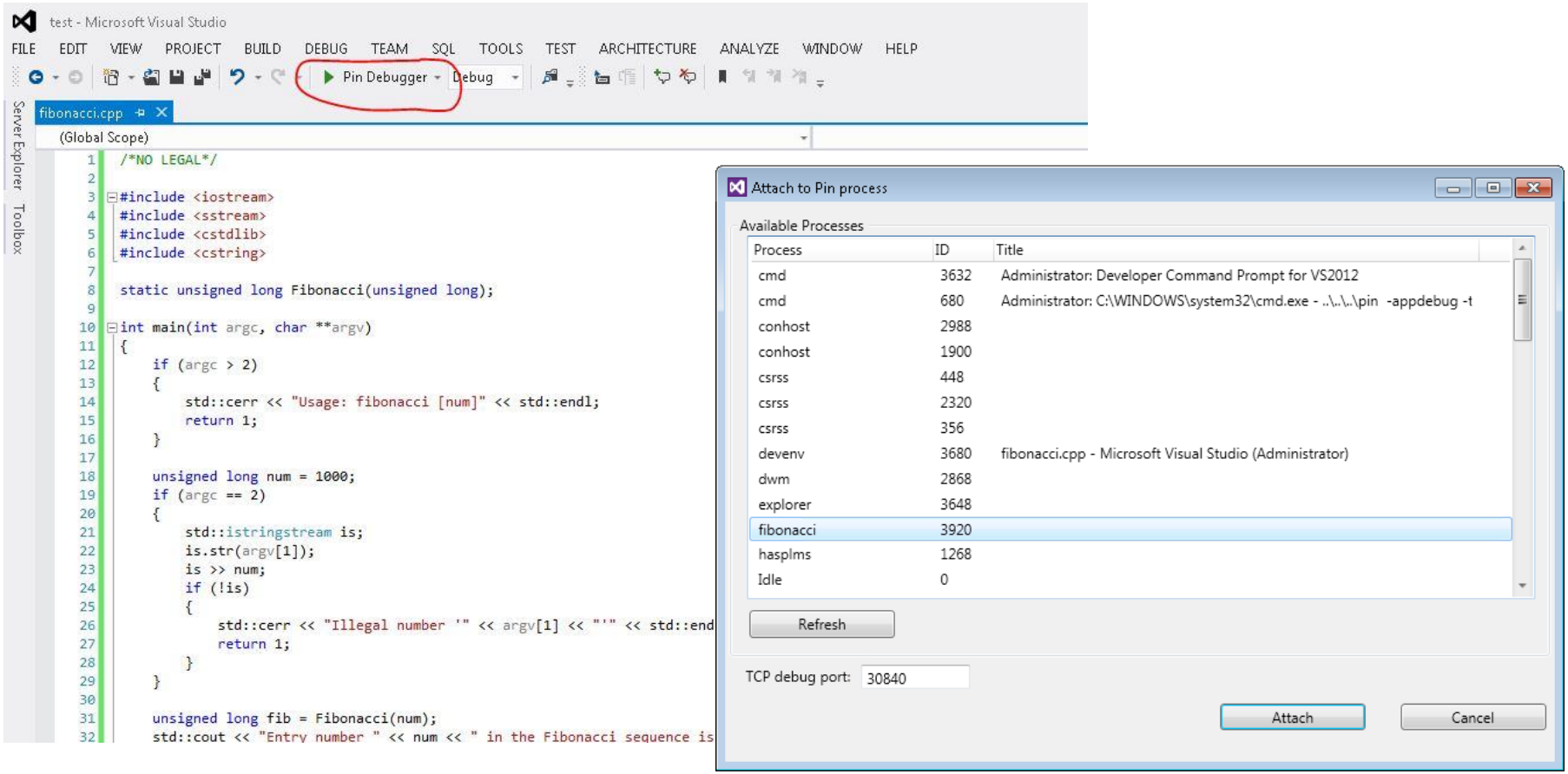
2. Start GDB, enter "target remote …"

```
$ gdb ./application
(gdb) target remote :1234
```

3. Set breakpoints, etc. Continue with "cont"

```
(gdb) break main
(gdb) cont
```

Debug the Application with Pin – Visual Studio plugin



- Look for the installer **pinadx-vsextension-X.Y.Z.msi** in the root of the Pin kit.

Extending the Debugger

- Normal debugging with Pin useful but limited
- Extending the debugger:
  - Add GDB commands via a Pin tool
  - Stop at "semantic breakpoint" via instrumentation
- Use the "monitor" keyword for implementing custom commands

Stack Debugger Pintool

```
$ pin -appdebug -t stack-debugger.so --
  ./app

$ gdb ./app
(gdb) target remote :1234
(gdb) monitor stackbreak 4000
Break when thread uses 4000 stack bytes.
(gdb) cont
Thread uses 4004 stack bytes.
[…]
(gdb) monitor stats
Maximum stack usage: 8560 bytes.
```

Commands implemented in Pintool

Stack-Debugger Instrumentation

- `Thread Start:`
  StackBase = %esp;
  MaxStack = 0;
- […]
- `sub $0x60, %esp`
  size = StackBase - %esp;
  if (size > MaxStack) MaxStack = size;
  if (size > StackLimit) TriggerBreakpoint();
- `cmp %esi, %edx`
- `jle <L1>`

After each stack-changing instruction

ManualExamples/stack-debugger.cpp

instrumentation routine

```
VOID Instruction(INS ins, VOID *)
{
    if (INS_RegWContain(ins, REG_STACK_PTR))
    {
        IPOINT where = (INS_HasFallThrough(ins)) ?
            IPOINT_AFTER : IPOINT_TAKEN_BRANCH;
        INS_InsertCall(ins, where, (AFUNPTR)OnStackChange,
            IARG_REG_VALUE, REG_STACK_PTR,
            IARG_THREAD_ID, IARG
    }
}

VOID OnStackChange(ADDRINT sp,
{
    size_t size = StackBase - sp;
                  StackMax = size;
                ) {
                s " << size << " stack bytes.";
                reakpoint(ctxt, tid, FALSE, os.str());
    }
}
```

analysis routine

Triggers debugger breakpoint

Insert only after instructions that write to %esp

ManualExamples/stack-debugger.cpp

```
int main() {
    […]
    PIN_AddDebugInterpreter(HandleDebugCommand, 0);
}

BOOL HandleDebugCommand(const string &cmd, string *result) {
    if (cmd == "stats")
    {
        return TRUE;
    }
    else if (cmd.find("stackbreak ") == 0)
    {
        StackLimit = /* parse limit */;
        ostringstream os;
        os << "Break when thread uses " << StackLimit << " stack bytes.";
        *result = os.str();
        return TRUE;
    }
    return FALSE;  // Unknown command
}
```

Hooks the GDB "monitor" command. E.g.:

(gdb) monitor stats

(gd

Receives text after "monitor"

This string written to GDB session

Other Debugger Tools

- Breakpoint on buffer overrun
- Debug from a recorded log file
- Reverse debugging from a recording
- Design your own custom debugger tool

Part 4
optimizing Pin tools performance

Reducing Instrumentation Overhead

Total Overhead = Pin Overhead + Pintool Overhead

~5% for SPECfp and ~50% for SPECint

Pin team's job is to minimize this

Usually much larger than pin overhead

Pintool writers can help minimize this!

Reducing the Pintool's Overhead

Pintool's Overhead

Instrumentation Routines Overhead + Analysis Routines Overhead

Frequency of calling an Analysis Routine x Work required in the Analysis Routine

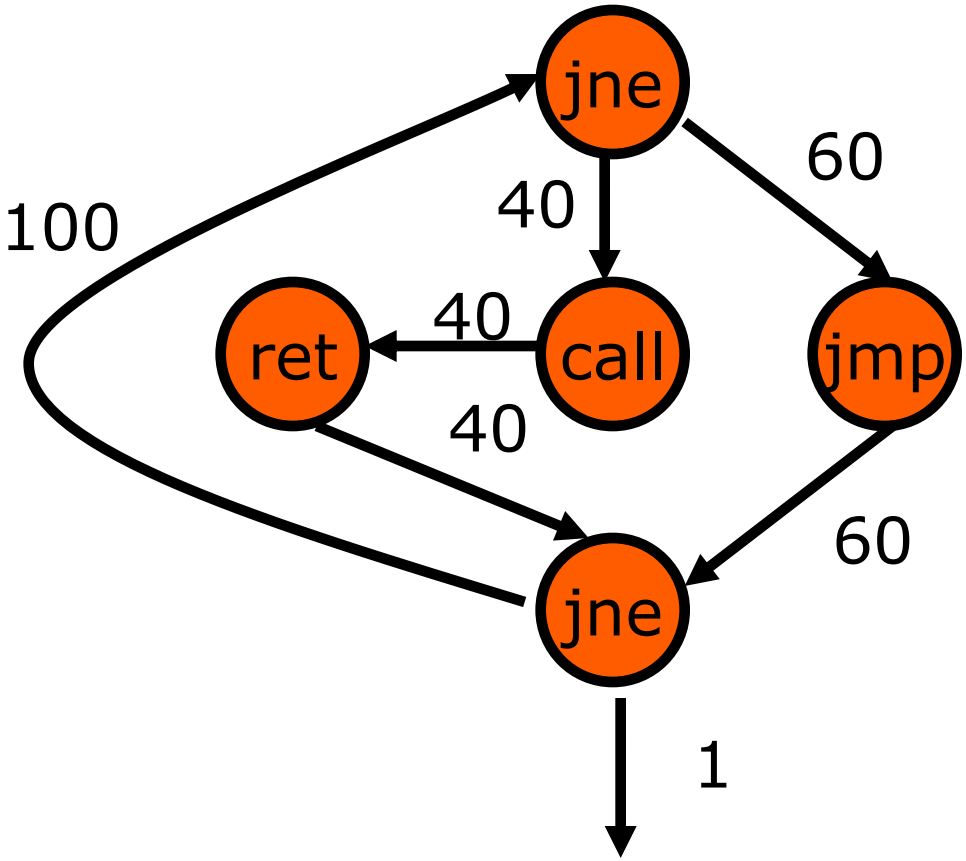
Work required for transiting to Analysis Routine + Work done inside Analysis Routine

Tip #1
Reducing Work in Analysis Routines

- Key: Shift computation from analysis routines to instrumentation routines whenever possible

- This usually has the largest speedup

Counting control flow edges



Edge Counting: a Slower Version

```
...
void docount2(ADDRINT src, ADDRINT dst, INT32 taken)
{
    COUNTER *pedg = Lookup(src, dst);
    pedg->count += taken;
}
```

Analysis

```
void Instruction(INS ins, void *v) {
    if (INS_IsBranchOrCall(ins))
    {
       INS_InsertCall(ins, IPOINT_BEFORE, (AFUNPTR)docount2,
                      IARG_INST_PTR, IARG_BRANCH_TARGET_ADDR,
                      IARG_BRANCH_TAKEN, IARG_END);
    }
}
...
```

Instrumentation

Edge Counting: a Faster Version

Analysis

```
void docount(COUNTER* pedge, INT32 taken) {
    pedg->count += taken;
}
void docount2(ADDRINT src, ADDRINT dst, INT32 taken) {
    COUNTER *pedg = Lookup(src, dst);
    pedg->count += taken;
}
```

Instrumentation

```
void Instruction(INS ins, void *v) {
    if (INS_IsDirectBranchOrCall(ins)) {
        COUNTER *pedg = Lookup(INS_Address(ins),
                INS_DirectBranchOrCallTargetAddress(ins));
        INS_InsertCall(ins, IPOINT_BEFORE, (AFUNPTR) docount,
                IARG_ADDRINT, pedg, IARG_BRANCH_TAKEN, IARG_END);
    }
    else if INS_IsIndirectBranchOrCall(ins) {
        INS_InsertCall(ins, IPOINT_BEFORE, (AFUNPTR) docount2,
                        IARG_INST_PTR, IARG_BRANCH_TARGET_ADDR,
                        IARG_BRANCH_TAKEN, IARG_END);
    }
}
…
```

Tip #2
Reduce Analysis Calls Frequency

- Key: Instrument at the largest granularity whenever possible

- Instead of inserting one call per instruction, insert one call per basic block or trace

Slower Instruction Counting

```
counter++;
sub   $0xff, %edx
counter++;
cmp   %esi, %edx
counter++;
jle   <L1>
counter++;
mov   $0x1, %edi
counter++;
add   $0x10, %eax
```

Faster Instruction Counting

Counting at BBL level

```
counter += 3
sub   $0xff, %edx

cmp   %esi, %edx

jle   <L1>
```

```
counter += 2
mov   $0x1, %edi

add   $0x10, %eax
```

Counting at Trace level

```
sub   $0xff, %edx

cmp   %esi, %edx

jle   <L1>
```

```
mov   $0x1, %edi

add   $0x10, %eax
counter += 5
```

```
counter+=3
```

L1

Tip #3
Reducing Work for Analysis Transitions

- Reduce number of arguments to analysis routines
- Inline analysis routines
- Use conditional instrumentation
- See how in next slides

Reduce Number of Arguments

- Eliminate arguments only used for debugging
- Instead of passing TRUE/FALSE, create 2 analysis functions
  - Instead of inserting a call to:
    Analysis(BOOL val)
  - Insert a call to one of these:
    AnalysisTrue()
    AnalysisFalse()
- **IARG_CONTEXT is very expensive (> 10 arguments)**
  - **Use the cheaper IARG_CONST_CONTEXT**

Inlining

Inlinable

```
int docount0(int i) {
    x[i]++
    return x[i];
}
```

Not-inlinable

```
int docount1(int i) {
    if (i == 1000)
        x[i]++;
    return x[i];
}
```

Not-inlinable

```
int docount2(int i) {
    x[i]++;
    printf("%d", i);
    return x[i];
}
```

Not-inlinable

```
void docount3() {
    for(i=0;i<100;i++)
        x[i]++;
}
```

Inlining

- Use the –log_inline invocation switch to record inlining decisions in pin.log

```
pin -log_inline –t mytool – app
```

- Look in pin.log

```
Analysis function (0x2a9651854c) from mytool.cpp:53  INLINED

Analysis function (0x2a9651858a) from mytool.cpp:178 NOT INLINED
    The last instruction of the first BBL fetched is not a ret instruction
```

- Look at source or disassembly of the function in mytool.cpp at line 178

```
0x0000002a9651858a push rbp
0x0000002a9651858b mov rbp, rsp
0x0000002a9651858e mov rax, qword ptr [rip+0x3ce2b3]
0x0000002a96518595 inc dword ptr [rax]
0x0000002a96518597 mov rax, qword ptr [rip+0x3ce2aa]
0x0000002a9651859e cmp dword ptr [rax], 0xf4240
0x0000002a965185a4 jnz 0x11
```

  - The function could not be inlined because it contains a control-flow changing instruction (other than ret)

Conditional instrumentation

- A common scenario where the analysis routine has a single "if-then"
  - The "If" part is always executed
  - The "then" part is rarely executed
  - Useful cases:
    1. "If" can be inlined, "Then" is not
    2. "If" has small number of arguments, "then" has many arguments (or IARG_CONTEXT)

- Pintool writer breaks analysis routine into two:
  - *INS_InsertIfCall (ins, …, (AFUNPTR)doif, …)*
  - *INS_InsertThenCall (ins, …, (AFUNPTR)dothen, …)*

IP-Sampling (a Slower Version)

```
const INT32 N = 10000; const INT32 M = 5000;

INT32 icount = N;

VOID IpSample(VOID* ip) {
   --icount;
   if (icount == 0) {
       fprintf(trace, "%p\n", ip);
       icount = N + rand()%M; //icount is between <N, N+M>
   }
}

VOID Instruction(INS ins, VOID *v) {
   INS_InsertCall(ins, IPOINT_BEFORE, (AFUNPTR)IpSample,
                  IARG_INST_PTR, IARG_END);
}
```

IP-Sampling (a Faster Version)

```
INT32 CountDown() {
     --icount;
     return (icount==0);
}
VOID PrintIp(VOID *ip) {
   fprintf(trace, "%p\n", ip);
   icount = N + rand()%M; //icount is between <N, N+M>
}
```

inlined

not inlined

```
VOID Instruction(INS ins, VOID *v) {
   // CountDown() is always called before an inst is executed
   INS_InsertIfCall(ins, IPOINT_BEFORE, (AFUNPTR)CountDown,
                    IARG_END);

   // PrintIp() is called only if the last call to CountDown()
   // returns a non-zero value
   INS_InsertThenCall(ins, IPOINT_BEFORE, (AFUNPTR)PrintIp,
                      IARG_INST_PTR, IARG_END);
}
```

Jitting time

- Jitting is expensive
  - Takes far more time to jit an instruction than to execute a jitted instruction

- Portions of a workload where very many IPs are being jitted, and executed a small number of times
  - Jitting time dominates execution time
  - E.g.
    - startup of a GUI app
    - Compiler compiling a non-large file
  - Vs Loop executing a large number of times
    - Jitting time is amortized over execution time

Optimizing Your Pintools - Summary

- Baseline Pin has fairly low overhead for non-jitting portions of workloads (~5-20%)

- Adding instrumentation can increase overhead significantly, but you can help!

1. Move work from analysis to instrumentation routines
2. Explore larger granularity instrumentation
3. Explore conditional instrumentation
4. Understand when Pin can inline instrumentation

Summary

- **Pin is Intel's dynamic binary instrumentation engine**
- **Pin can be used to instrument all user level code**
  - **Windows, Linux, OSX, Android**
  - **IA-32, Intel64**
  - **Product level robustness**
  - **Jit-Mode for full instrumentation: Thread, Function, Trace, BBL, Instruction**
  - **Probe-Mode for Function Replacement/Wrapping/Instrumentation only.**
  - **Pin supports multi-threading, no serialization of jitted application nor of instrumentation code**
- **Pin API makes Pin tools easy to write**
  - **Presented many tools, many fit on 1 ppt slide**
- **Pin performance is good**
  - **Pin APIs provide for writing efficient Pin tools**
- **Popular and well supported**
  - **30,000+ downloads, 700+ citations**
- **Free Download**
  - **www.pintool.org**
  - **Includes: Detailed user manual, source code for 100s of Pin tools, tutorials**
- **Pin User Group**
  - **http://tech.groups.yahoo.com/group/pinheads/**
  - **Pin users and Pin developers answer questions**

Final note

- Use the Pin manual !

  www.pintool.org -> User's manual

- **A lot** more information about using Pin

- Many more topics – beyond this tutorial
  - How to debug your Pin tool
  - Trace buffers
  - System calls instrumentation
  - Instruction decoding APIs (XED)
  - … And many others

Now go and write your Pin tools!