Dynamic Probes for Linux

A Universal Debugging Mechanism for User and Kernel Space

LinuxWorld Expo 2002
New York

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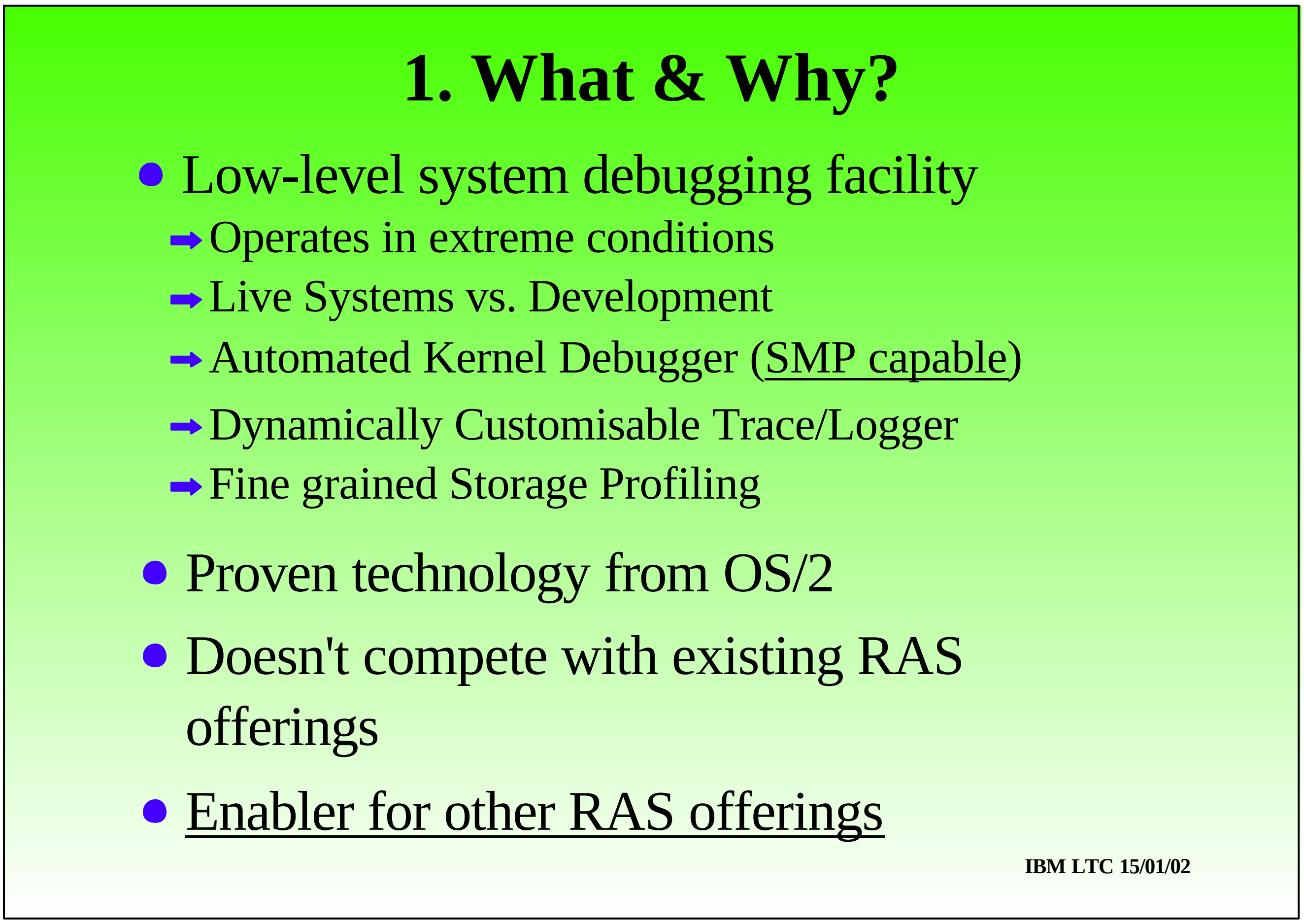
15th January 2002

0. Overview

1. What and Why?
2. DProbes Components
3. Trace Daemon Interface
4. What is a Probepoint?
5. The Probepoint Specification
6. Watchpoint Probes
7. RPN Interpreter
8. RPN Command Categories
9. RPN Invoked External Facilities
10. RPN Program Storage
11. Example RPN Probe Program
12. DProbes Command
13. Successful Employment of DProbes
14. What's Next?
15. Questions



1. What & Why?

- Low-level system debugging facility
  - ➡ Operates in extreme conditions
  - ➡ Live Systems vs. Development
  - ➡ Automated Kernel Debugger (SMP capable)
  - ➡ Dynamically Customisable Trace/Logger
  - ➡ Fine grained Storage Profiling
- Proven technology from OS/2
- Doesn't compete with existing RAS offerings
- Enabler for other RAS offerings

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- What is DProbes and why did we choose this project:
- it's a low-level debugger that is almost seamless in operation so it appropriate for us in production environment.
- It's fully automated and does not use an interactive user interface.
- It's dependence of system facilities is negligible but it has access to the lowest level system resources, which gives it the characteristic of being an automated kernel debugger. But it's much more than that:
- It's impact on system performance is negligible in particular there is no requirement to halt other processors in an SMP environment - compare this with a typical KDB.
- Data about the system is collect by an automated breakpoint mechanism, called probes, which make is also a tracing capability - which is dynamic because code does not have to be prepared for use by DProbes.
- It can also be used for profiling purposes - especially storage profiled by means of the watchpoint facility.
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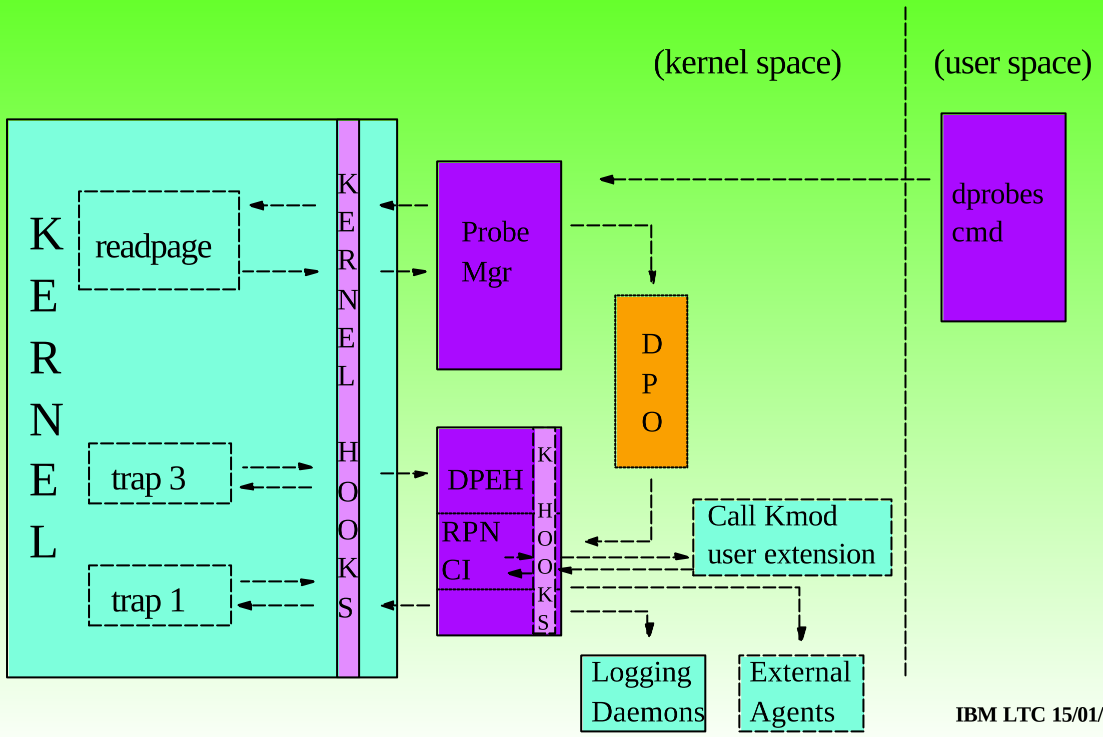
- Why we chose this project:
- It had a proven track-record in OS/2 as a major tools for dealing with the most elusive production environment problems that typically became critical situations.
- There wasn't anything else that compare with DProbes - Open-source development essentially has to be non-competitive since it's for free and it co-operative model of development. (Cygnus developed an probing mechanism with some internal details in common with DProbes, but nothing like as extensive - RH site. There have also been similar small-scale projects run at some universities.
- Most importantly DProbes is an enabler for other Serviceability tools as we shall see.

2. DProbes Components



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- In essence this is what DProbes looks like:
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- Most of it's function is in kernel space. There are two key components:
- 1) The probe manager that looks after the installation and track of whether probes are places (probepoint locations).
- There's a data object that describes a probe: the Dynamic Probe Object.
- The probe mgr essentially hooks the readpage routine to install probepoints whenever a page of code is brought into memory. (it is more complex than this - but avoid going into details here - wait for questions).
-
- 2) The other components is the Dynamic Probe Event Handler, which responds to a breakpoint interrupt.
- It hooks the single-step and breakpoint interrupt vectors under IA32 architecture.
- Part of the DPO is a probe handler program, written in a Reverse Polish Notation language. This contains the instructions, per probepoint, that need to be interpreted when a probepoint "fires". Part of the DPEH is the RPN Command Interpreter (RPN CI) which performs this function.
- The RPN CI may call external facilities such as logging daemons - for tracing purposes
- The RPN CI may transfer control to external agents (no return guaranteed) such as lkcd, kdb, core dump, etc..
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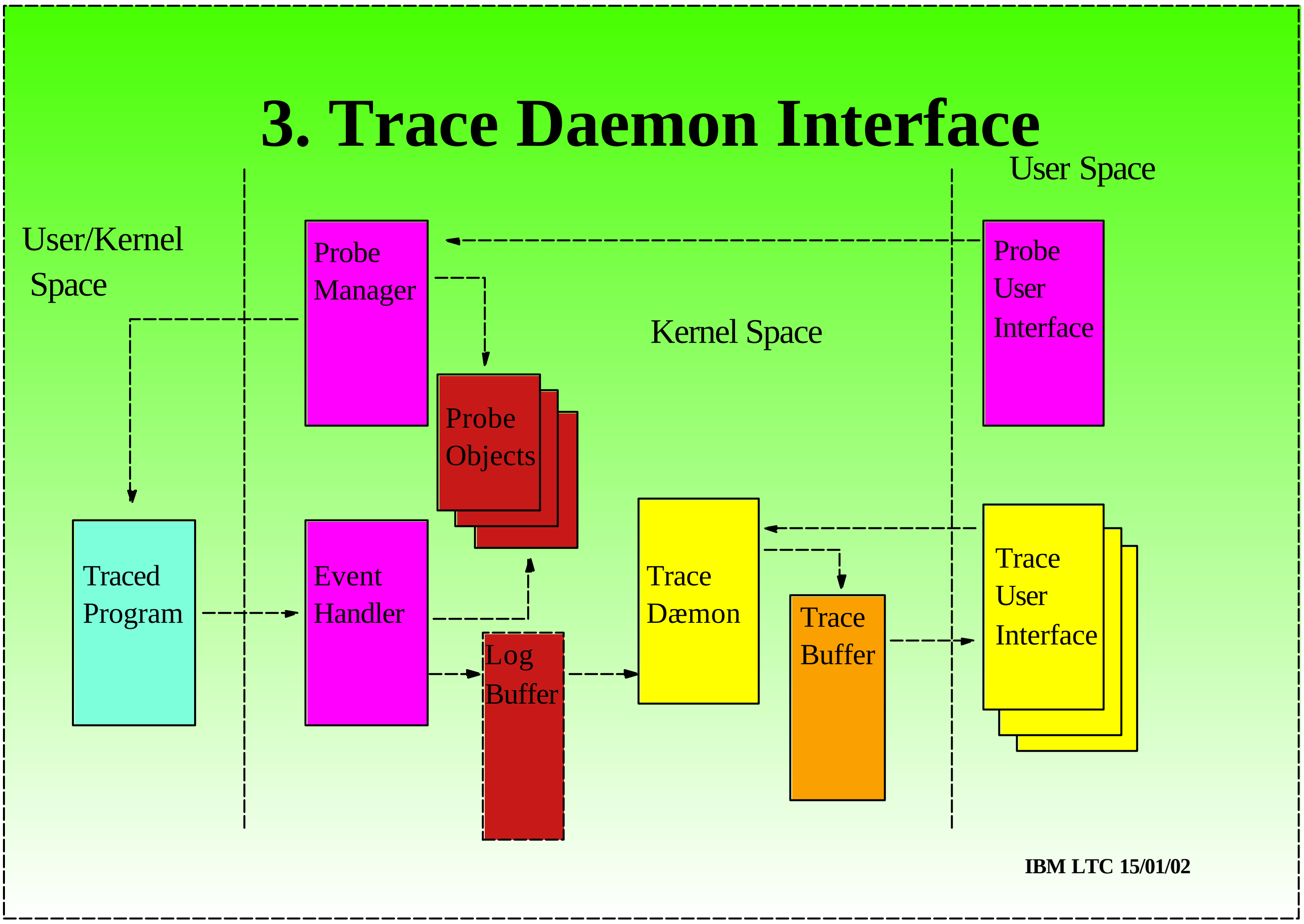
- Finally, there is a command line interface to control the activation and deactivation of probes.



3. Trace Daemon Interface

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- Dynamic Probes provides the debugging engine.
- It operates in kernel space as a self-contained debugger effectively encapsulated in an interrupt handler with minimal dependence on system services.
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- It uses a breakpoint mechanism to insert its probes.
- There is a Log buffer for staging traced data.
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- The only requirement of a system tracing mechanism is that its operates on a dæmon principle that provides an callable interface what can be driven from an interrupt handler.
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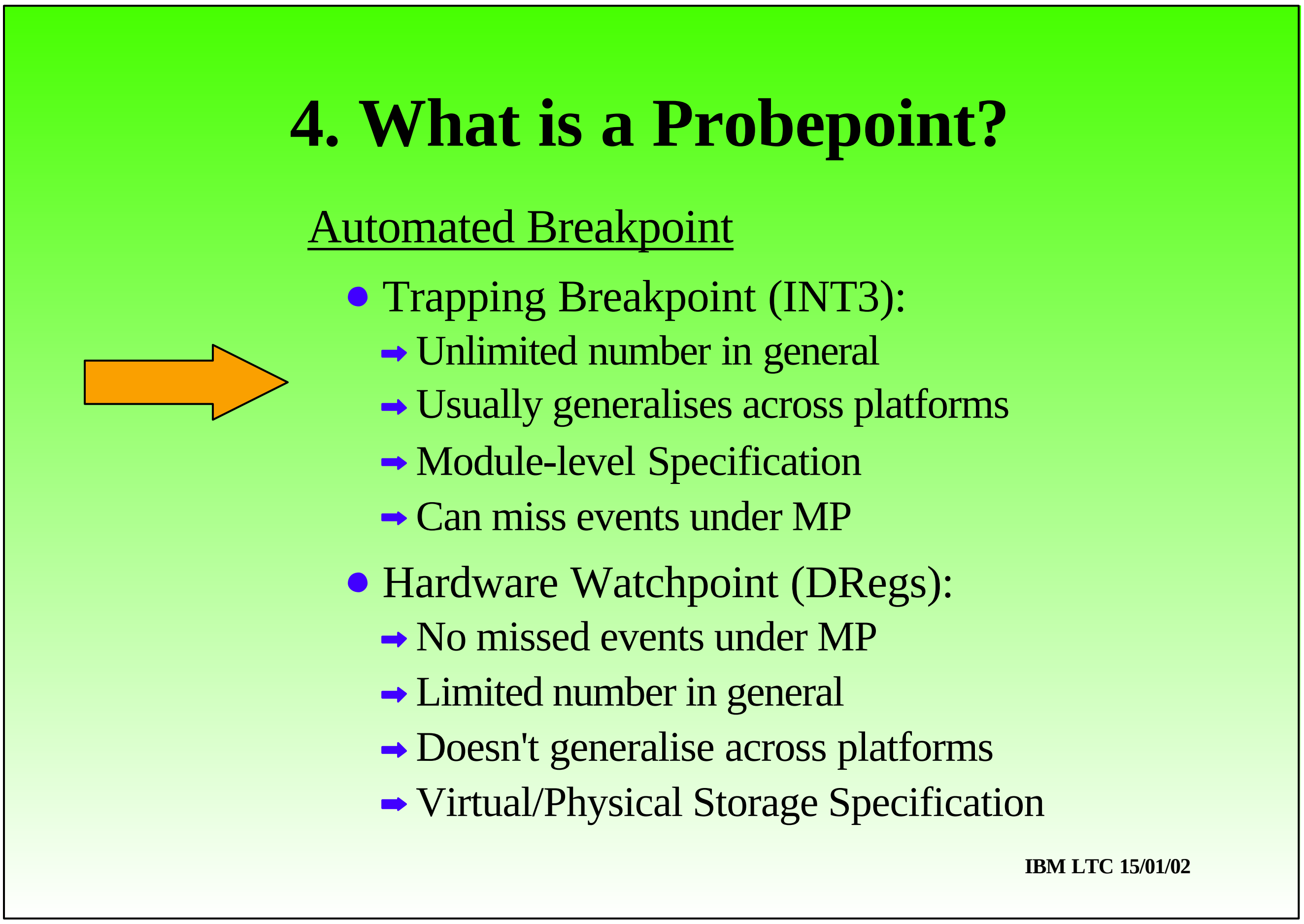
- The Linux Trace Toolkit from Opersys meets these requirements.



4. What is a Probepoint?

Automated Breakpoint

- Trapping Breakpoint (INT3):
  - ➡ Unlimited number in general
  - ➡ Usually generalises across platforms
  - ➡ Module-level Specification
  - ➡ Can miss events under MP
- Hardware Watchpoint (DRegs):
  - ➡ No missed events under MP
  - ➡ Limited number in general
  - ➡ Doesn't generalise across platforms
  - ➡ Virtual/Physical Storage Specification

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- A the heart of DProbes is the Probepoint, which is essentially an automated breakpoint.
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- There are in general two way to implement breakpoints. Each has it merits:
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- The trapping breakpoint is implemented using an instruction replacement technique (INT3 under IA32).
- There's no limit to the number of concurrently installed breakpoints.
- This mechanism generalises across other architectures
- We can canonically define probes with reference to a module rather than storage location - discussed next foil.
- However there is a theoretical exposure under MP: because we need unlimited access to system resources, the DPEH runs in privileged mode, which means we can't generally emulate the original instruction after the breakpoint fires. We have to single-step it in situ. This means temporarily removing the breakpoint and thus exposing us to a miss if the same probe was executed on another processor. In practice this is not a problem, since we tend to be concerned with races in two different pieces of code for the same data, rather than the same piece of code. However it's really a problem the stop-cpus switch does allow execution on other processors to be suspended during single-step
-
- The alternative mechanism is to use the inbuilt debugging H/W sometimes called the "watchpoint" mechanism.
- The MP miss problem doesn't occur
- However, the number of concurrent watchpoint can be severely limited (4 on IA32).
- Also it's very tied to a particular architecture and so doesn't generalise easily.
- Finally watchpoints are specified by storage location without reference to context or module which as the potential to cause unnecessary hits which would have to be filtered.
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- We choose primarily the trapping breakpoint mechanism for probepoints in code. These are defined relative to a module.
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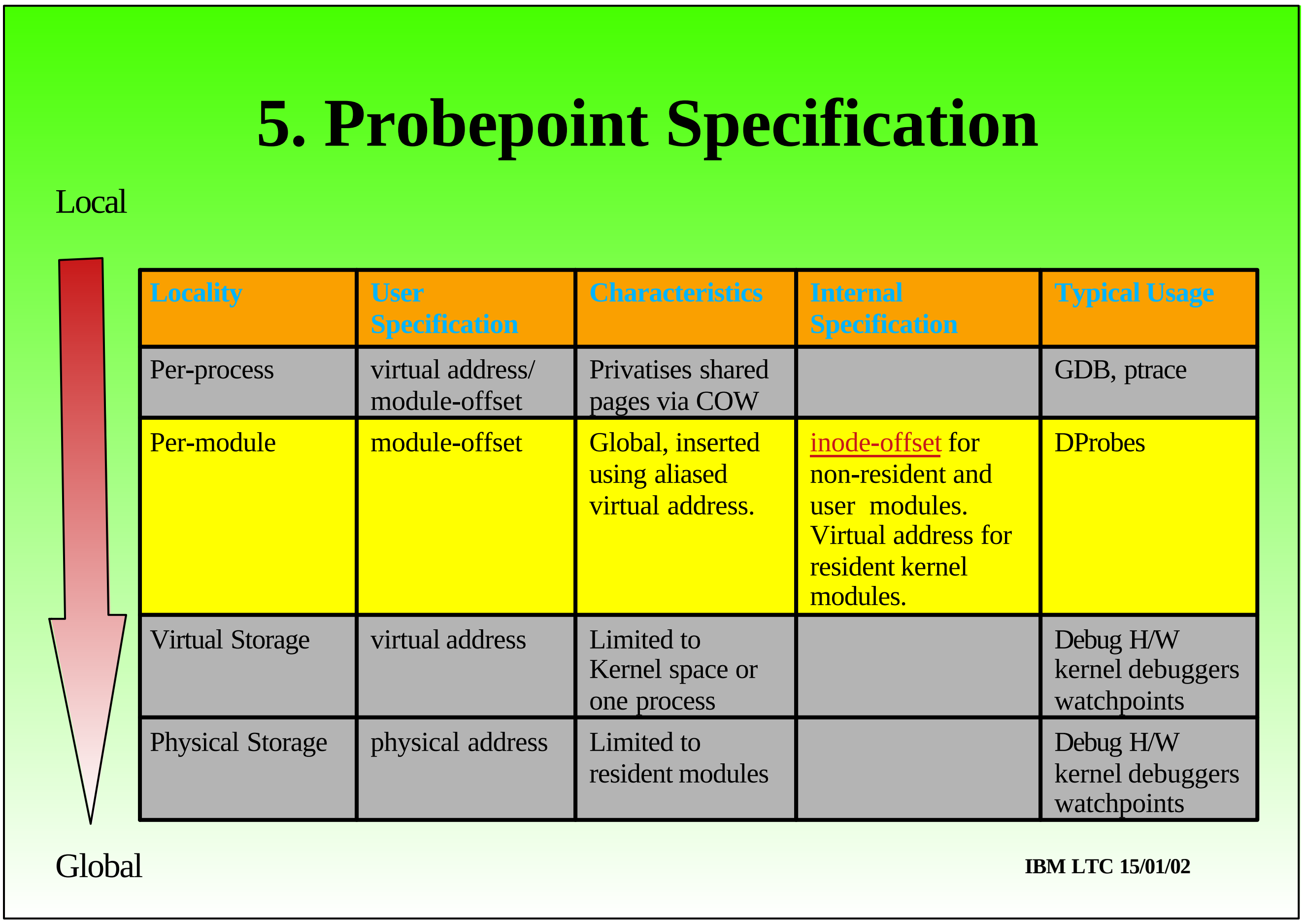

5. Probepoint Specification

Local

Locality	User Specification	Characteristics	Internal Specification	Typical Usage
Per-process	virtual address/ module-offset	Privatises shared pages via COW		GDB, ptrace
Per-module	module-offset	Global, inserted using aliased virtual address.	inode-offset for non-resident and user modules. Virtual address for resident kernel modules.	DProbes
Virtual Storage	virtual address	Limited to Kernel space or one process		Debug H/W kernel debuggers watchpoints
Physical Storage	physical address	Limited to resident modules		Debug H/W kernel debuggers watchpoints

Global

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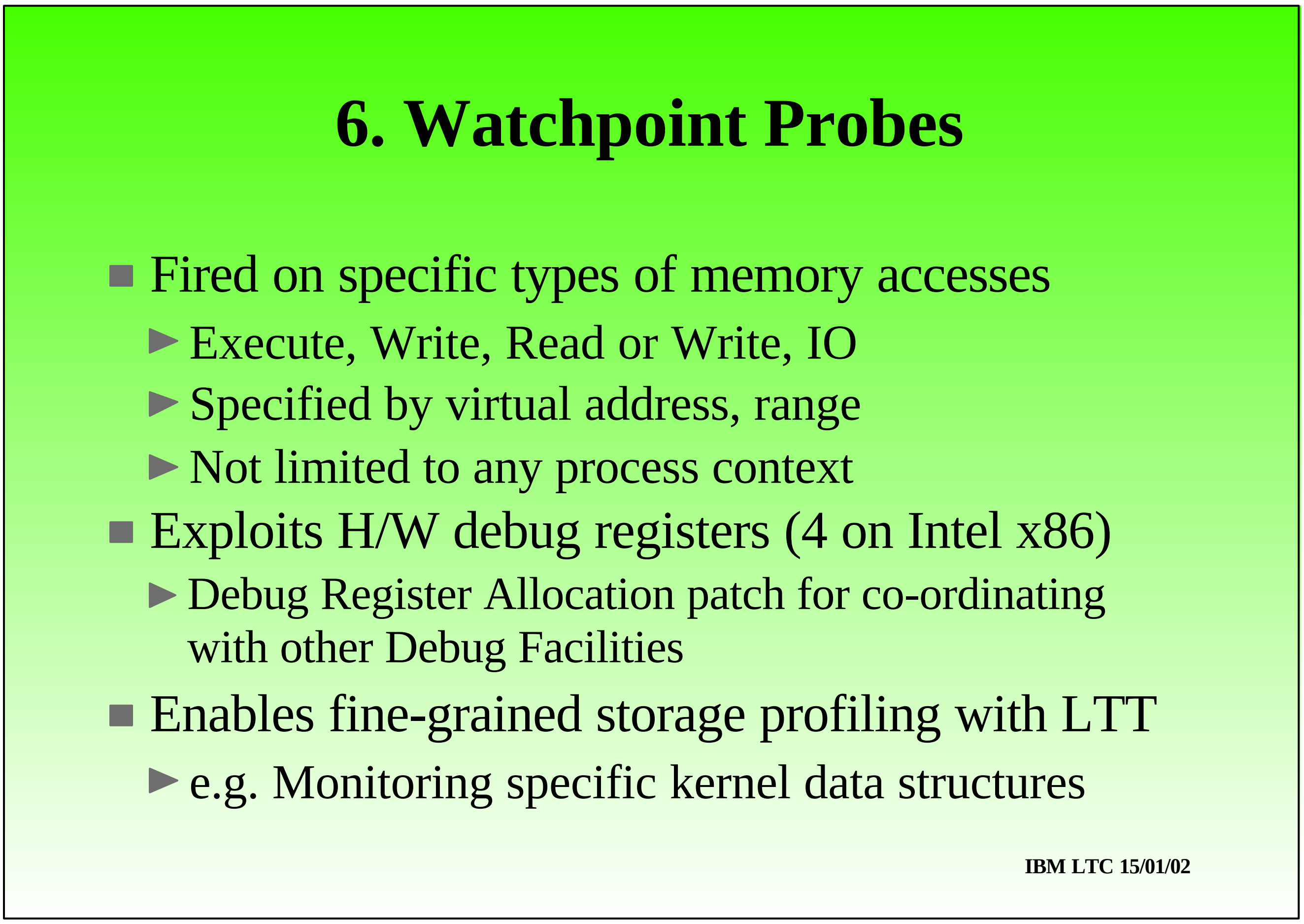
- We mentioned on the previous foil that the probepoint is defined relative to a module. This slide compares the merits and employment of various breakpoint tracking strategies.
- GDB defines breakpoints per process using ptrace. The placement of a breakpoint causes privatisation of a page (COW), with a resulting impact to the swap device.
- Debuggers using watchpoints - typically KDB place breakpoints in kernel space and have to filter unnecessary interrupts if the want a per-process view. It is difficult to relate such breakpoints to a user module since the virtual storage mapping may be different per process.
- On some architectures watchpoints may be defined by physical storage location (e.g. S/390) but again this is difficult to relate to a user's module because the physical mapping may change with paging activity.
- DProbes uses a module-relative approach. BPs are inserted using the physical address to avoid COW proliferation of privatised pages. We track the BP using inode-offset. This gives us a global context to the probe without the impact to the swap device.



6. Watchpoint Probes

- Fired on specific types of memory accesses
  - Execute, Write, Read or Write, IO
  - Specified by virtual address, range
  - Not limited to any process context
- Exploits H/W debug registers (4 on Intel x86)
  - Debug Register Allocation patch for co-ordinating with other Debug Facilities
- Enables fine-grained storage profiling with LTT
  - e.g. Monitoring specific kernel data structures

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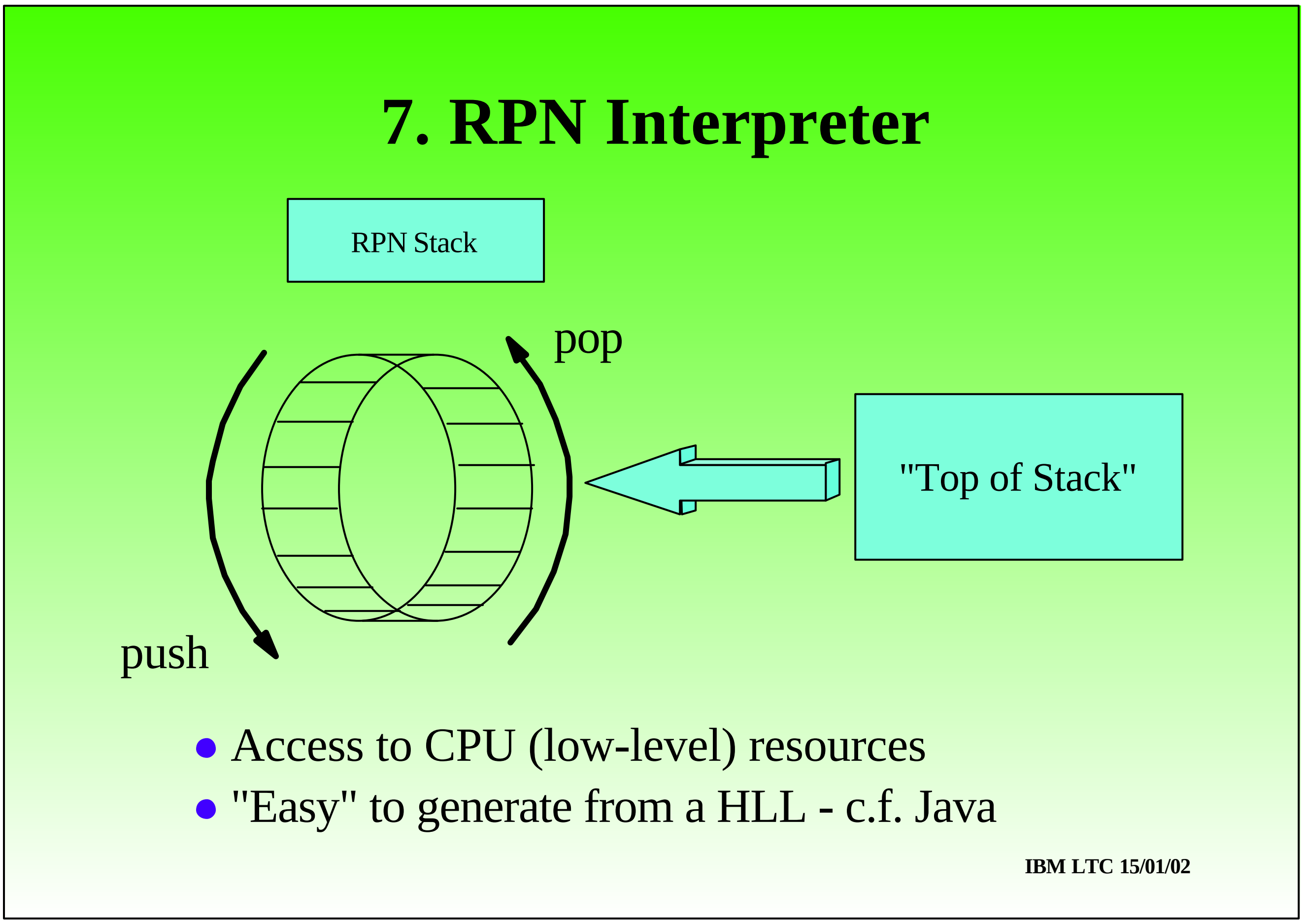
- We do however also exploit watchpoints in the watchpoint probes (as opposed to the breakpoint probes).
- These probes are virtual-storage based and global without a module or process context.
- They permit memory accesses to be probed whether read/write/execute or IO
-
- IA32 limits us to a maximum of 4 WPs. (However we have devise a mechanism for simulating a generalised extension to this - details cannot be revealed at this stage but essentially it hooked into the paging mechanism).
- Linux does not cater well for multiple users of debugging registers - so we have also provided a DR allocation patch.



7. RPN Interpreter

RPN Stack

pop

push

"Top of Stack"

- Access to CPU (low-level) resources
- "Easy" to generate from a HLL - c.f. Java

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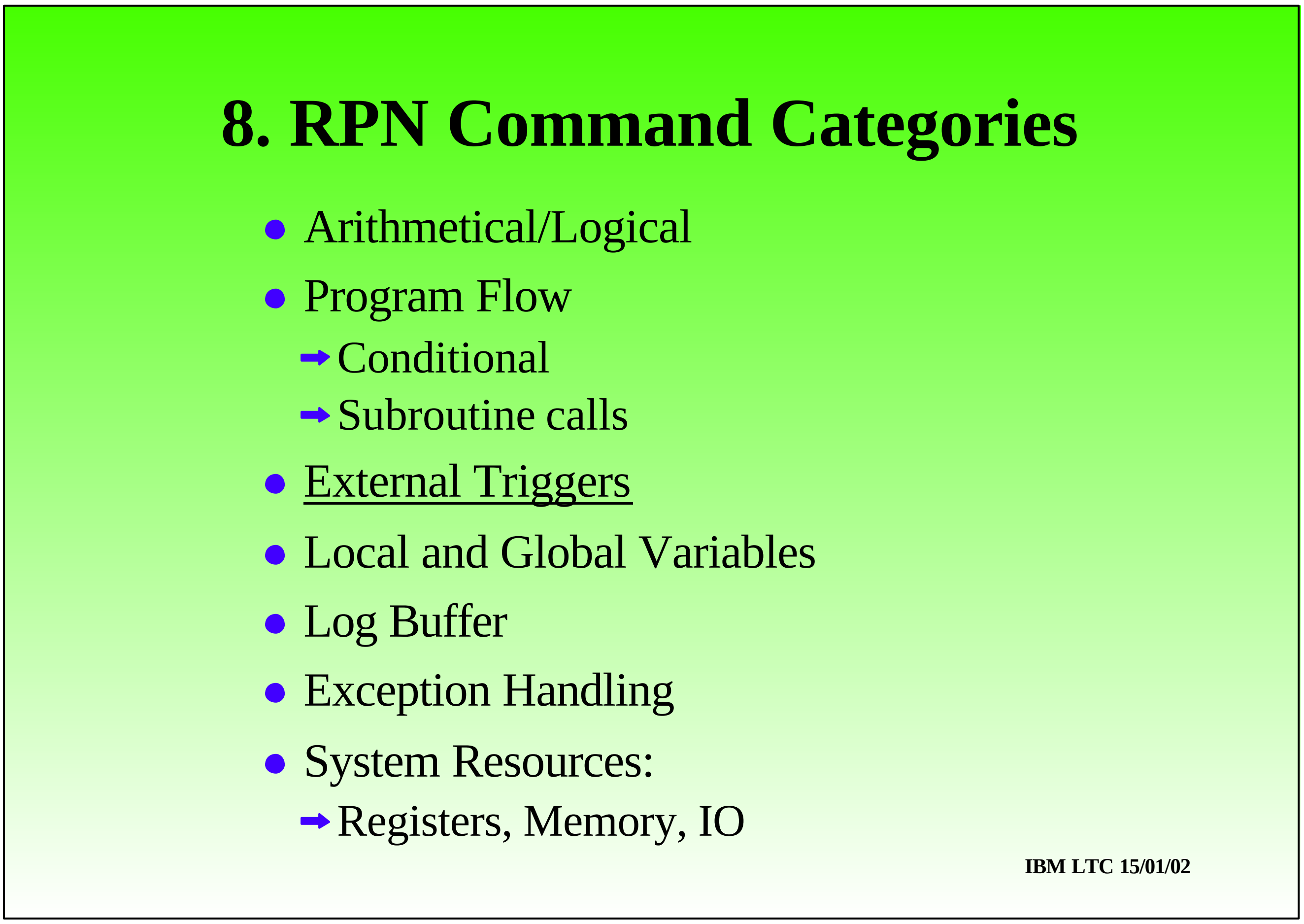
- The heart of the DPEH is the RPN command interpreter.
- Two questions:
  - what is RPN
  - why use RPN
-
- languages - such as List, use a stack on which to place operands then execute the operation, which the operands to be popped off the stack and the result pushed onto the stack. It's "Reverse" because syntactically one codes operands before operation. It's "Polish" probably because it was invented by a Pole.
-
- RPN interpreters are very easy to implement.
- They give easy access to low-level resources while generalising across architectures
- They permit high-level languages to be defined which generate RPN code - compare with Java and the JVM which is an RPN-based virtual machine.



8. RPN Command Categories

- Arithmetical/Logical
- Program Flow
  - ➡ Conditional
  - ➡ Subroutine calls
- External Triggers
- Local and Global Variables
- Log Buffer
- Exception Handling
- System Resources:
  - ➡ Registers, Memory, IO

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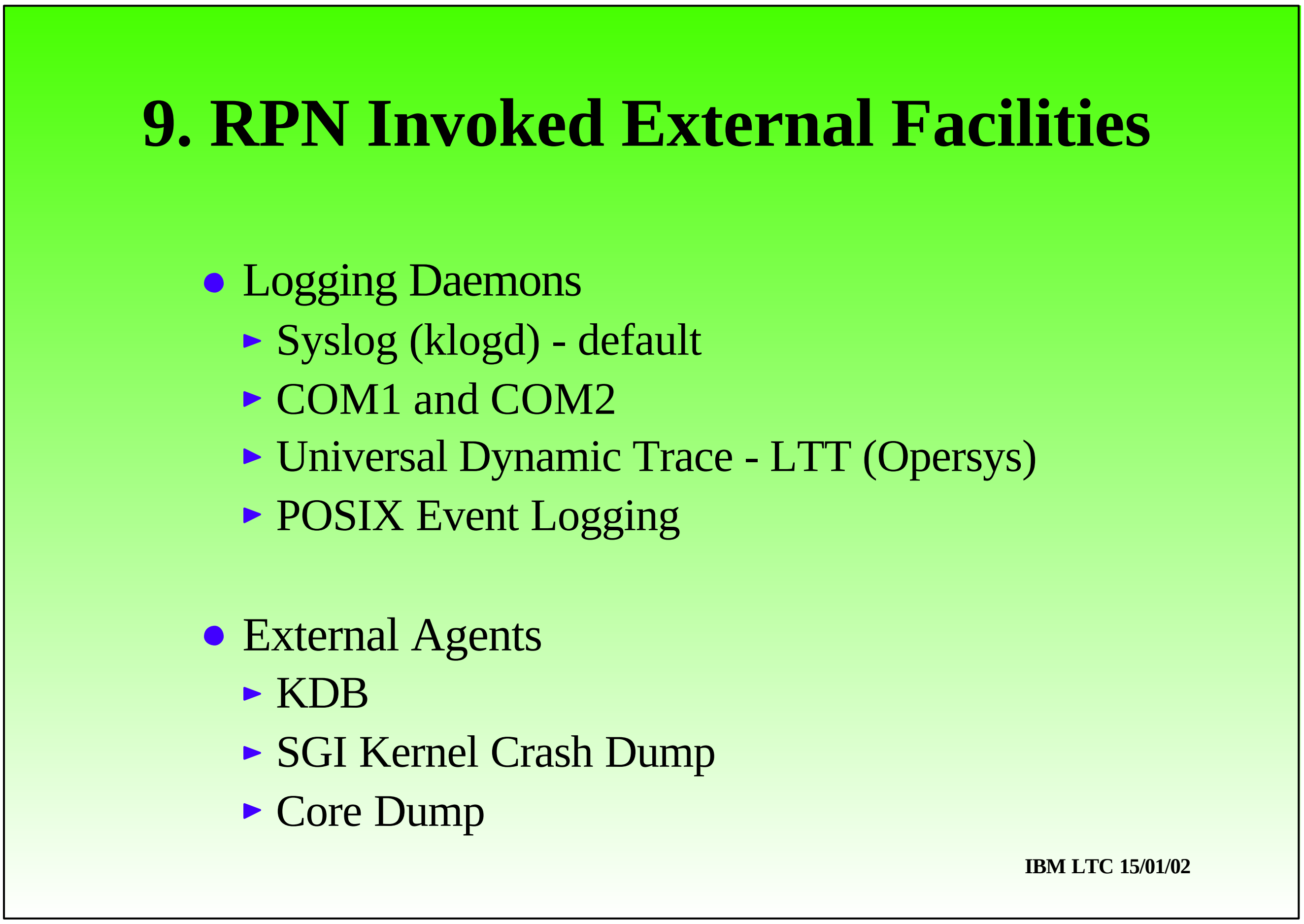
- The RPN command language comprises the following categories of command:
-
- Basic arithmetical and logical instructions
- Program flow including conditional logic and subroutine calls.
- Mechanisms for invoking external agents and daemon - External Triggers.
- Local and Global storage for use by the RPN program#
- Exception handling to recover from unexpected environmental conditions such as memory not accessible.
- Access to system resources. CPU regs, Memory, Kernel data items, IO ports etc..



9. RPN Invoked External Facilities

- Logging Daemons
  - Syslog (klogd) - default
  - COM1 and COM2
  - Universal Dynamic Trace - LTT (Opersys)
  - POSIX Event Logging
- External Agents
  - KDB
  - SGI Kernel Crash Dump
  - Core Dump

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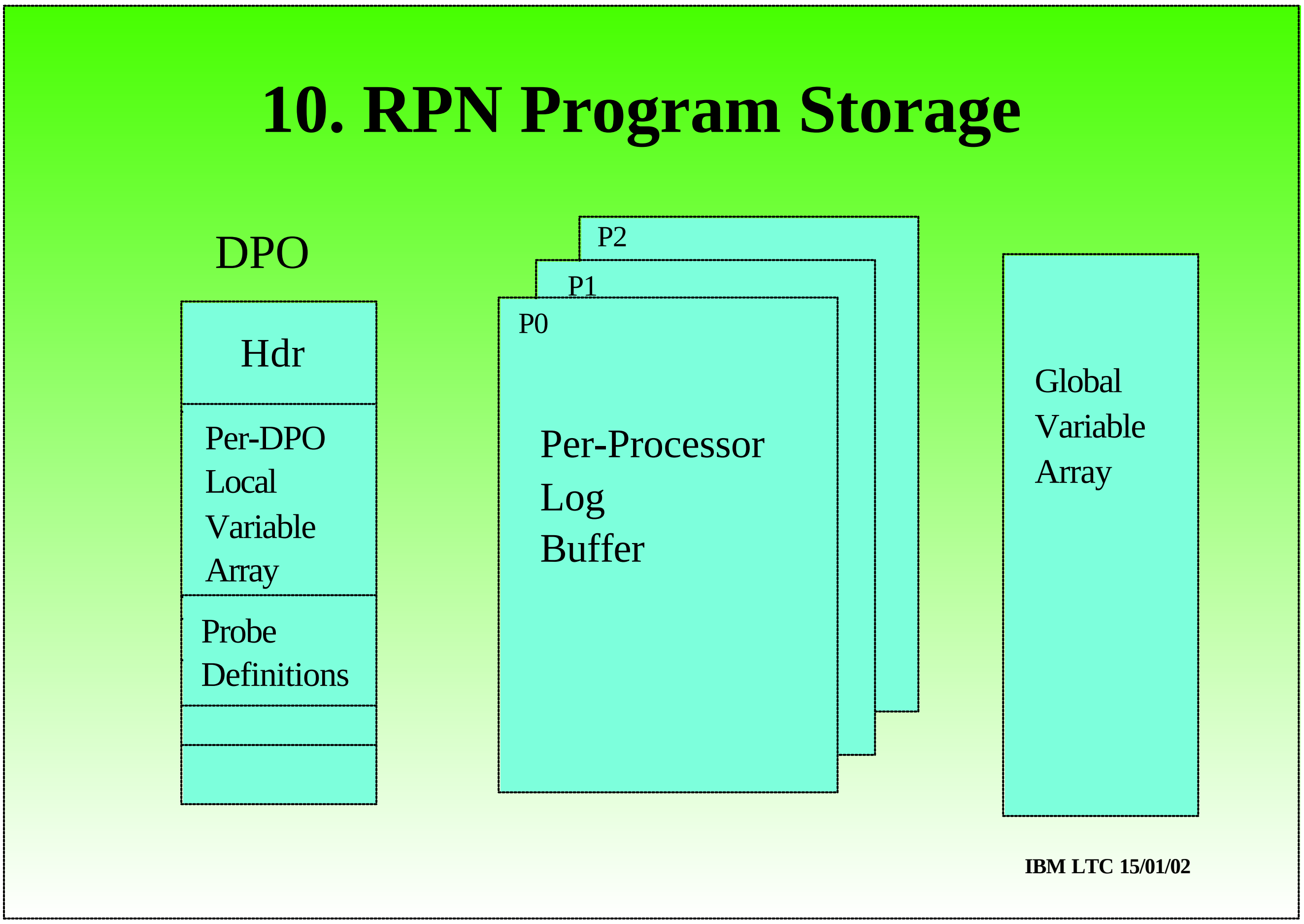
- Externally triggered facilities come in two types:
- Logging Daemons, to which are passed a log buffer and control is returned to the DPEH. Examples include: syslog, com ports, LTT, Event Log.
- External Agents transfer control to the external facility without expectation of return. Examples of these are KDB,lkcd, code dump.
- These type types are handled slightly differently by the DPEH. Because Logging Daemons tend to want to record only one event per attempted execution of a code location - we avoid log replications by delaying logging until the original instruction executes without faulting - think about recoverable page faults and the effect it would have on a trace if an event were recorded per trial execution. This behaviour btw can be overridden using the logonfault facility.
- With external agents we restore the original instruction and give control to the agent without single-stepping.



10. RPN Program Storage

DPO

Hdr

Per-DPO Local Variable Array

Probe Definitions

P2

P1

P0

Per-Processor Log Buffer

Global Variable Array

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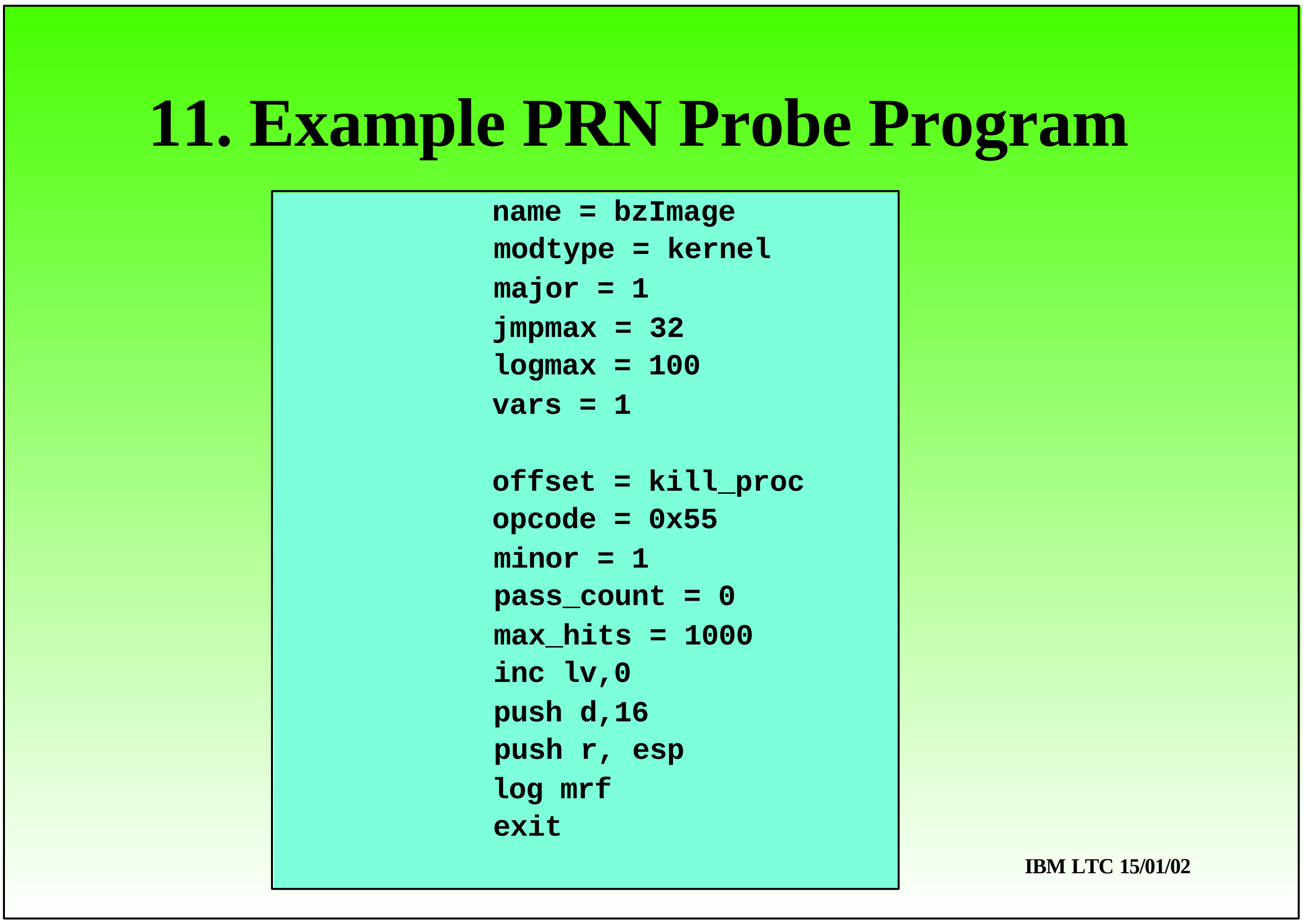
- There are three types of working storage available to a probe-handler:
- The local variable array that allows data to be share among probe handlers for a given module.
- The log buffer, which is defined per-processor to avoid unnecessary serialisation. This is used to stage the logged data which is eventually passed to the Logging Daemon.
- The global variable array allows data to be shared among all probe handlers, whatever their module.



11. Example PRN Probe Program

```
name = bzImage
modtype = kernel
major = 1
jmpmax = 32
logmax = 100
vars = 1

offset = kill_proc
opcode = 0x55
minor = 1
pass_count = 0
max_hits = 1000
inc lv,0
push d,16
push r, esp
log mrf
exit
```

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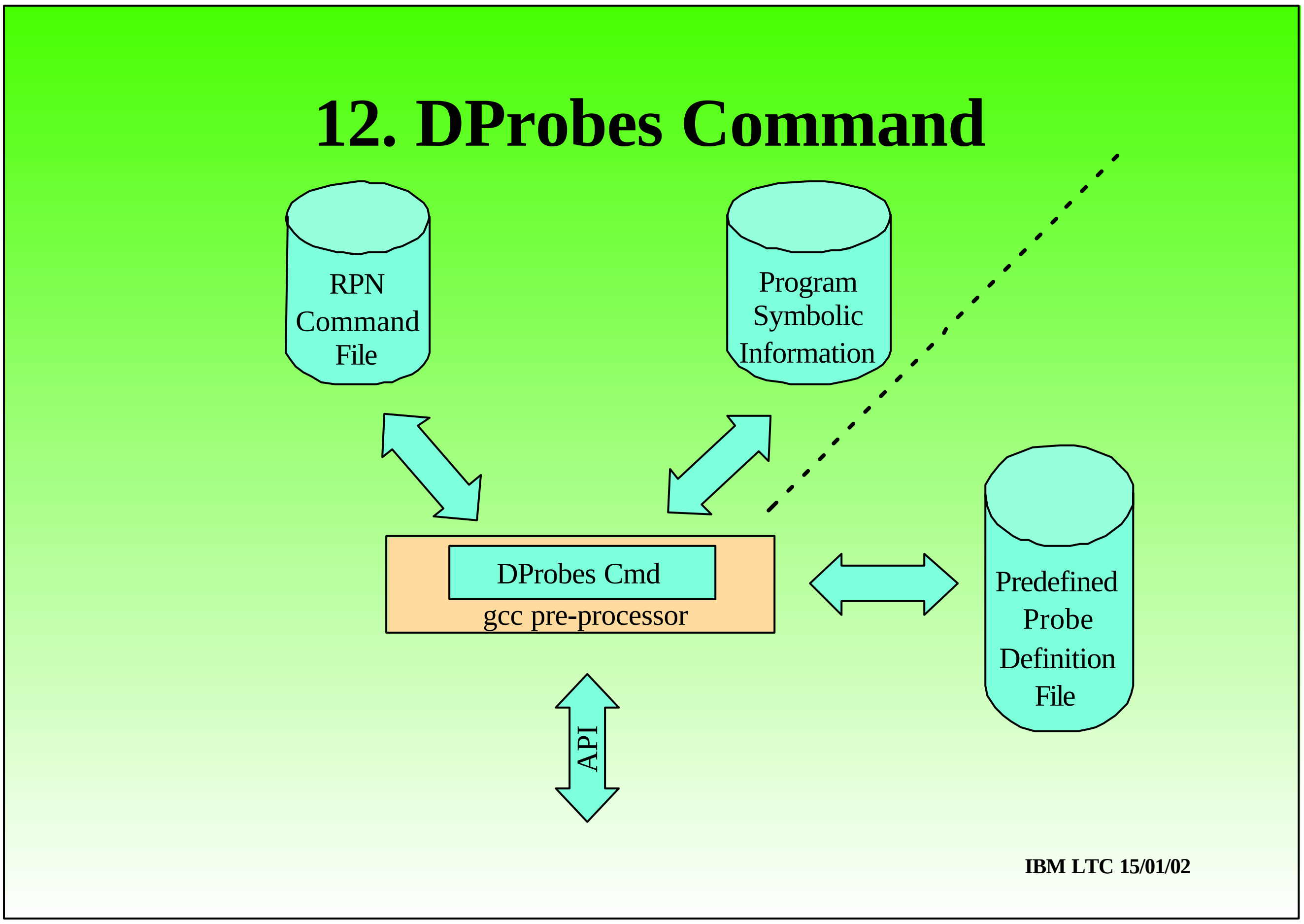
- This is an example RPN probe handler definition.
-
- There's a header section that defines the module, number of local variables and other controls.
-
- Then there are a number of probe definition that follow. Each has a header followed by the RPN program.
-
- The probe header gives the location, in this case kill_proc and we also specify the original opcode for sanity reasons particularly where an address is given instead of a symbol.
- The program increments local variable 0, and logs the parameters pointed to by the ESP register on entry to kill_proc.



12. DProbes Command

RPN Command File

Program Symbolic Information

DProbes Cmd

gcc pre-processor

Predefined Probe Definition File

API

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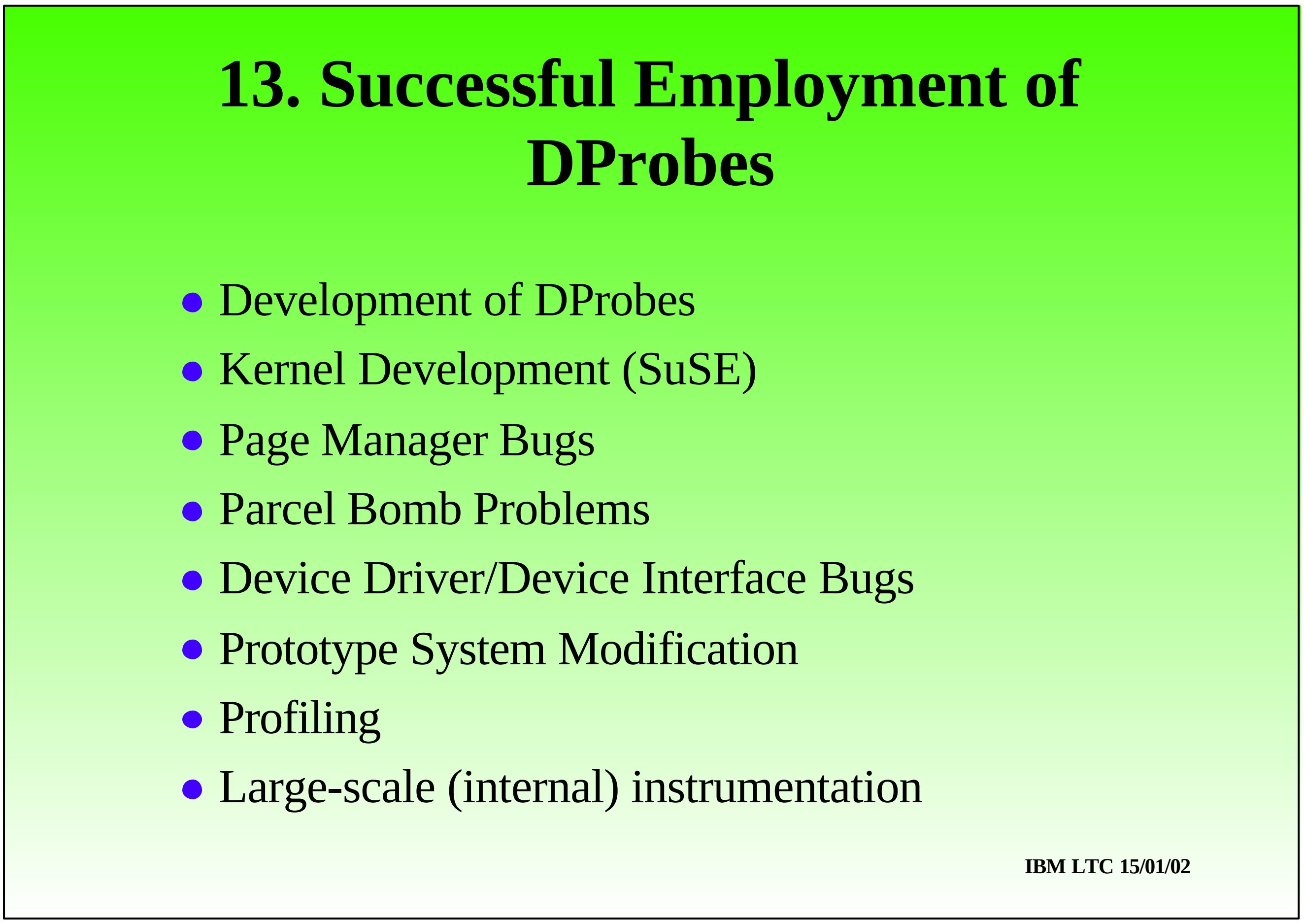
- The DProbes command takes as input either:
- The RPN file and optionally Symbolic program information
- Or, a predefined probed definition file. This is essentially a pre-compiled version of the RPN file, in a form ready to pass to the DProbes API. It permits probes to be defined using symbolic information present only when the probed program is compiled with debugging options, then to have the debugging information stripped,
- The DProbes command invokes the gcc pre-processor - this allows standard C-like pre-processor constructs in the RPN file and for symbols to be substituted from the command line.



13. Successful Employment of DProbes

- Development of DProbes
- Kernel Development (SuSE)
- Page Manager Bugs
- Parcel Bomb Problems
- Device Driver/Device Interface Bugs
- Prototype System Modification
- Profiling
- Large-scale (internal) instrumentation

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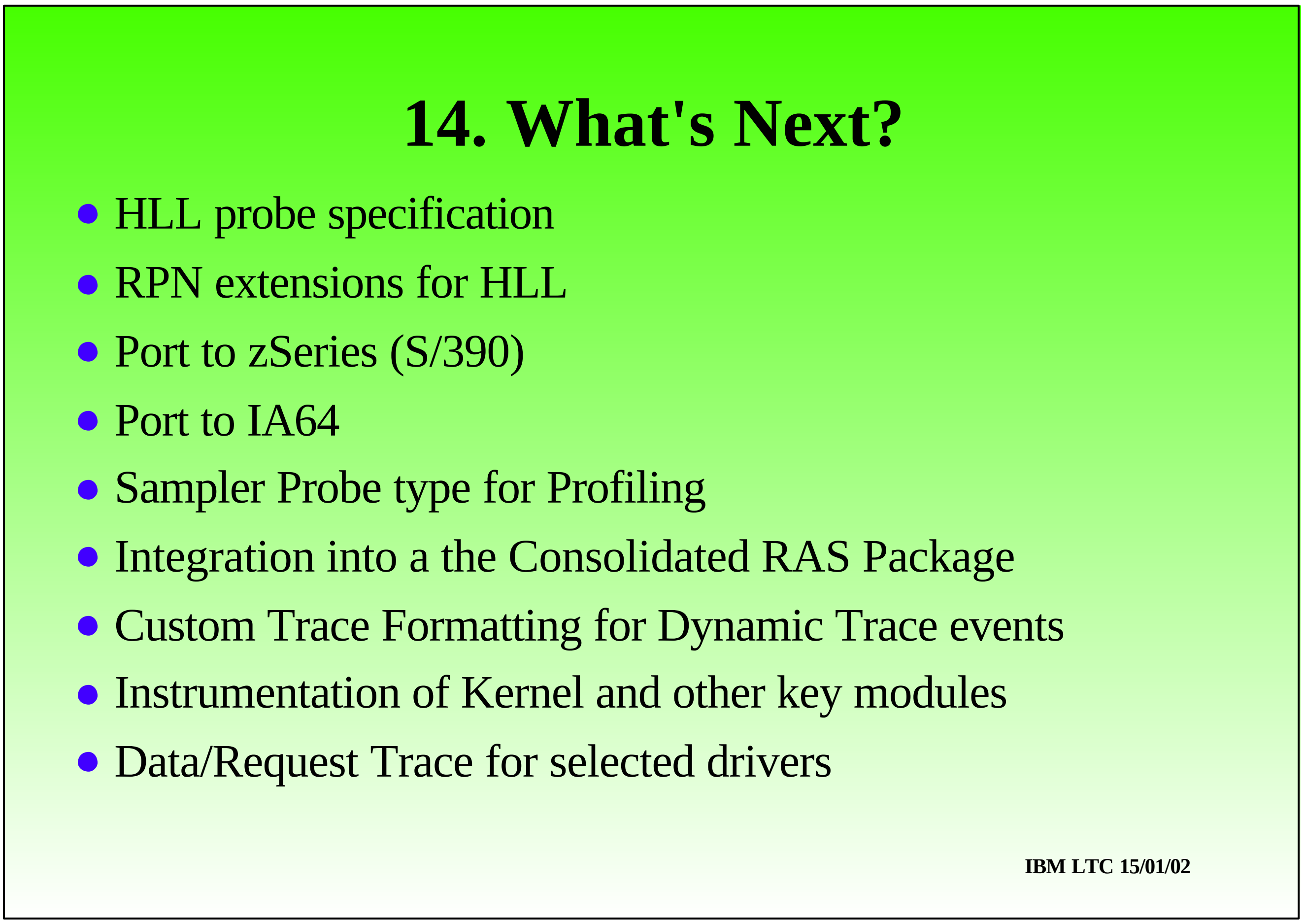
- This is where we and others have successfully used DProbes:
-
- We used it to debug itself
- SuSE use it to debug the linux kernel - its easier than recompiling in printk statements.
- RJM used in to solve a number of OS page manager problems that were impossible to re-create at will and only occurred in a customer's production environment. Probes were placed in the context switching code path!!!
- The parcel bomb problem is where work request are enqueued asynchronously to some facility. If a problem occurs when a request is processed, the cause - the enquing process is long since gone. DProbes can be used to intercept and monitor enquing actions and catch the culprit. An example of this occurred with OS/2 Presentation Manager.
- We can trace requests to device drivers
- It has been used to prototype system modifications - by intercepting an API and dynamically changing one or more parameters.
- The local and global variables facilitate profiling. However we are enhancing DProbes to specifically for profiling.
- As a tracing mechanism DProbes can be used extensively with minimal system impact - e.g. 400 - 1000 concurrent tracepoints.



14. What's Next?

- HLL probe specification
- RPN extensions for HLL
- Port to zSeries (S/390)
- Port to IA64
- Sampler Probe type for Profiling
- Integration into a the Consolidated RAS Package
- Custom Trace Formatting for Dynamic Trace events
- Instrumentation of Kernel and other key modules
- Data/Request Trace for selected drivers

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- We are working on the following new features:
-
- A HLL interface - initially C-like - may be later Java-like
- A number of RPN extensions to support the HLL: e.g. exception handling, working storage enhancements. More RPN commands for manipulating the RPN stack.
- We are working with the Poughkeepsie tools team on a port to zSeries (S/390)
- The first drop of an IA64 port is almost ready for release.
- We are implementing a new probe type for profiling purposes - the sampler probe along with per-processor instance data variables.
- DProbes has been integrated into a consolidated RAS package along with KDB, LKCD, LTT
- We are providing a custom trace formatting mechanism for Dynamic Trace = (DProbes + LTT)
- We employ dynamic trace to instrument drivers and the kernel.
- We will use GKHI to simplify the kernel patch and to provide a user exit to give an open-ended extension to the RPN language. In addition we will use GKHI to simplify the RAS Package.

15. Questions?

End of Presentation

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