Devoxx University: Performance Methodology

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Aleksey Shipilev

Speaker Bio

- 7+ years of (Java) Performance
  - 3 years at Intel
  - 4 years at Sun/Oracle

Projects

- Apache Harmony
- Oracle/OpenJDK
- SPECjbb201x
- https://github.com/shipilev/

Kirk Pepperdine

Speaker Bio

- 15 year Performance tuning across many industries
  - Background in super and exotic computing platforms
- Helped found www.javaperformancetuning.com
- Developed Java performance seminar (www.kodewerk.com)
- Member of Java Champion program, Netbeans Dream Team
- Recently founded JClarity,
  - a company who's purpose is to redefine performance tooling
  - Invite you to join Friends of JClarity (www.jclarity.com)


Java Performance Tuning
Chania (Crete) Greece
June 25, 2012

#include <disclaimer.h>

The resemblance of any opinion, recommendation or comment made during this presentation to performance tuning advice is merely coincidental.

Measure Don't Guess

- Hypothesis free investigations
- Progress through a series of steps to arrive at a conclusion

Introduction

Computer Science → Software Engineering

- Way to construct software to meet functional requirements
- Abstract machines
- Abstract and composable, “formal science”

Software Performance Engineeering

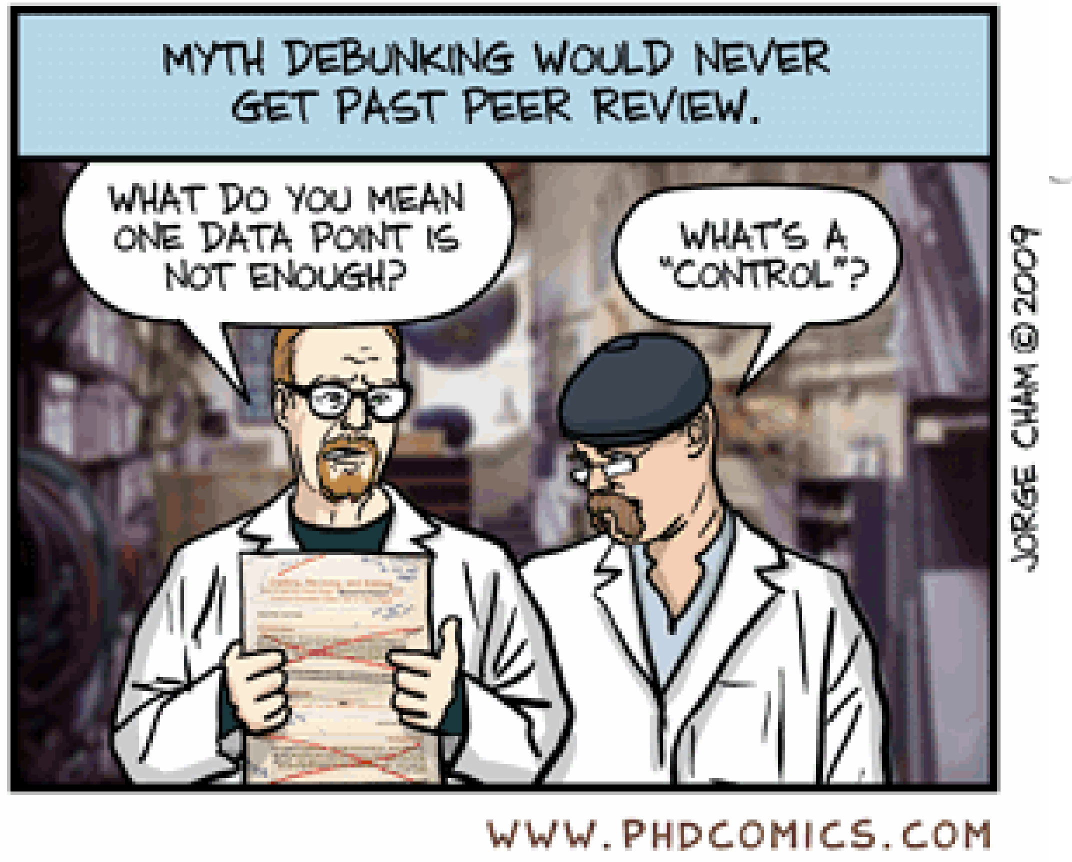
- “Real world strikes back!”
- Researching complex interactions between hardware, software, and data
- Based on empirical evidence

Benchmarking

Experimental Setup

You can't go any further without the proper test environment

- **Relevant:** reproduces the phenomena
- **Isolated:** leaves out unwanted effects
- **Measurable:** provides the metrics
- **Reliable:** produces consistent result



"Piled Higher and Deeper" by Jorge Cham
www.phdcomics.com

Relevant and Isolated

- Hardware
  - Production like
    - Phantom bottlenecks
  - Quiet
- Software
  - Test harness
    - Load injector and acceptor
- Data
  - Production like in volumes and veracity

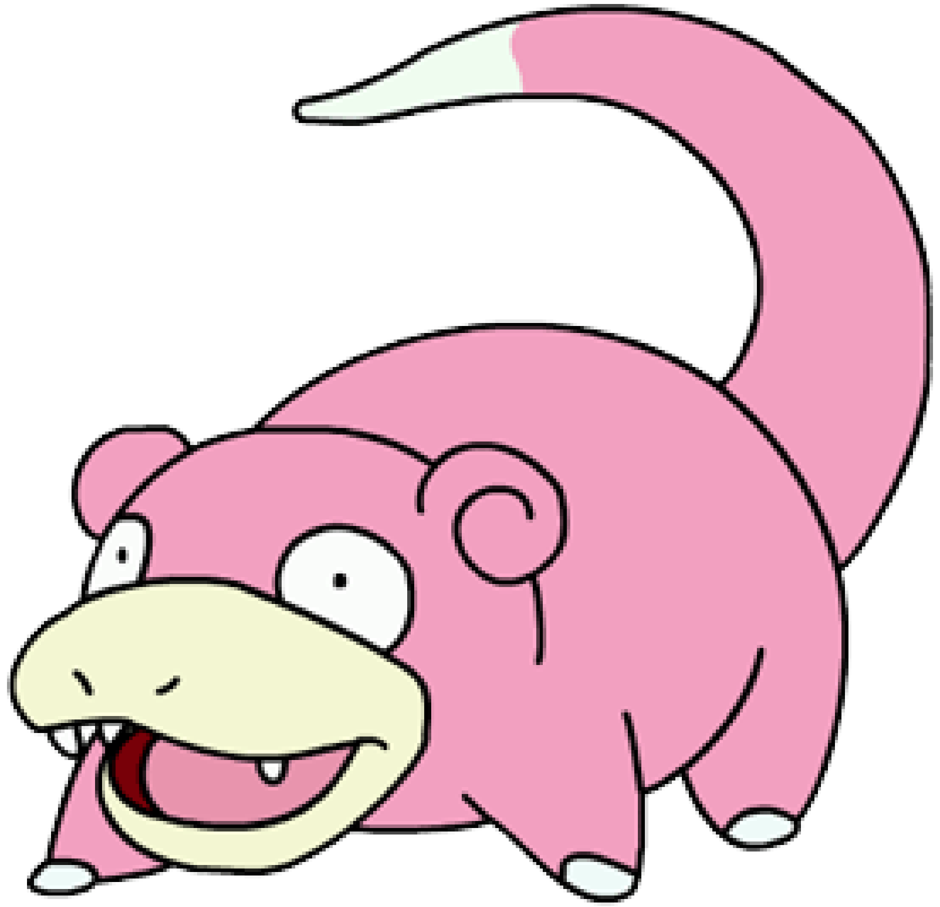
Measurable and Reliable

- Usage Patterns
  - Describes load
  - Use case + number of users and transactional rates, velocity
  - Performance requirements
    - Trigger metric is most likely average response time
- Validation
  - Test the test!
  - Make the sure your bottleneck isn't in the test harness!

Performance Testing Steps

- Script usage patterns into a load test
- Install/configure application to the same specs as production
- Setup monitoring
  - Performance requirements
  - OS performance counters and garbage collection
- Kill everything on your system
- Spike test to ensure correctness
- Load test
- Validate results
- Repeat as necessary

Demo 1



Introducing the test

Metrics

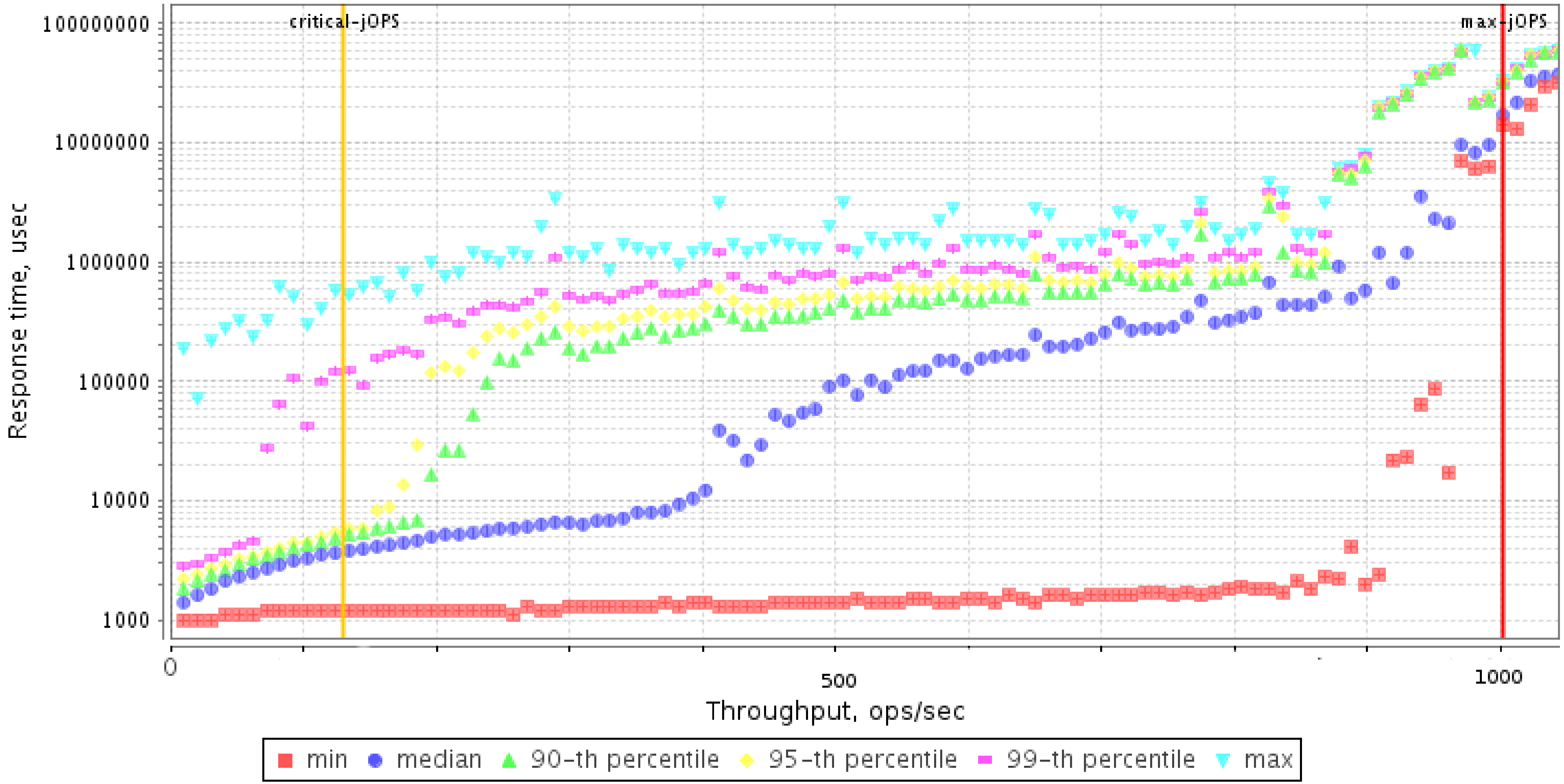
Throughput (Bandwidth)

- How many operations are done per time unit?
- Have many forms: ops/sec, MB/sec, frags/sec
- Easiest to measure
- Easiest to interpret

Time (Latency)

- How much time one operation took?
- Targets many things: latency, response time, startup time
- Generally hard to measure (reliably)

Bandwidth vs. Latency



Source: upcoming SPECjbb2013

Little's Law

The nice artifact of the queuing theory

$$L = \lambda\tau$$

L: number of outstanding requests, concurrency level

λ: throughput

τ: service time

Implications:

- Under the same L, λ is inversely proportional to τ
- Under known λ and τ, you can infer the L

Pop Quiz

Imagine the application with two distinct phases

- **Part A** takes 70% of time, potential speedup = 2x
- **Part B** takes 30% of time, potential speedup = 6x
- Which one to invest in?

Pop Quiz

Imagine the application with two distinct phases

- **Part A** takes 70% of time, potential speedup = 2x
- **Part B** takes 30% of time, potential speedup = 6x
- Which one to invest in?

Optimize B:

Optimize A:

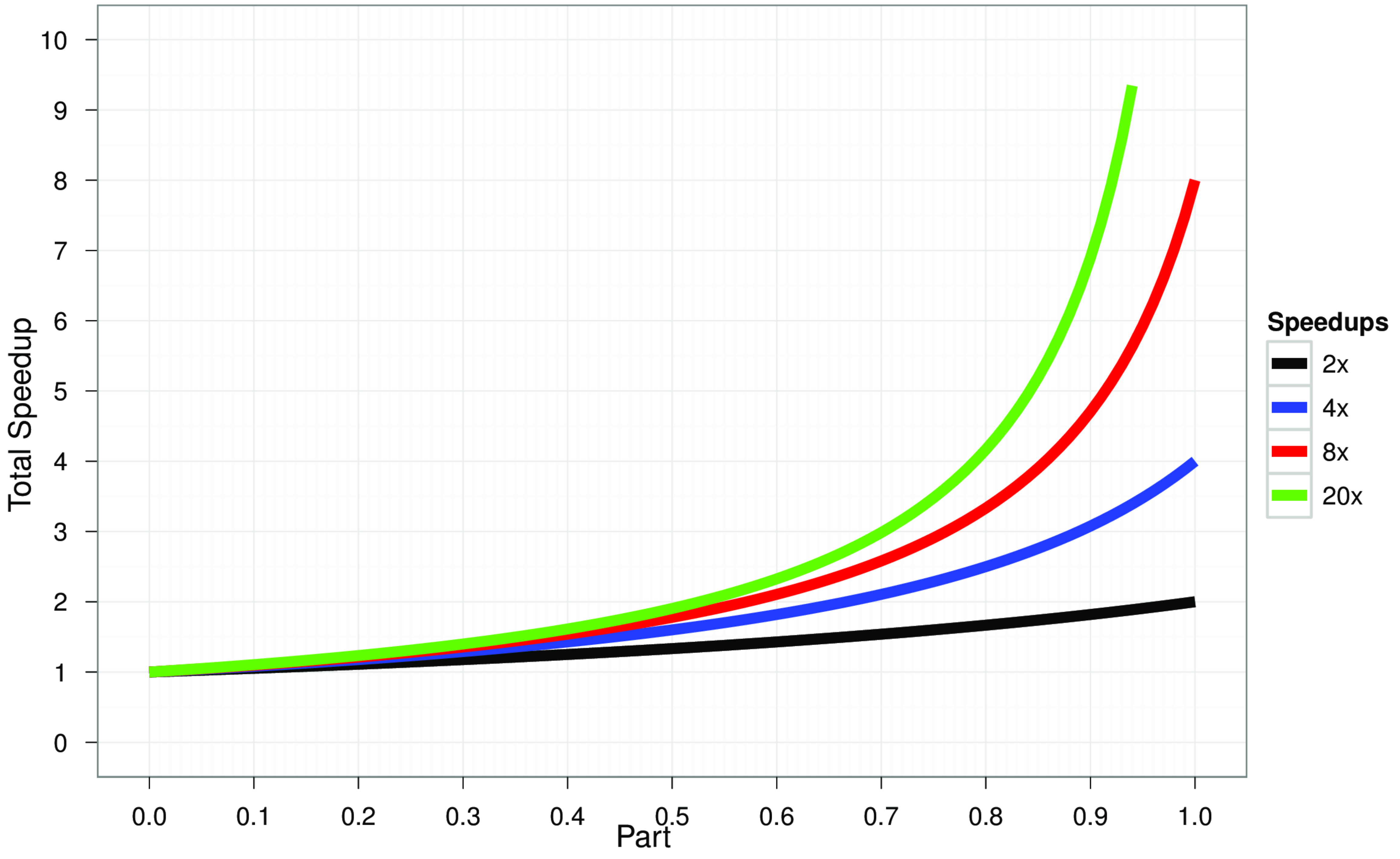
Ahmdal's Law

We can generalize this observation as:

$$Part(A) = \frac{A}{A + B}$$

$$SpeedUp = \frac{1}{(1 - Part(A)) + \frac{Part(A)}{SpeedUp(A)}}$$

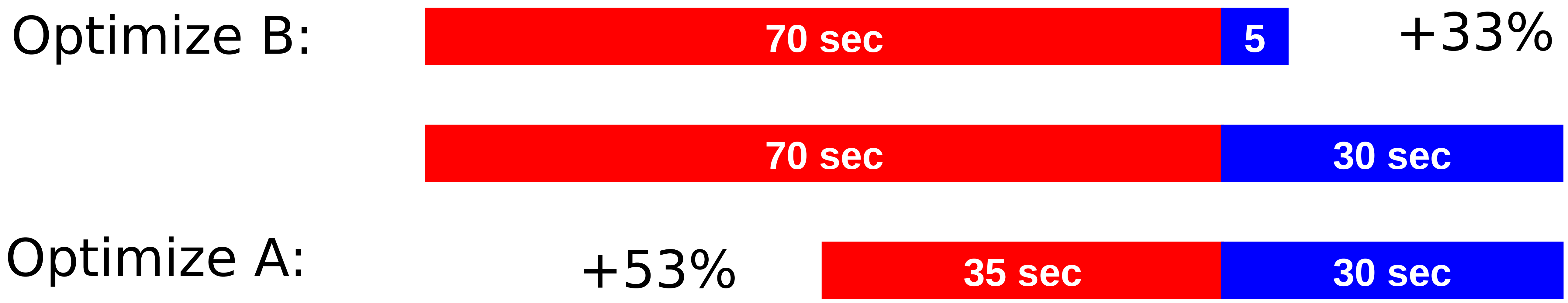
Ahmdal's Law Limits Speedups



Applying Ahmdal's Law

Imagine the application with two distinct phases

- **Part A** takes 70% of time, potential speedup = 2x
- **Part B** takes 30% of time, potential speedup = 6x
- Which one to invest in?



Where Ahmdal's Law Breaks Down

Composability

- Given two functional blocks, A and B
- The difference with executing (A seq B) or (A par B)?

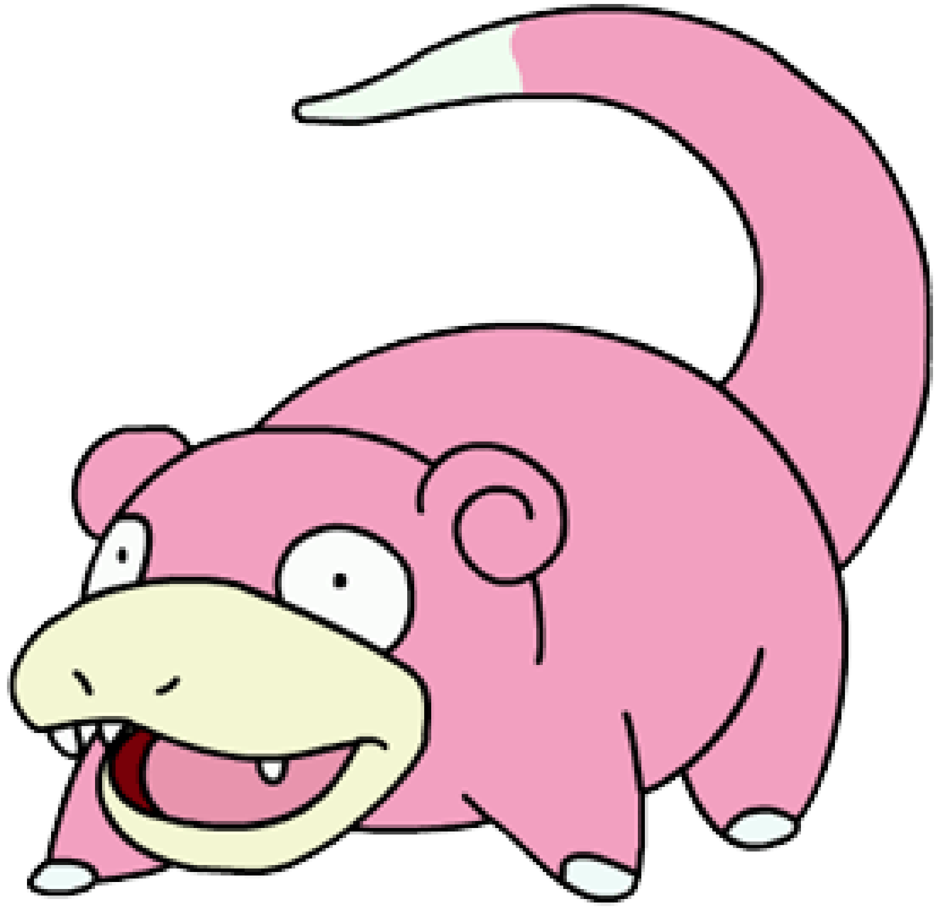
Functional-wise:

- Result(A seq B) == Result(A par B)
- “Black box abstraction”

Performance-wise:

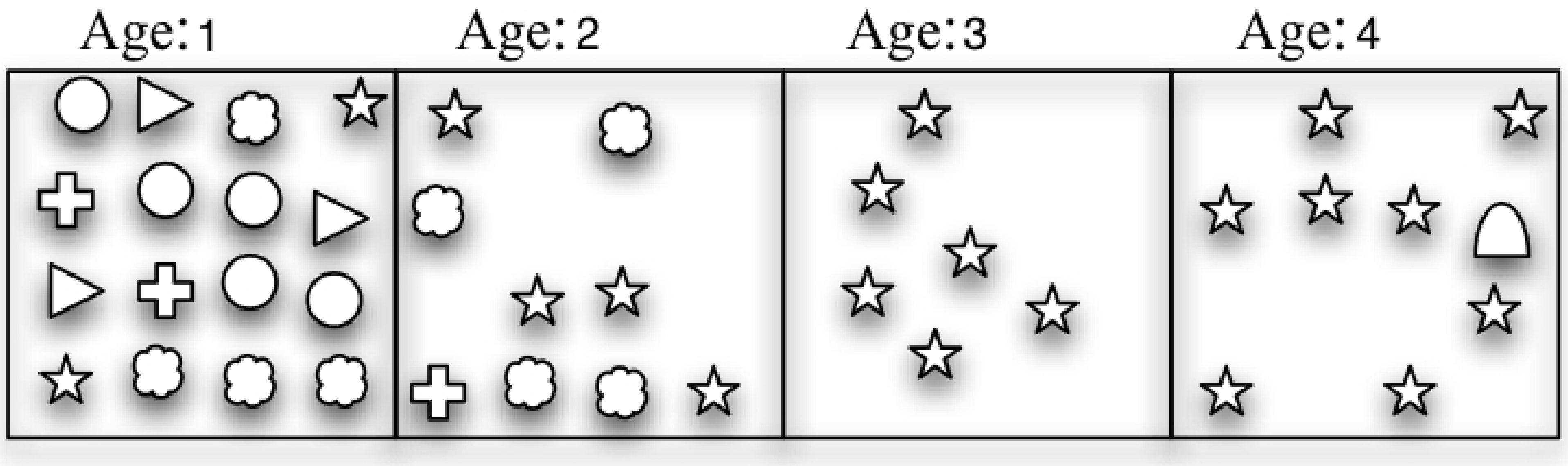
- Performance(A seq B) **???** Performance(A par B)
- No one really knows!

Demo 2

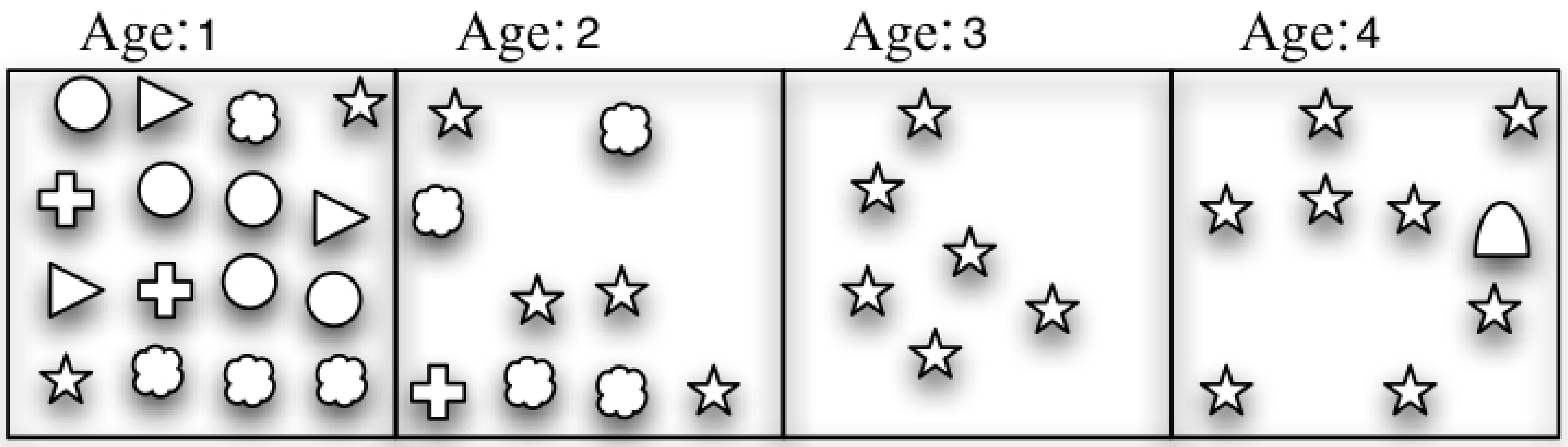


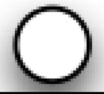
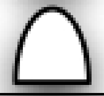
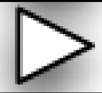
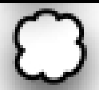
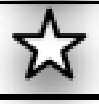
Ensure test is reliable

Generational Counts



Generational Counts (2)



Object	Generations	Count	Classify
	1	1	Normal
	1, 2	2	Normal
	4	1	Cached
	1	1	Normal
	1, 2	2	Normal
	1, 2, 3, 4	4	Leak

How to speed up the application?

Change something somewhere in some specific way!

How to speed up the application?

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How to speed up the application?

Change something somewhere in some specific way!

- What?
- Where?
- How?

How to speed up the application?

Change something somewhere in some specific way!

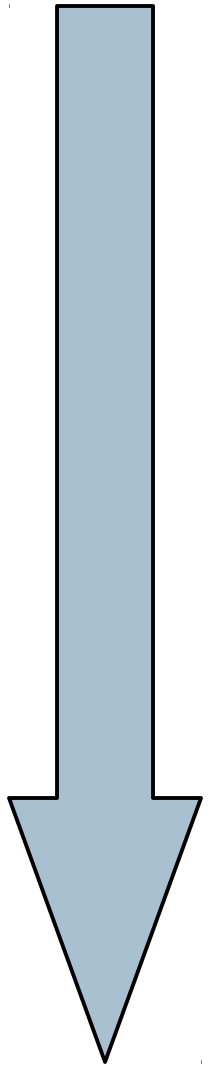
- What prevents the application to work faster?
- Where it resides?
- How to change it to stop messing with performance?

How to speed up the application?

Change something somewhere in some specific way!

- What prevents the application to work faster?
  Courage, experience, and monitoring tools
- Where it resides?
  Courage, experience, and profiling tools
- How to change it to stop messing with performance?
  Courage, experience, your brain, and your favorite IDE

Top-Down Approach (classic)



System Level

- Network, Disk, CPU/Memory, OS

Application Level

- Algorithms, Synchronization, Threading, API

Microarchitecture Level

- Code/data alignment, Caches, Pipeline stalls

Top-Down Approach (Java)

System Level

- Network, Disk, CPU/Memory, OS

JVM Level

- GC, JIT, Classloading

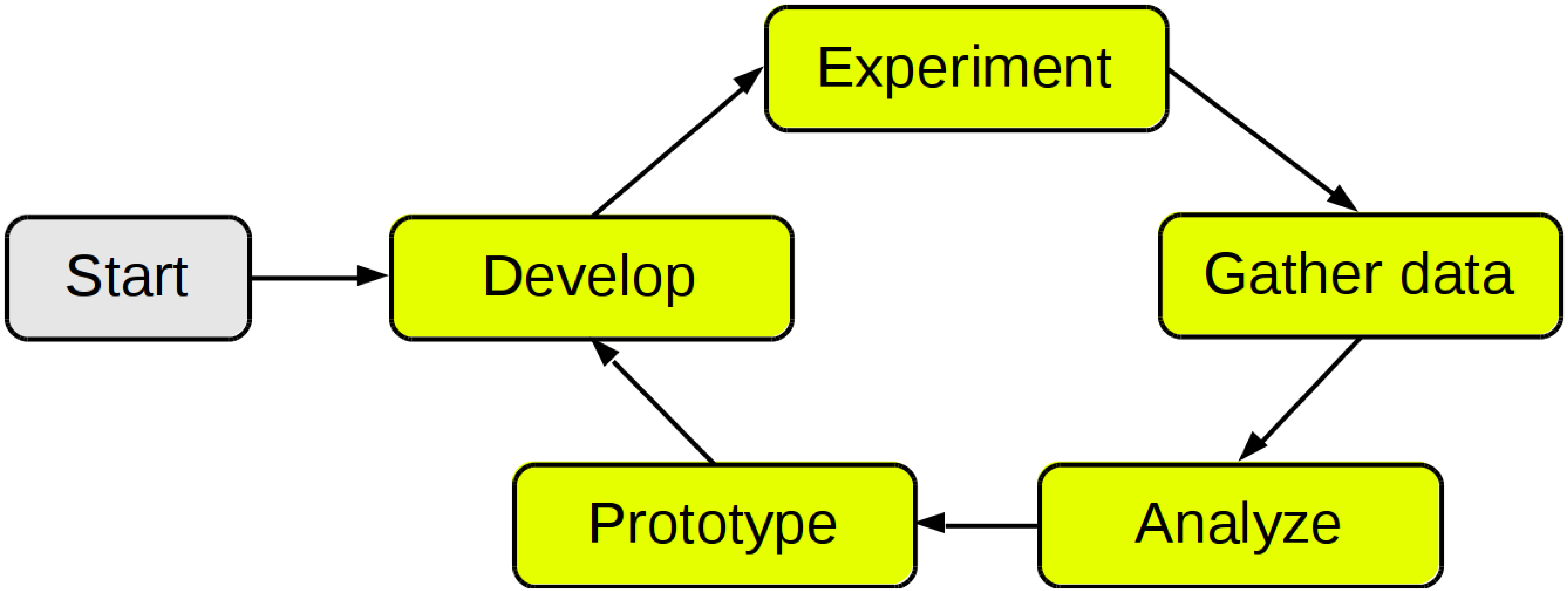
Application Level

- Algorithms, Synchronization, Threading, API

Microarchitecture Level

- Code/data alignment, Caches, Pipeline stalls

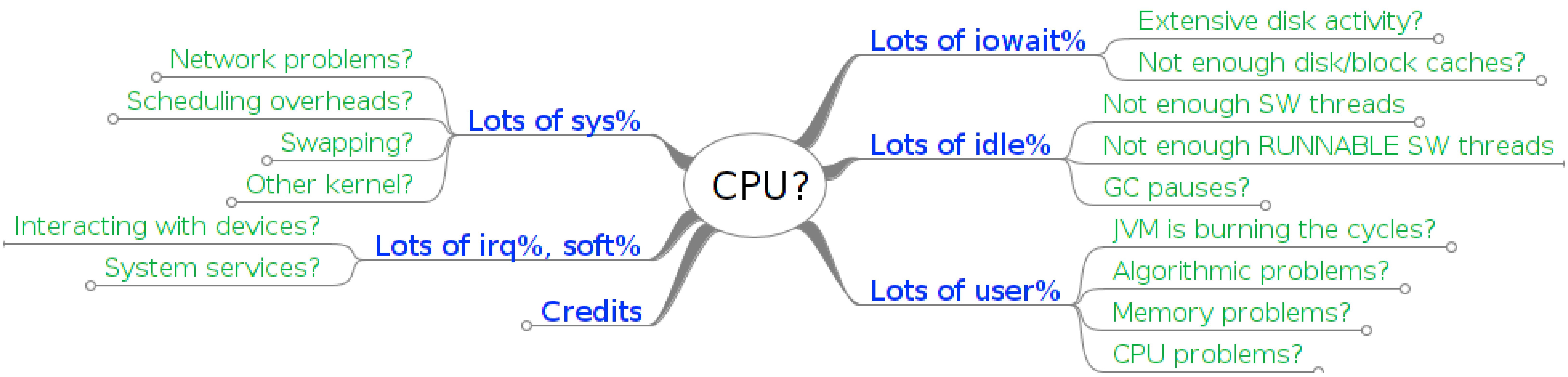
+ Iterative Approach



- **Start new phase when functional tests are passed**
- **Single change per cycle**
- **Document the changes**

System Level

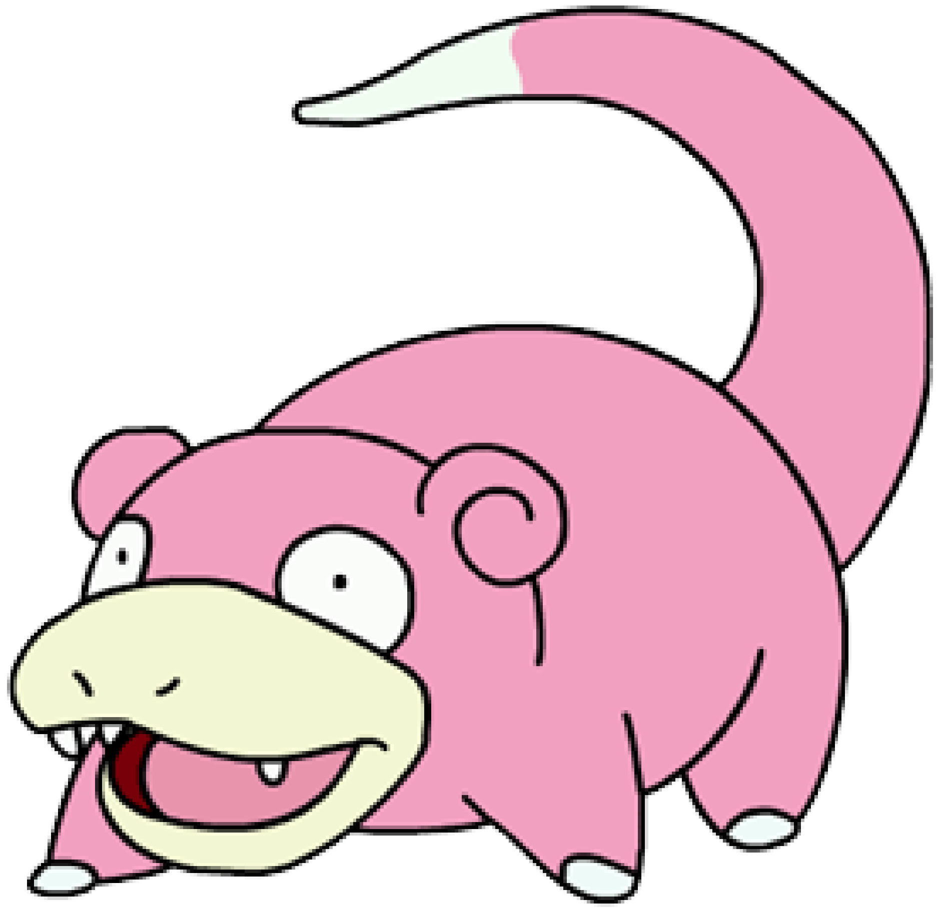
System Level (CPU)



The entry point is CPU utilization!

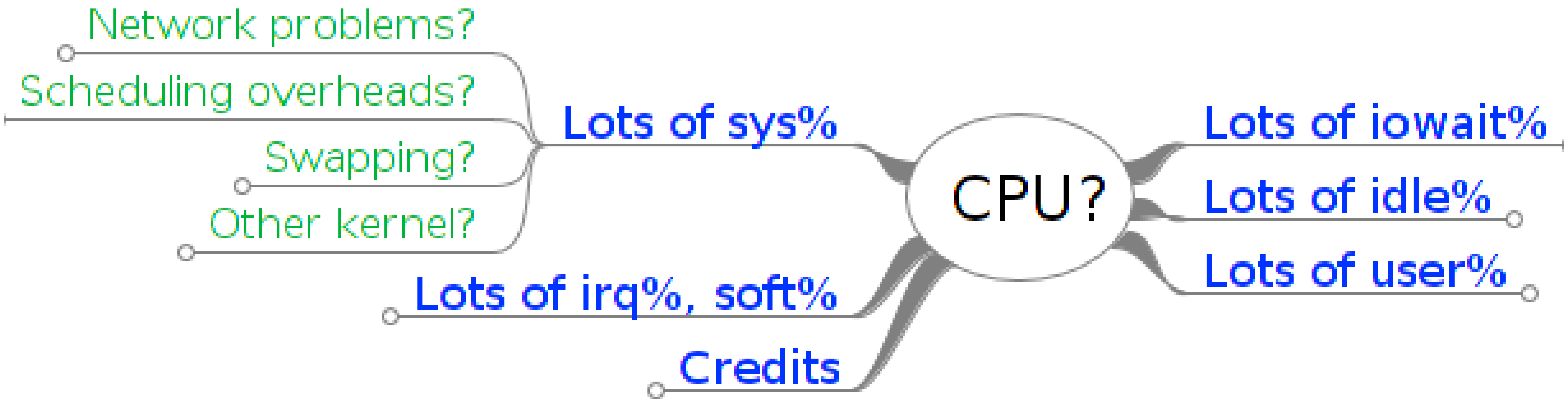
- Then, you have multiple things to test for
- Depending on **sys%**, **irq%**, **iowait%**, **idle%**, **user%**
- Need tools to examine each particular branch

Demo 3



First dive into the monitoring

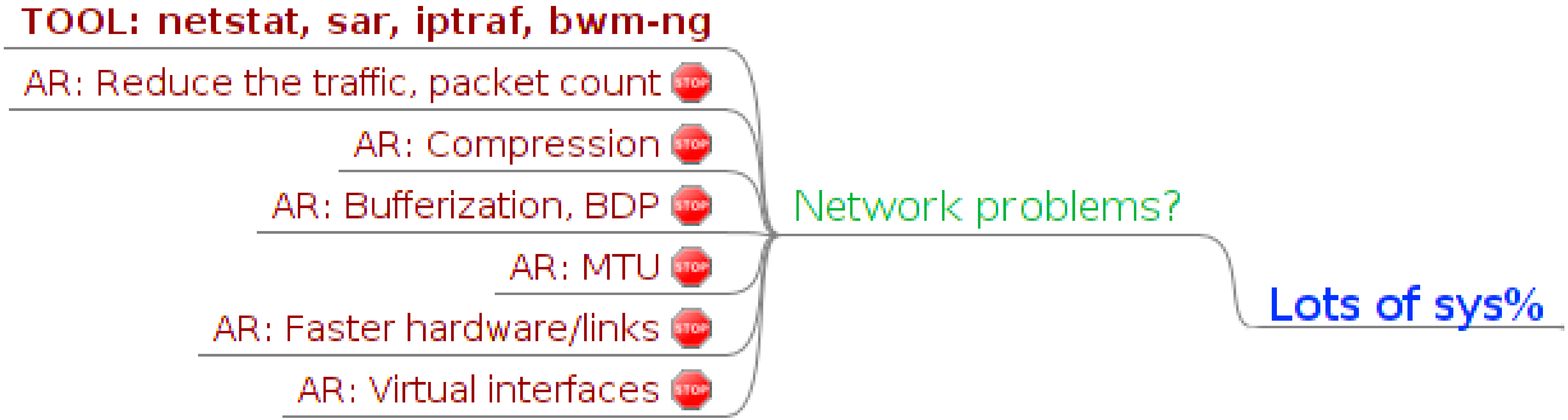
System Level (sys%)



Not particularly the application code fault

- Most obvious contender is network I/O
- Then, scheduling overheads
- Then, swapping
- Then, in minor cases, other kernel

System Level (sys%, network)



One of the major contributors to sys%

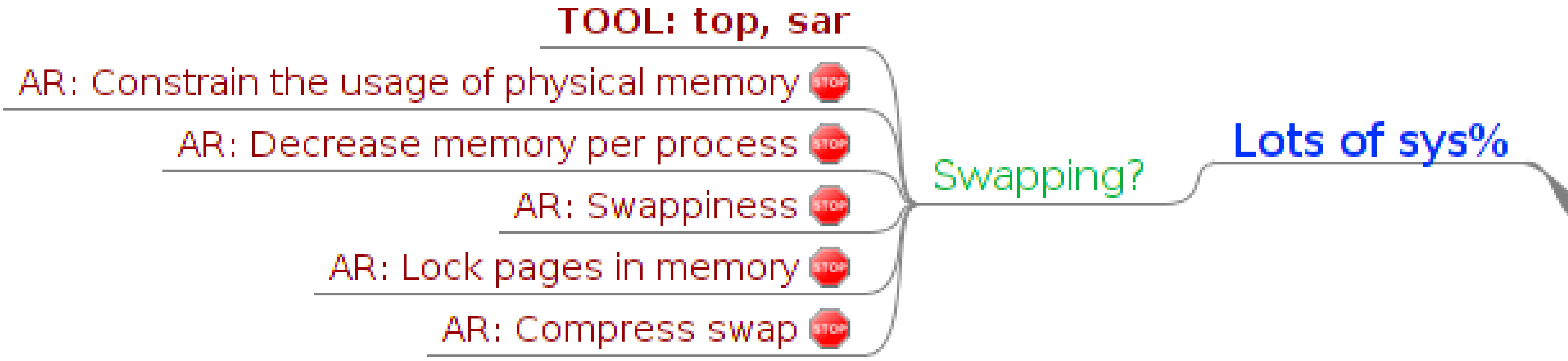
- In many cases, hardware/OS configuration is enough
- In other cases, application changes might be necessary

System Level (sys%, scheduling)

The symptom of the unbalanced threading

- Lots of voluntary context switches (thread thrashing)
- Lots of involuntary context switches (over-saturation)

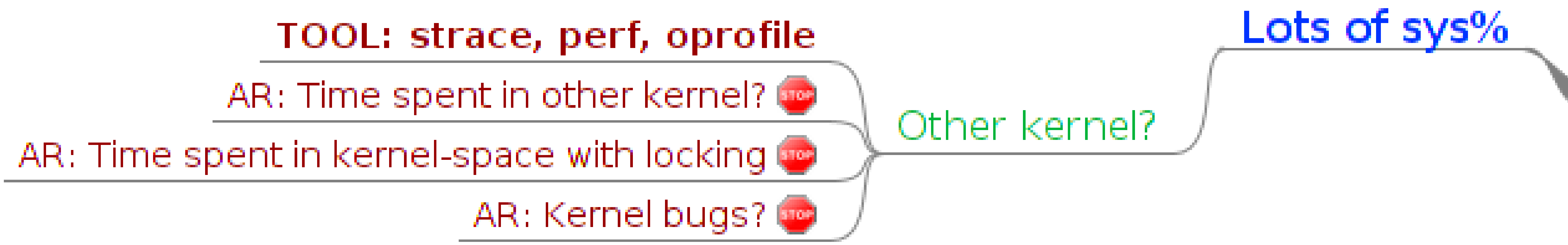
System Level (sys%, swapping)



Swapping is the killer for Java performance

- The target is to avoid swapping at all costs
- Swapping out other processes to save the memory is good

System Level (sys%, other)



Sometimes kernel is your enemy

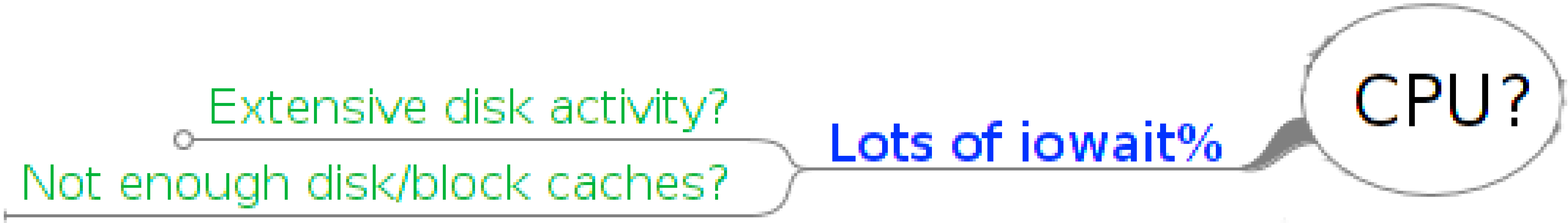
- Unusual API choices from the JVM and/or application
- (Un)known bugs

System Level (irq%, soft%)

Usual thing when interacting with the devices

- Sometimes IRQ balancing is required
- Sometimes IRQ balancing is expensive

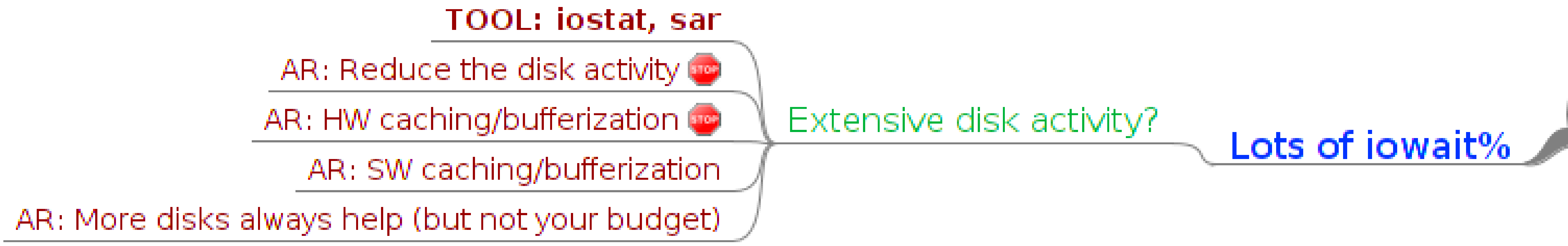
System Level (iowait%)



Expected contributor with disk I/O

- Watch for disk activity
- Watch for disk throughput
- Watch for disk IOPS

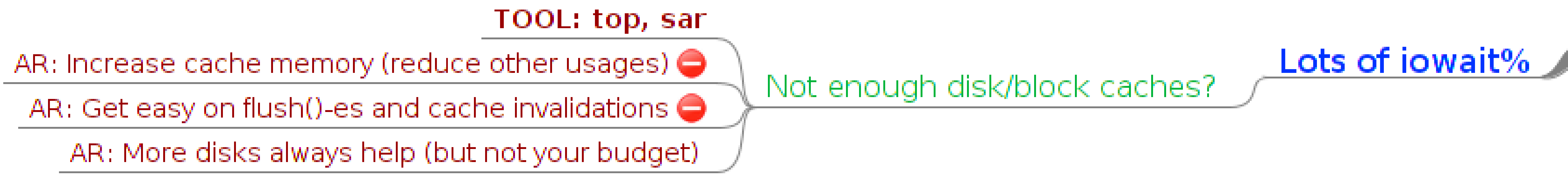
System Level (iowait%, disk)



Is that amount of I/O really required?

- Caching, bufferization are your friends
- More (faster) disks can solve throughput/IOPS problems

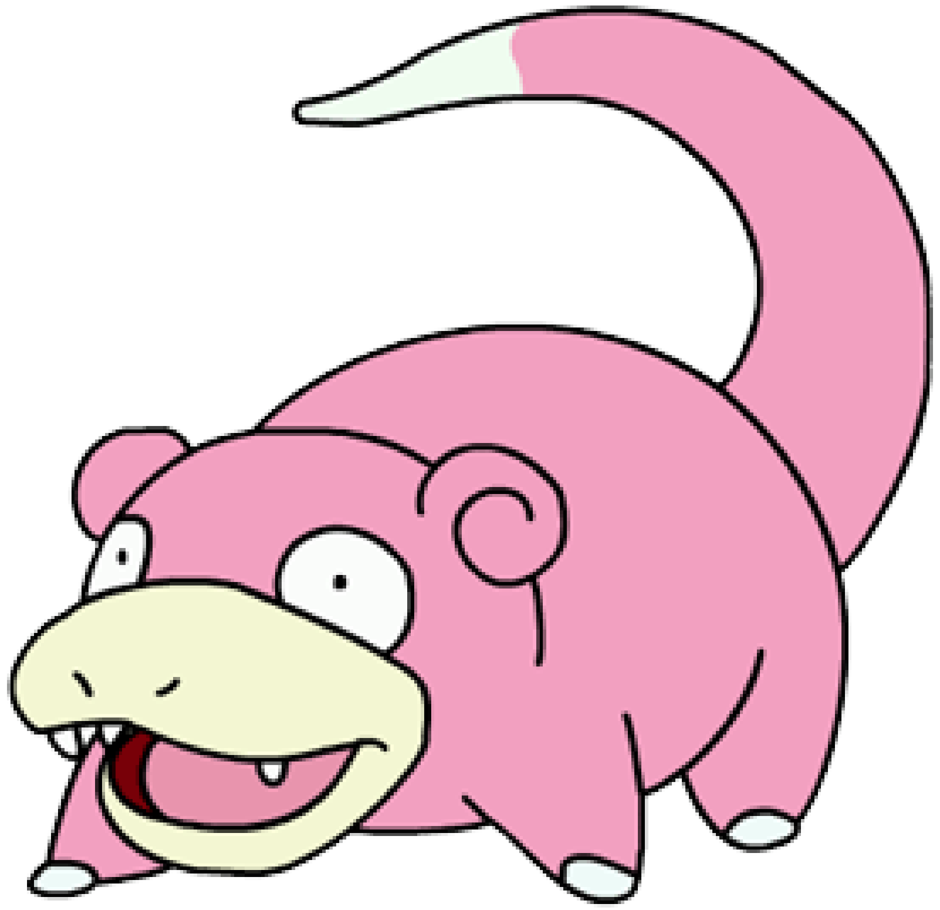
System Level (iowait%, caches)



More caching helps?

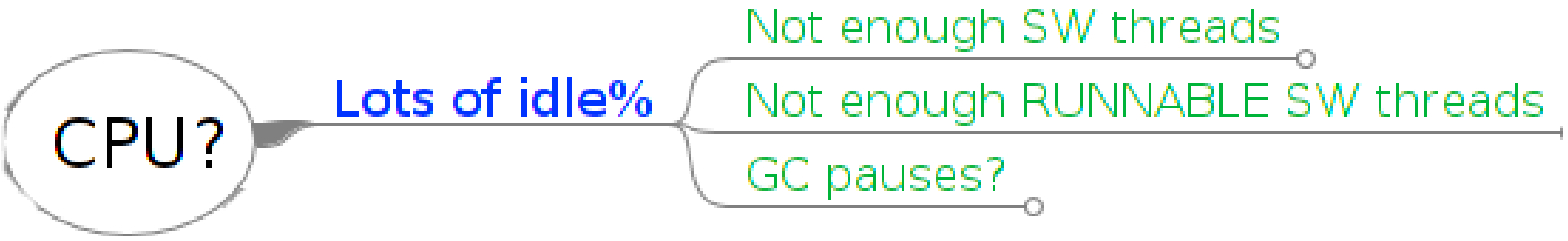
- Reduce other physical memory usages, free up for caches
- Trade in performance over consistency

Demo 4



Fixing the iowait problem → next step

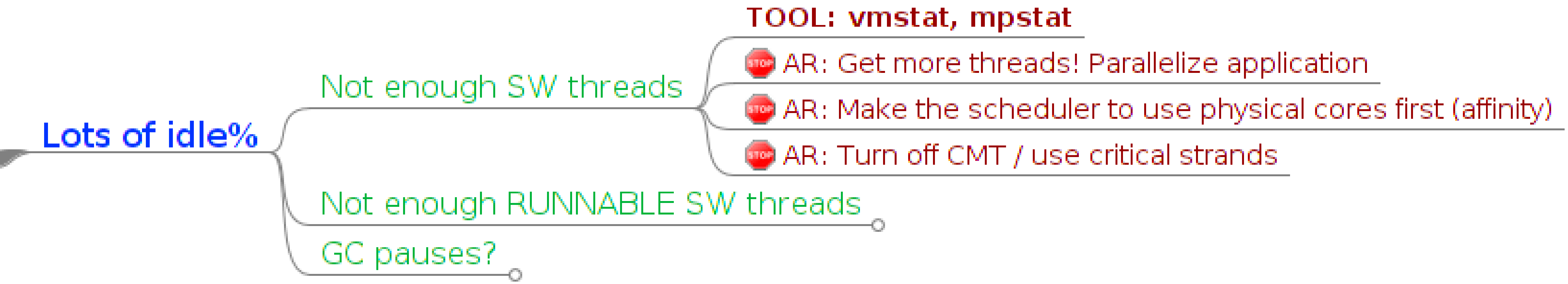
System Level (idle%)



There are resources, but nobody uses them?

- This is admittedly easy to diagnose
- ...and very easy to miss

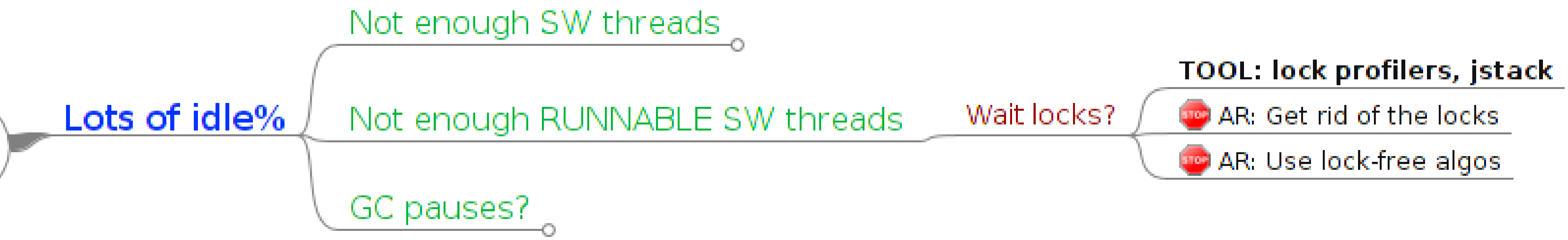
System Level (idle%, threads)



Running low-threaded applications on manycore hosts

- The signal for you to start parallelizing
- Or, reduce the number of available HW strands

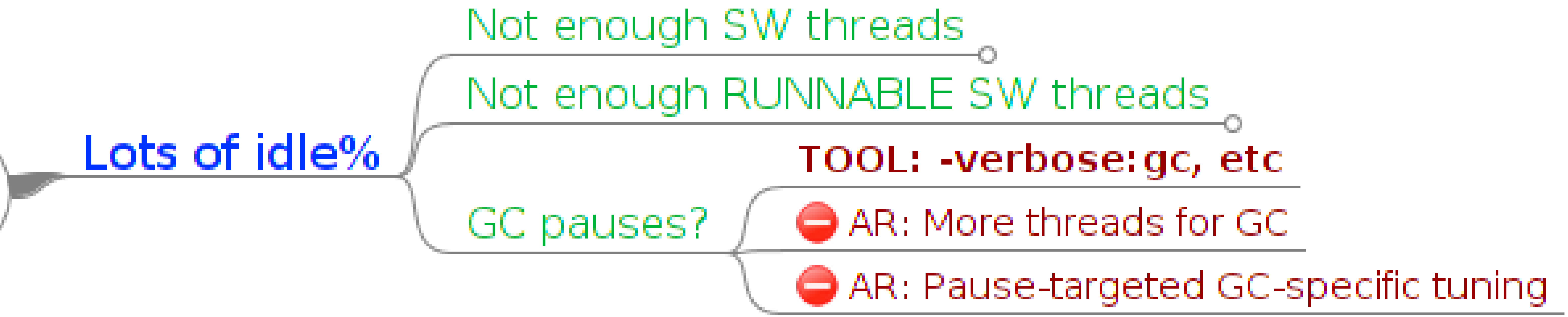
System Level (idle%, threads)



There are not enough threads ready to run

- Locking?
- Waiting for something else?

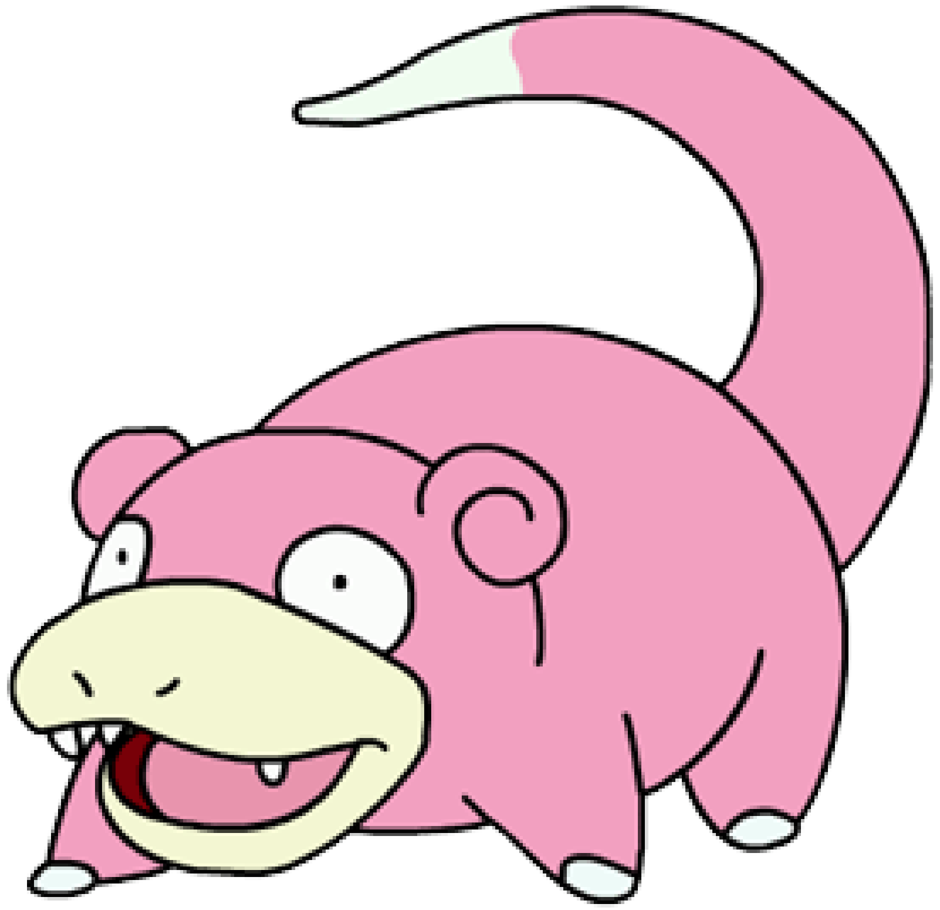
System Level (idle%, GC)



Very rare, and surprising case

- Application is highly threaded
- GC is frequently running with low thread count
- The average CPU utilization is low

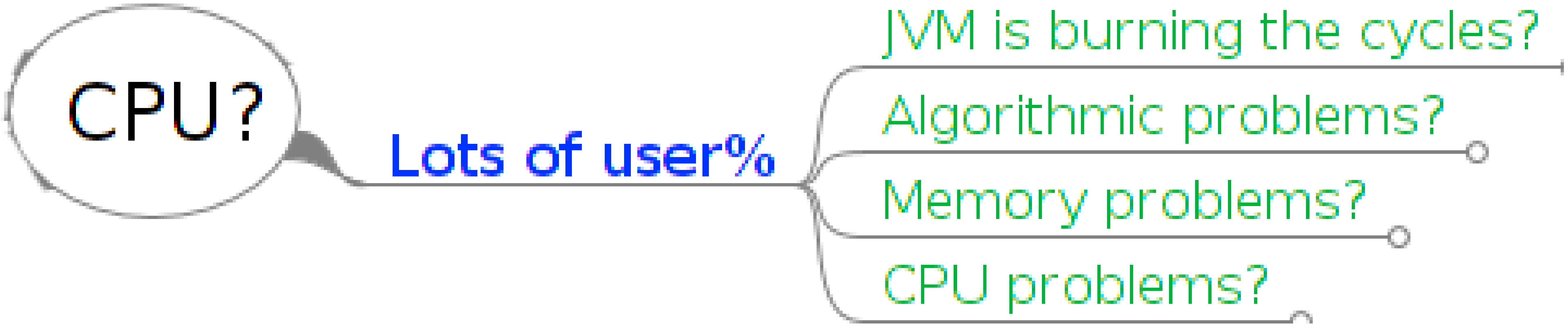
Demo 5



Fixing the idle problem → next step

Application/ JVM Level

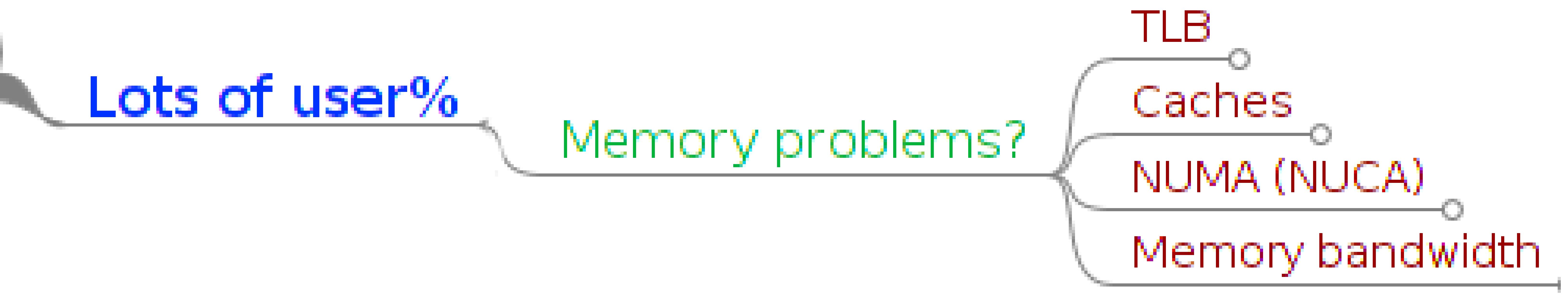
Application Level (user%)



Application/JVM is finally busy

- This is where most people start
- This is where profilers start to be actually useful

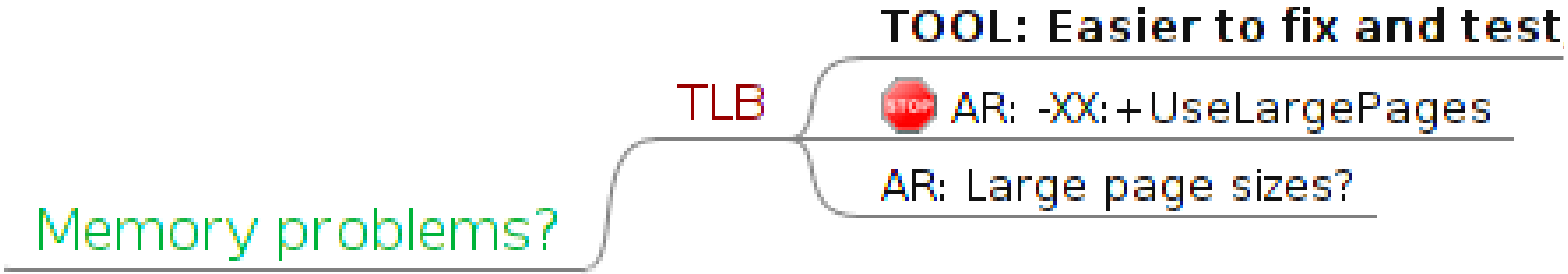
Application Level (Memory)



Memory

- The gem and the curse of von-Neumann architectures
- Dominates most of the applications (in different forms)

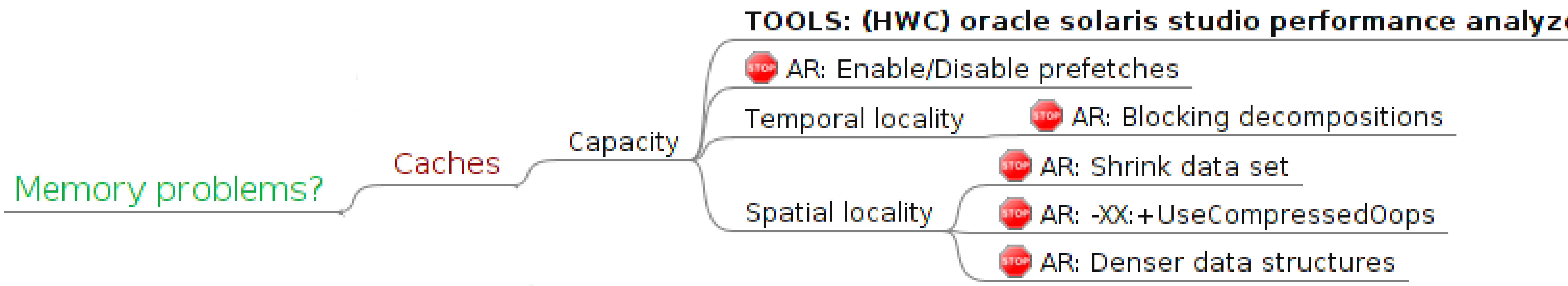
Application Level (TLB)



TLB

- Very important for memory-bound workloads
- “Invisible” artifact of virtual memory system

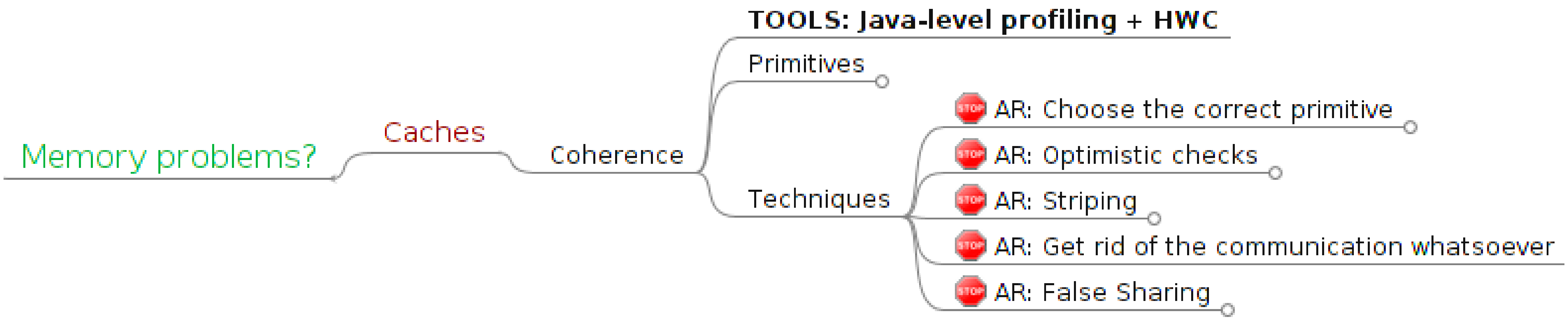
Application Level (Caches)



CPU caches: capacity

- Important to hide memory latency (and bandwidth) issues
- Virtually all applications today are memory/cache-bounded

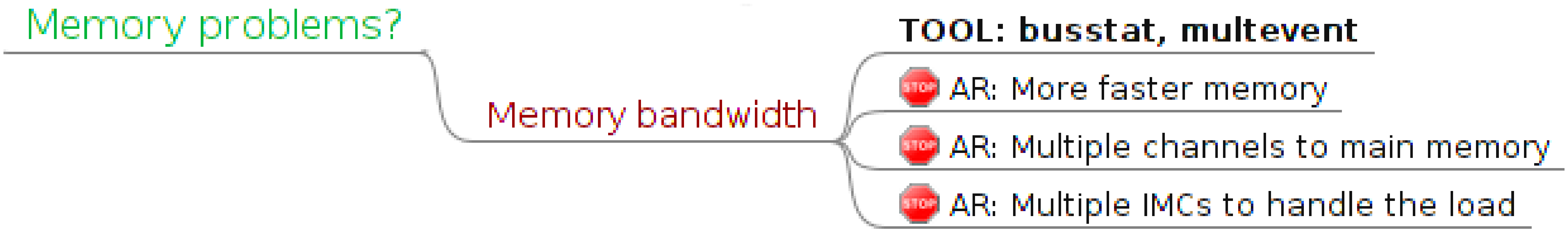
Application Level (Caches)



CPU Caches: coherence

- Inter-CPU communication is managed via cache coherence
- Understanding this is the road to master the communication

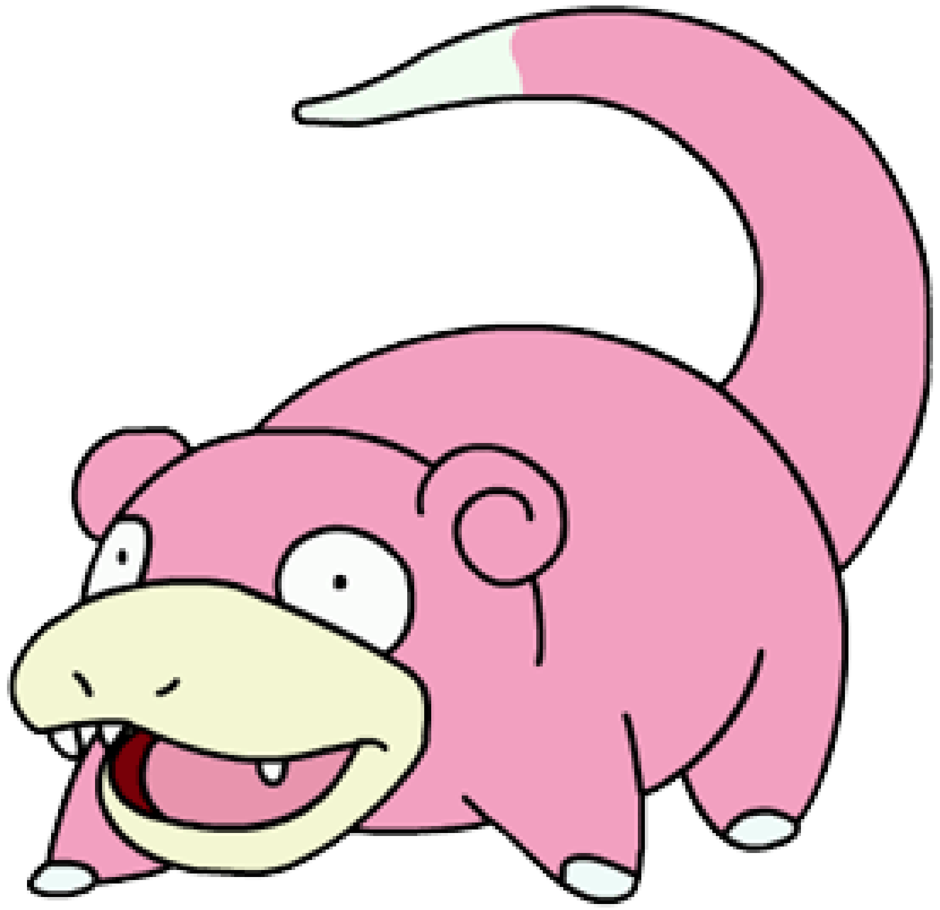
Application Level (Bandwidth)



Memory Bandwidth

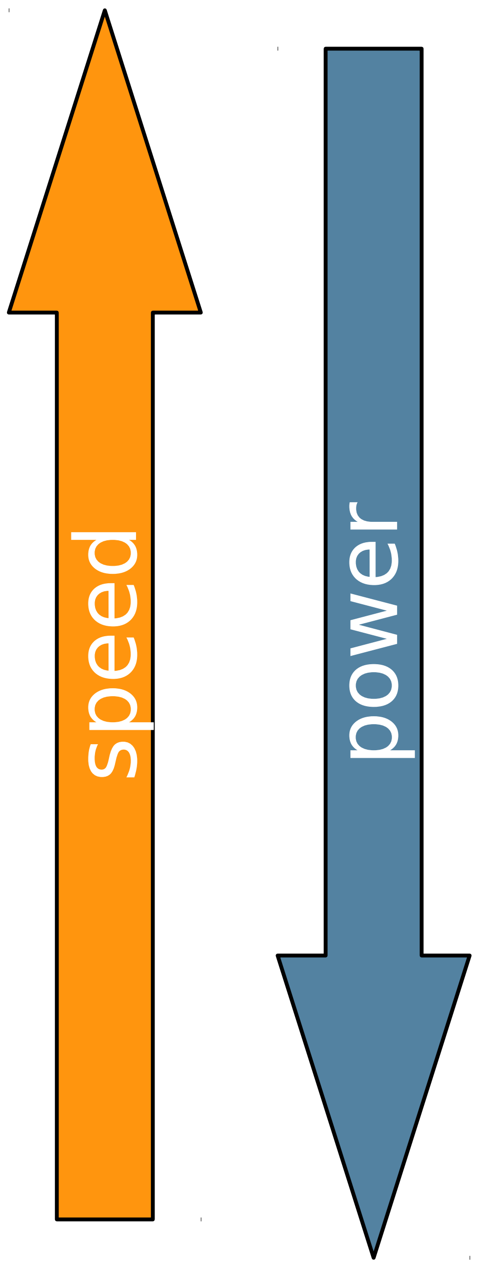
- Once caches run out, you face the memory
- Dominates the cache miss performance
- Faster memory, multiple channels help

Demo 6



Solving the concurrency problem → next step

Coherence: Primitives



Plain unshared memory

Plain shared memory

- Provide communication

Volatile

- All above, plus visibility

Atomics

- All above, plus atomicity

Atomic sections

- All above, plus group atomicity

Spin-locks

- All above, plus mutual exclusion

Wait-locks

- All above, plus blocking

Coherence: Optimistic Checks

It is possible at times to make an optimistic check

- Fallback to pessimistic version on failure
- The optimistic check has less power, but more performant

```
AtomicBoolean isSet = ...;
if (!isSet.get() &&
        isSet.compareAndSet(false, true) {
     // one-shot action
}
```

Coherence: Optimistic Checks

It is possible at times to make an optimistic check

- Fallback to pessimistic version on failure
- The optimistic check has less power, but more performant

```
ReentrantLock lock = ...;
int count = -LIMIT;
while (!lock.tryLock()) {
    if (count++ > 0) {
        lock.lock();
        break;
    }
}
```

Coherence: Striping

It is possible at times to split the shared state

- Much less contention on modifying the local state
- The total state is the superposition of local states

Example: thread-safe counter

- `synchronized { i++; }`
- `AtomicInteger.inc();`
- `ThreadLocal.set(ThreadLocal.get() + 1);`
- `AtomicInteger[random.nextInt(count)].inc();`

Coherence: No-coherence zone

If you can remove the communication, do that!

- Immutability to enforce
- Thread local states

Example: ThreadLocalRandom @ JDK7

- Random: use CAS to maintain the state
- ThreadLocalRandom: essentially, ThreadLocal<Random>
  - Can use plain memory ops to maintain the state

Coherence: (False) Sharing

Communication quanta = cache line

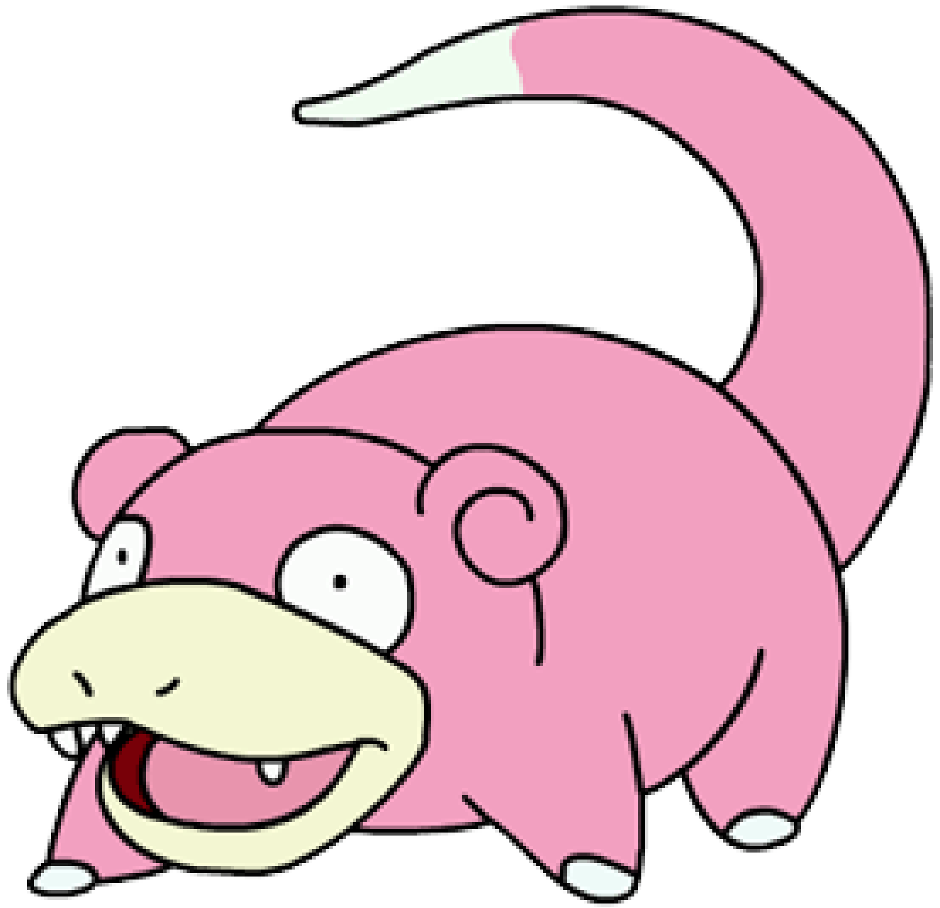
- 32 – 128 bytes long
- Helps with bulk memory transfers, cache architecture
- Coherence protocols working on cache lines

```
...------][----AA--BB----][------...
```

False Sharing

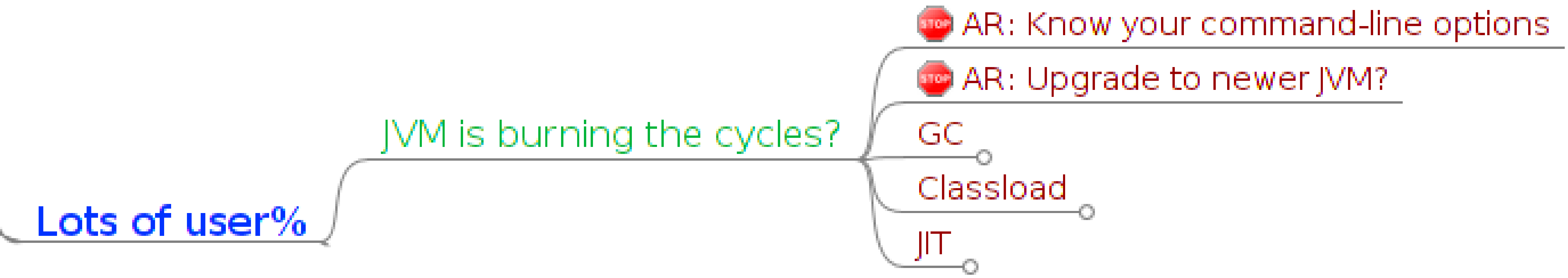
- CPUs updating the adjacent fields?
- Cache line ping-pong!

Demo 7



Diagnosing with allocation profiles

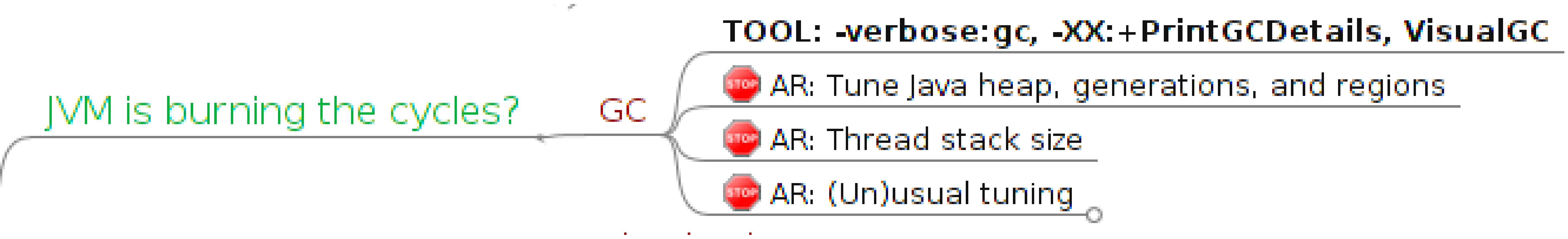
JVM Level



JVM is the new abstraction level

- Interacts with the application, mangles into application
- JVM performance affects application performance

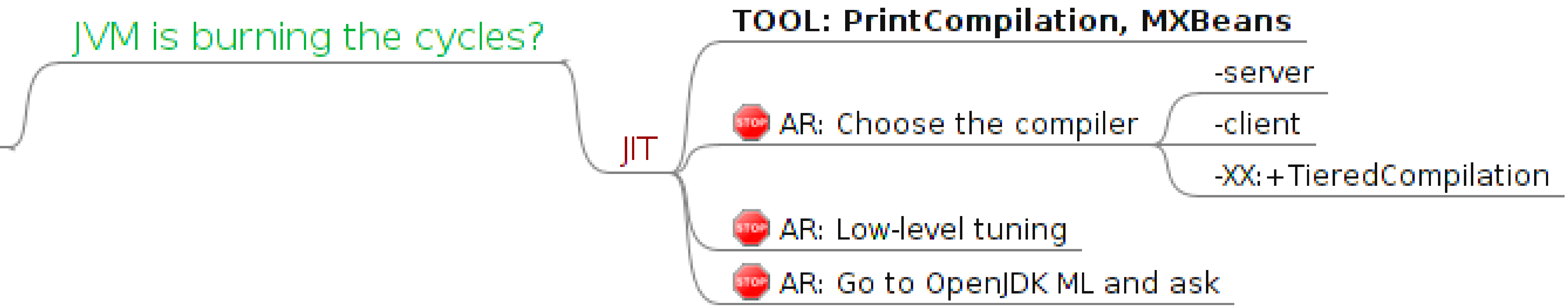
JVM Level (GC)



GC

- Most usual contender in JVM layer
- Lots of things to try fixing (not covered here, see elsewhere)

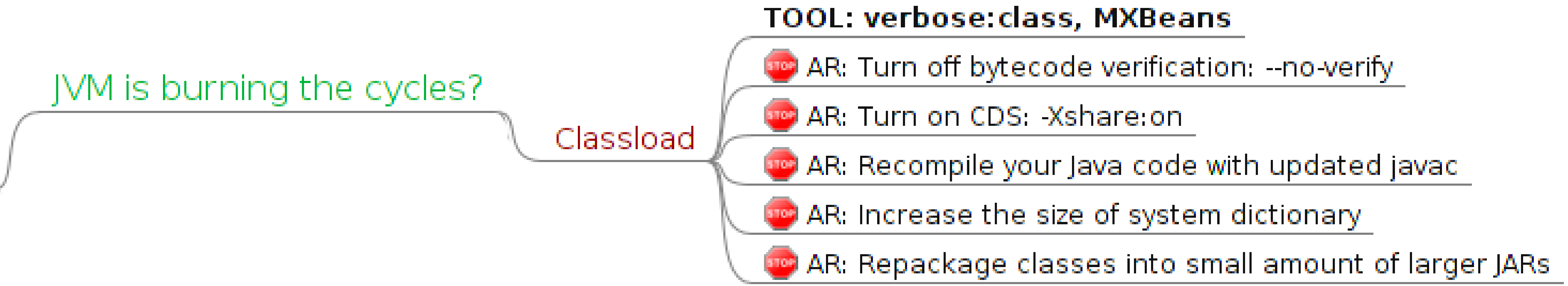
JVM Level (JIT)



JIT

- Very cool to have your code compiled
- Sometimes it's even cooler to get the code compiled better

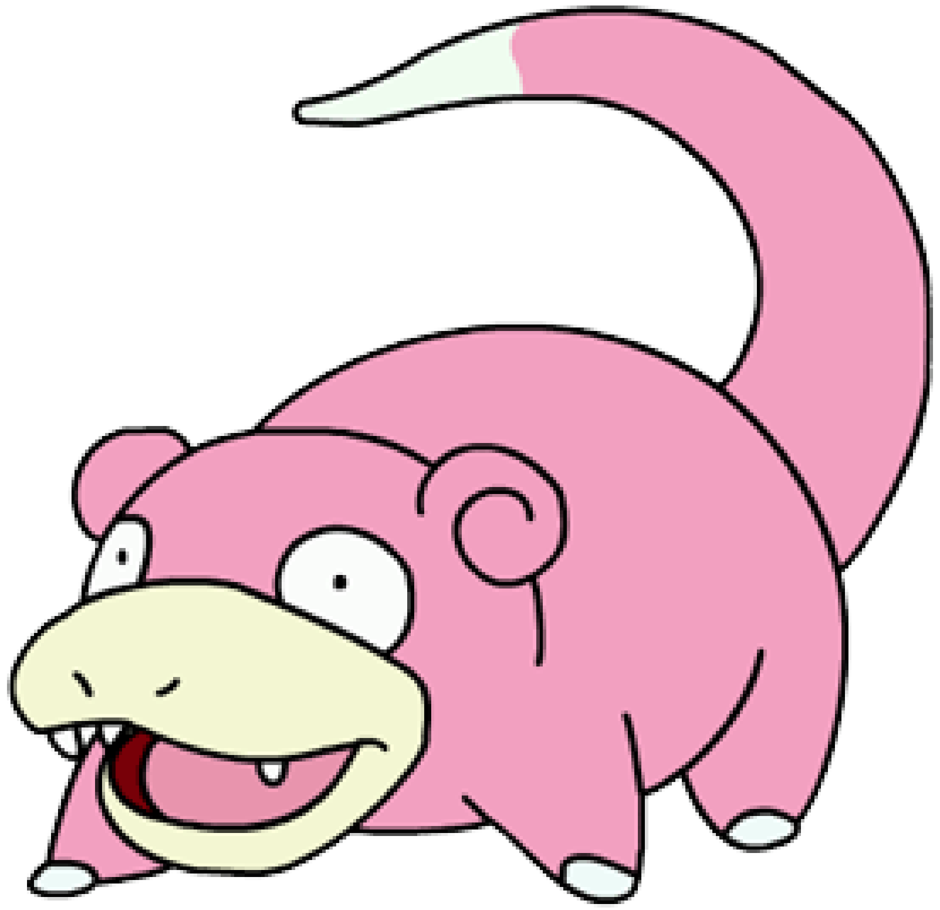
JVM Level (Classload)



Classload

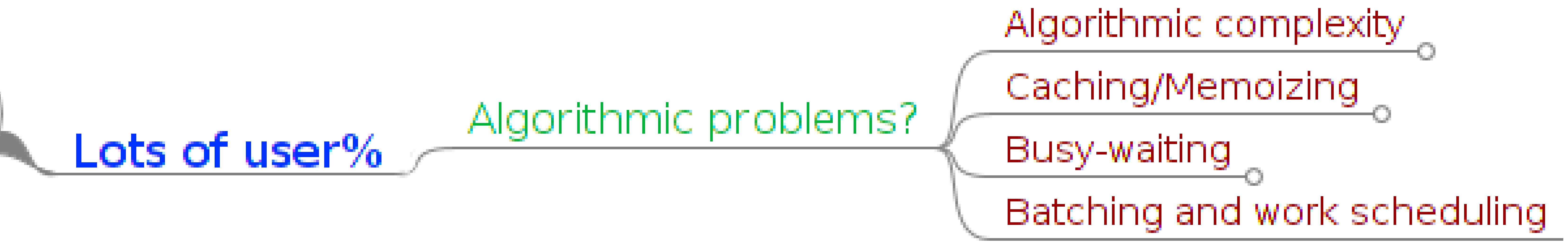
- Important for startup metrics; not really relevant for others
- Removing the loading obstacles is the road to awe

Demo 8



Fixing the allocation problem

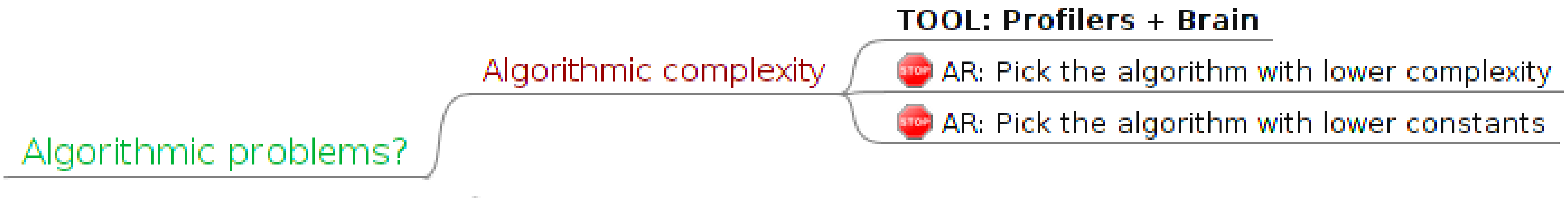
Application Level



Application level

- In many, many cases, silly oversights in algorithms use
- Cargo cult of approaches, patterns, code reuse

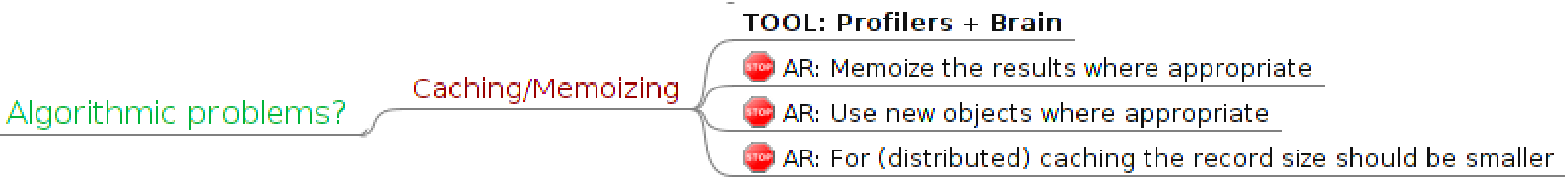
Application Level (Algos)



Algorithmic Complexity

- Figuring out the straight-forward code has huge complexity
- Sometimes, the low-O code is slower than high-O code

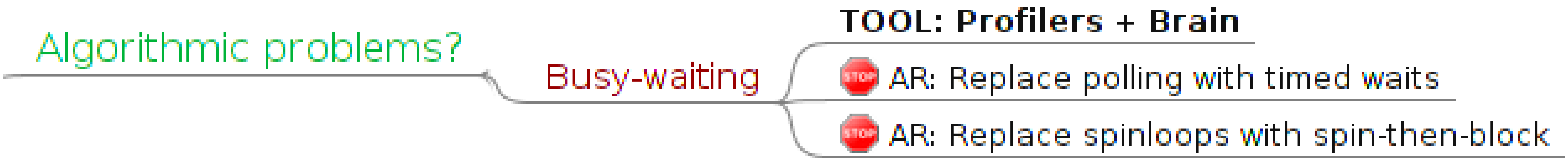
Application Level (Caching)



Application Caching

- Seems to be the answer to most performance problems?
- In fact, blows up the footprint, heap occupancy, etc

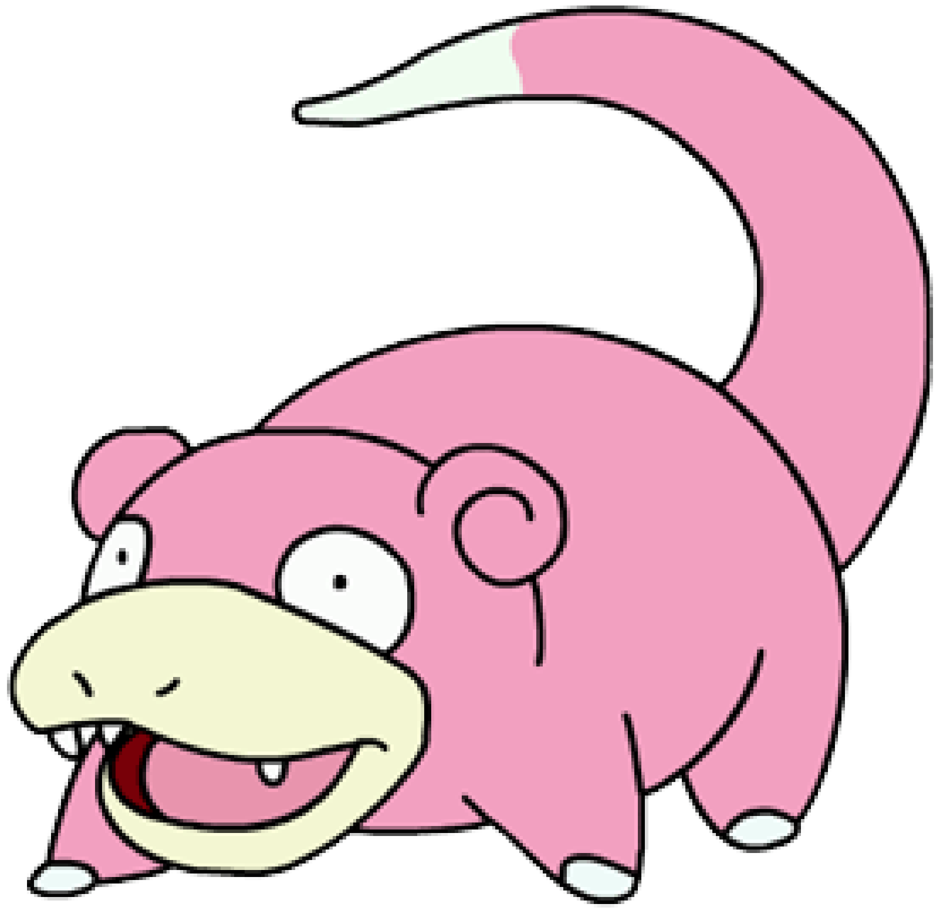
Application Level (Busy-waits)



Application Busy-Waits

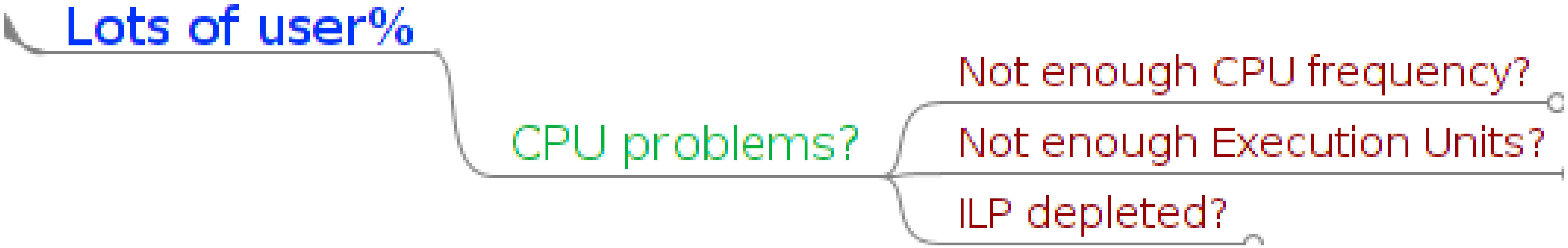
- The natural instinct: blocked waits (with helping)
- For latency-oriented: busy-waits are profitable

Demo 9



Analyzing with execution profiles

uArch Level (CPU)



CPU

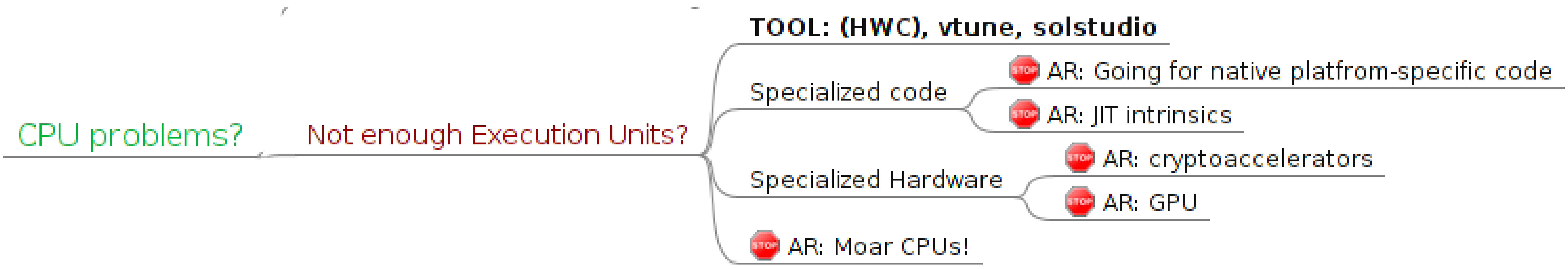
- Most applications are not getting here
- A very simple capacity problem

uArch Level (CPU, frequency)

CPU Frequency

- Exception: affects the memory/speculating performance
- How many servers out there are running with “ondemand”?

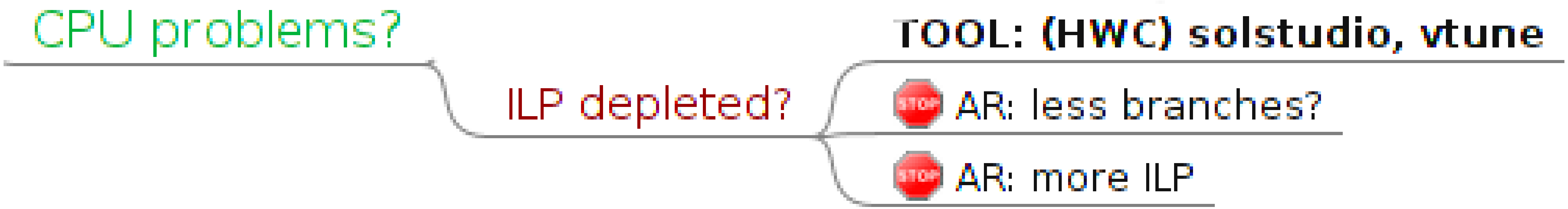
uArch Level (CPU, EU)



CPU, Execution Units

- Heavily-threaded hardware shares the CPU blocks
- Easy to run out of specific units with the homogeneous work

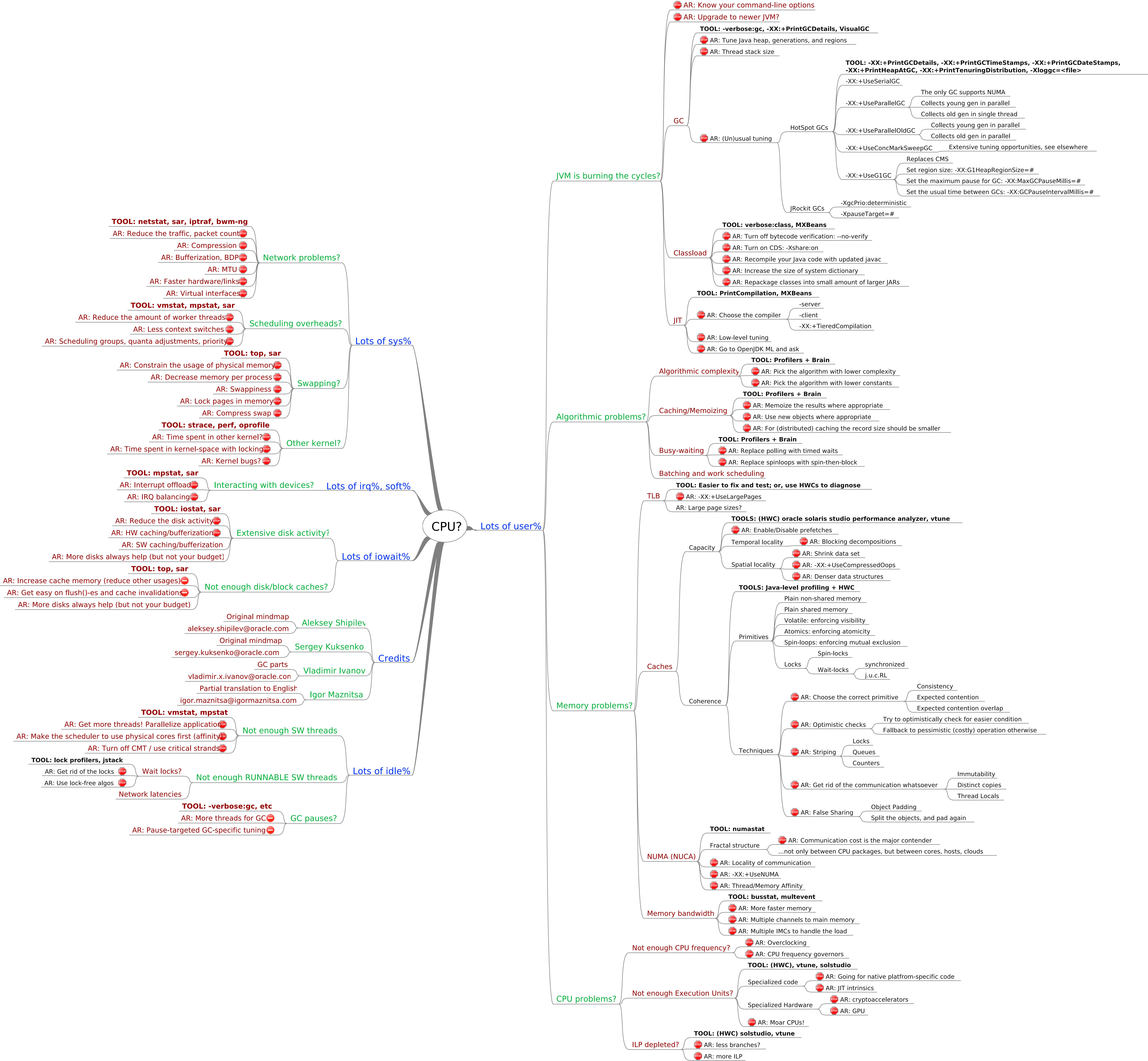
uArch Level (CPU, ILP)



Instruction Level Parallelism

- CPUs speculate aggressively
- Exposing less dependencies in the code help to speculate

Closing Thoughts


CPU?
Lots of user%
JVM is burning the cycles?
AR: Know your command-line options
AR: Upgrade to newer JVM?
GC
TOOL: -verbose:gc, -XX:+PrintGCDetails, VisualGC
AR: Tune Java heap, generations, and regions
AR: Thread stack size
AR: (Un)usual tuning
HotSpot GCs
TOOL: -XX:+PrintGCDetails, -XX:+PrintGCTimeStamps, -XX:+PrintGCDateStamps,
-XX:+PrintHeapAtGC, -XX:+PrintTenuringDistribution, -Xloggc=<file>
-XX:+UseSerialGC
-XX:+UseParallelGC
The only GC supports NUMA
Collects young gen in parallel
Collects old gen in single thread
-XX:+UseParallelOldGC
Collects young gen in parallel
Collects old gen in parallel
-XX:+UseConcMarkSweepGC
Extensive tuning opportunities, see elsewhere
-XX:+UseG1GC
Replaces CMS
Set region size: -XX:G1HeapRegionSize=#
Set the maximum pause for GC: -XX:MaxGCPauseMillis=#
Set the usual time between GCs: -XX:GCPauseIntervalMillis=#
JRockit GCs
-XgcPrio:deterministic
-XpauseTarget=#
Classload
TOOL: verbose:class, MXBeans
AR: Turn off bytecode verification: --no-verify
AR: Turn on CDS: -Xshare:on
AR: Recompile your Java code with updated javac
AR: Increase the size of system dictionary
AR: Repackage classes into small amount of larger JARs
JIT
TOOL: PrintCompilation, MXBeans
AR: Choose the compiler
-server
-client
-XX:+TieredCompilation
AR: Low-level tuning
AR: Go to OpenJDK ML and ask
Algorithmic problems?
Algorithmic complexity
TOOL: Profilers + Brain
AR: Pick the algorithm with lower complexity
AR: Pick the algorithm with lower constants
Caching/Memoizing
TOOL: Profilers + Brain
AR: Memoize the results where appropriate
AR: Use new objects where appropriate
AR: For (distributed) caching the record size should be smaller
Busy-waiting
TOOL: Profilers + Brain
AR: Replace polling with timed waits
AR: Replace spinloops with spin-then-block
Batching and work scheduling
Memory problems?
TLB
TOOL: Easier to fix and test; or, use HWCs to diagnose
AR: -XX:+UseLargePages
AR: Large page sizes?
Caches
Capacity
TOOLS: (HWC) oracle solaris studio performance analyzer, vtune
AR: Enable/Disable prefetches
Temporal locality
AR: Blocking decompositions
Spatial locality
AR: Shrink data set
AR: -XX:+UseCompressedOops
AR: Denser data structures
Coherence
TOOLS: Java-level profiling + HWC
Primitives
Plain non-shared memory
Plain shared memory
Volatile: enforcing visibility
Atomics: enforcing atomicity
Spin-loops: enforcing mutual exclusion
Locks
Spin-locks
Wait-locks
synchronized
j.u.c.RL
Techniques
AR: Choose the correct primitive
Consistency
Expected contention
Expected contention overlap
AR: Optimistic checks
Try to optimistically check for easier condition
Fallback to pessimistic (costly) operation otherwise
AR: Striping
Locks
Queues
Counters
AR: Get rid of the communication whatsoever
Immutability
Distinct copies
Thread Locals
AR: False Sharing
Object Padding
Split the objects, and pad again
NUMA (NUCA)
TOOL: numastat
Fractal structure
AR: Communication cost is the major contender
...not only between CPU packages, but between cores, hosts, clouds
AR: Locality of communication
AR: -XX:+UseNUMA
AR: Thread/Memory Affinity
Memory bandwidth
TOOL: busstat, multevent
AR: More faster memory
AR: Multiple channels to main memory
AR: Multiple IMCs to handle the load
CPU problems?
Not enough CPU frequency?
AR: Overclocking
AR: CPU frequency governors
Not enough Execution Units?
TOOL: (HWC), vtune, solstudio
Specialized code
AR: Going for native platfrom-specific code
AR: JIT intrinsics
Specialized Hardware
AR: cryptoaccelerators
AR: GPU
AR: Moar CPUs!
ILP depleted?
TOOL: (HWC) solstudio, vtune
AR: less branches?
AR: more ILP
Lots of sys%
Network problems?
TOOL: netstat, sar, iptraf, bwm-ng
AR: Reduce the traffic, packet count
AR: Compression
AR: Bufferization, BDP
AR: MTU
AR: Faster hardware/links
AR: Virtual interfaces
Scheduling overheads?
TOOL: vmstat, mpstat, sar
AR: Reduce the amount of worker threads
AR: Less context switches
AR: Scheduling groups, quanta adjustments, priority
Swapping?
TOOL: top, sar
AR: Constrain the usage of physical memory
AR: Decrease memory per process
AR: Swappiness
AR: Lock pages in memory
AR: Compress swap
Other kernel?
TOOL: strace, perf, oprofile
AR: Time spent in other kernel?
AR: Time spent in kernel-space with locking
AR: Kernel bugs?
Lots of irq%, soft%
Interacting with devices?
TOOL: mpstat, sar
AR: Interrupt offload
AR: IRQ balancing
Lots of iowait%
Extensive disk activity?
TOOL: iostat, sar
AR: Reduce the disk activity
AR: HW caching/bufferization
AR: SW caching/bufferization
AR: More disks always help (but not your budget)
Not enough disk/block caches?
TOOL: top, sar
AR: Increase cache memory (reduce other usages)
AR: Get easy on flush()-es and cache invalidations
AR: More disks always help (but not your budget)
Credits
Aleksey Shipilev
Original mindmap
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Sergey Kuksenko
Original mindmap
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Vladimir Ivanov
GC parts
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Igor Maznitsa
Partial translation to English
igor.maznitsa@igormaznitsa.com
Lots of idle%
Not enough SW threads
TOOL: vmstat, mpstat
AR: Get more threads! Parallelize application
AR: Make the scheduler to use physical cores first (affinity)
AR: Turn off CMT / use critical strands
Not enough RUNNABLE SW threads
Wait locks?
TOOL: lock profilers, jstack
AR: Get rid of the locks
AR: Use lock-free algos
Network latencies
GC pauses?
TOOL: -verbose:gc, etc
AR: More threads for GC
AR: Pause-targeted GC-specific tuning

Q&A

DEVOXX™
the java™ community conference

Definitions

Utilization = how busy the resource is?

$$Utilization = \frac{ResourceBusyTime}{TotalTime}$$

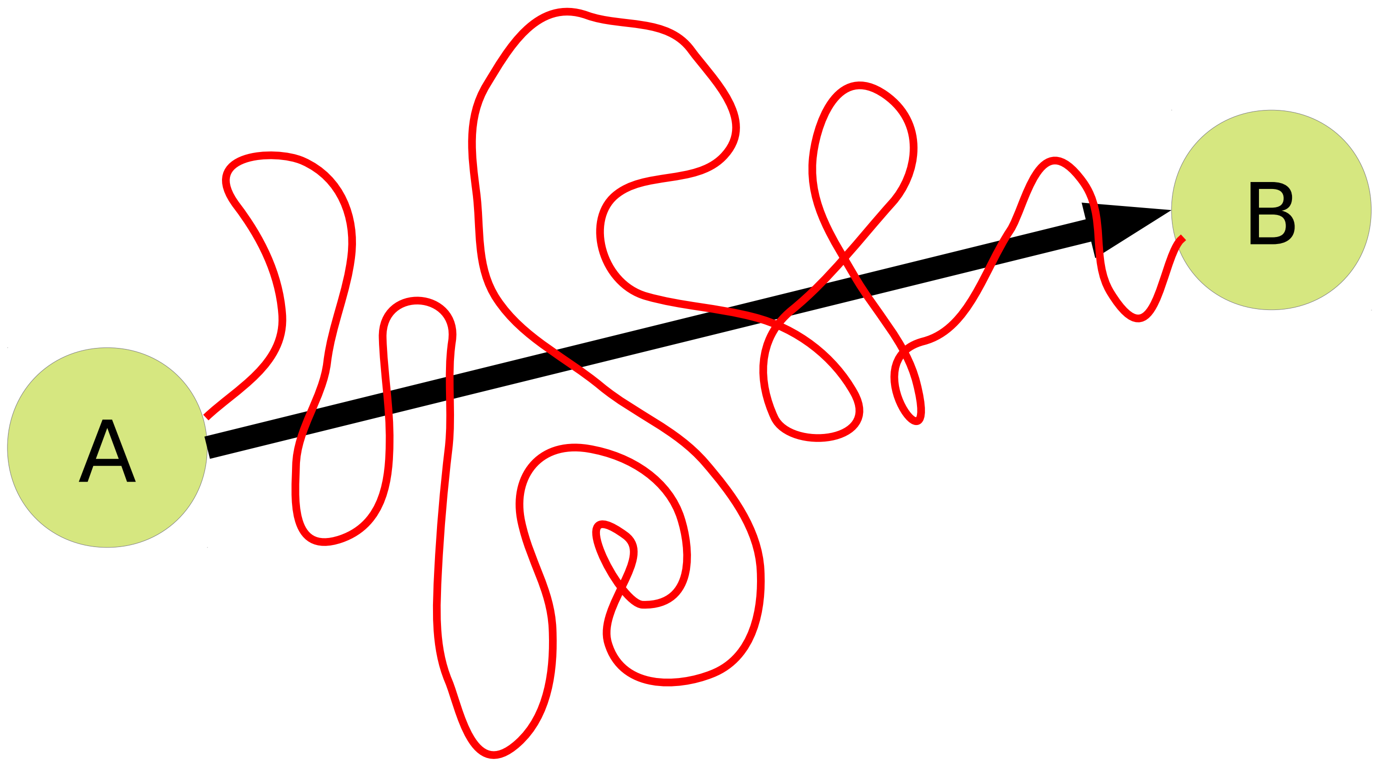
Idle = how free the resource is?

$$IdleTime = 1 - Utilization$$

Definitions

Efficiency = How much time is spent doing useful work?

- Not really possible to measure
- High Utilization != High Efficiency



Definitions

SpeedUp = A is N times faster than B means:

$$SpeedUp = \frac{time(B)}{time(A)} = \frac{throughput(A)}{throughput(B)}$$

Definitions

%Boost = A is P% faster than B means:

$$SpeedUp = 1 + \frac{n}{100\%}$$

$$Boost\% = (SpeedUp - 1) * 100\%$$

$$Boost\% = \frac{time(B) - time(A)}{time(A)}$$

$$Boost\% = \frac{throughput(A) - throughput(B)}{throughput(B)}$$

Definitions

Performance

= Scalar Field in Config Space

$$P : K^n \rightarrow \mathbb{R}$$

Scalability

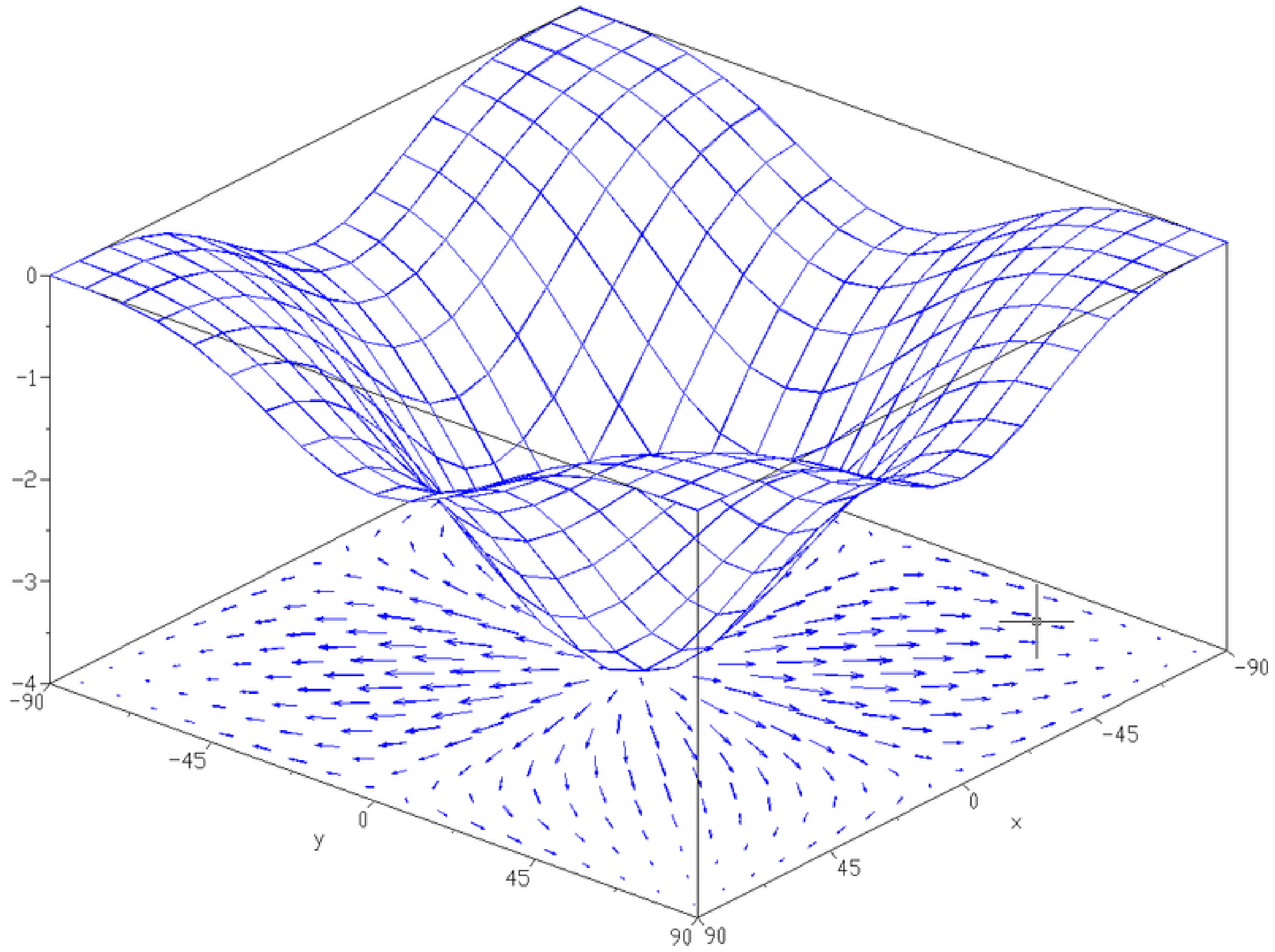
= Gradient of PSF

$$S = \nabla P$$

Resource Scalability

= specific component in SC vector

$$S_i = \frac{\partial P}{\partial R_i}$$



source: http://en.wikipedia.org/wiki/Gradient

Optimization Task

The configuration space can be humongous

- You don't want to traverse it all
- Or, you do want to exhaustive search if space is small

Random walks are inefficient

- Need to estimate the gradient in all N dimensions
- Means 2*N experiments per each step

Local estimates to rescue!

- Can predict if P would grow, should we add specific resource
- This is where the bottleneck analysis steps in

First step (mistakes)

We frequently hear:

- “I see the method foo() is terribly inefficient, let's rewrite it”
- “I see the profile for bar() is terribly high, at 5%, let's remove it”
- “I think our DBMS is a slowpoke, we need to migrate to [buzzword]”

Correct answer:

- Choose the metric!
- Make sure the metric is relevant!
- Your target at this point is improving the metric

Second step mistakes

“I can see the method foo() is terribly inefficient, let's rewrite!”

- ...what if the method is not used at all
- ...what if it accounts for just a few microseconds of time
- ...what if it does account for significant time, but...

Actually, not a bad idea

- ...as the part of controlled experiment
- ...if the changes are small, isolated, and painless to make

Second step mistakes

“I can see the method bar() accounts for 5% of time, let's remove it!”

- ...what if the CPU utilization is just 6.25%?
- ...what if this method pre-computes something reused later?
- ...what if this method is indeed problematic, but...

Second step mistakes

“I think our database is the problem! Let's migrate to [buzzword]!”

- ...what if the you just depleted the disk bandwidth?
- ...what if your IT had shaped the network connection?
- ...what if your poor database just needs a cleanup?
- ...what if the database is indeed the bottleneck, but...

TLBs Detailed

Virtual memory operates on virtual addresses

- But hardware needs physical addresses to access memory
- Needs virtual → physical translation
- Tightly cooperates with OS (walks through page tables)

Extreme cost to do a single translation

- Happens on each memory access
- Let's cache the translated addresses!
- TLB = Translation Look-aside Buffer
- Granularity: single memory page

TLB caches should be ultra-fast → TLBs are very small

- The solution is the other way around: larger pages