AMD's Prototype HSAIL-enabled JDK8 for the OpenJDK Sumatra Project

JVM LANGUAGE SUMMIT

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AGENDA

- Sumatra OpenJDK project
- GPU workload fundamentals
- AMD APU and Heterogeneous System Architecture (HSA)
- AMD HSAIL-enabled offload demo JDK
- Summary

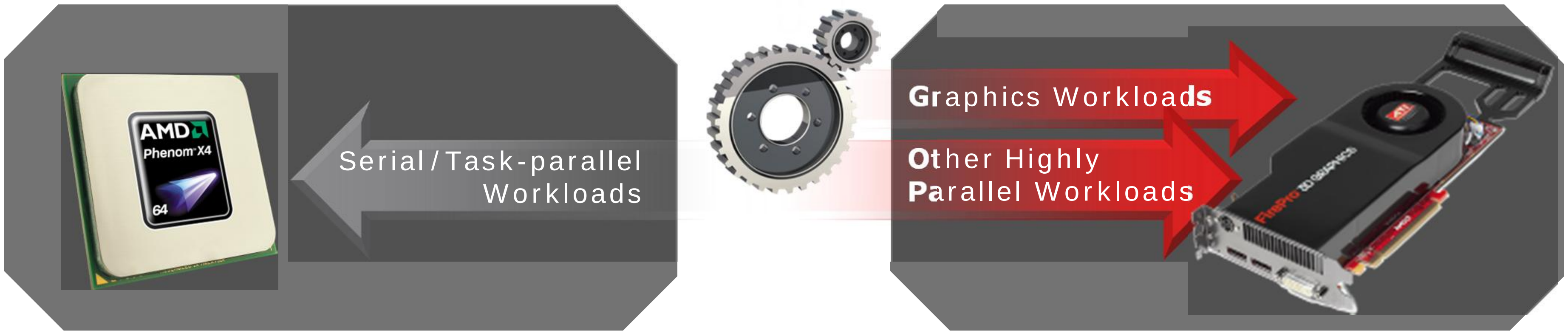
SUMATRA OPENJDK PROJECT

- Intending to enable Java applications to take advantage of GPU/APU
  - More or less transparently to the application
  - No application native code required
- Project started by Oracle and AMD shortly before JavaOne 2012
- GPU/APUs offer a lot of processing power
  - 2000 ASCI RED, Sandia National Laboratories
    - World's #1 supercomputer
    - http://www.top500.org/system/ranking/4428
    - ~3,200 GFLOPS
  - 2010 AMD Radeon™ HD 5970
    - ~4,700 GFLOPS
    - Already obsolete in my desk drawer
- HSA/OpenCL/CUDA standardize how to express both the GPU compute and host programming requirements
  - But not easy to use from Java without a lot of native code and expertise
  - Existing APIs include Aparapi, JOCL, OpenCL4Java, and others

IDEALLY, WE CAN TARGET COMPUTE AT THE MOST SUITABLE DEVICE

CPU excels at sequential, branchy code, I/O interaction, system programming.
Most Java applications have these characteristics and excel on the CPU.

GPU excels at data-parallel tasks, image processing, and data analysis.
Java is used in these areas/domains, but does not exploit the capabilities of the GPU as a compute device.



IDEAL DATA PARALLEL ALGORITHMS/WORKLOADS

- GPU SIMDs are optimized for data-parallel operations
  - Performing the same sequence of operations on different data at the same time
  - Each GPU core gets a unique work item id, often used as an array index
- The body of loops are a good place to look for data-parallel opportunities

```
// Each loop iteration is independent
for (int i=0; i< 100; i++)
    out[i] = in[i]*in[i];
```

- As a JDK 8 Stream operation:
  - This is a thread-safe calculation and could be a parallel stream

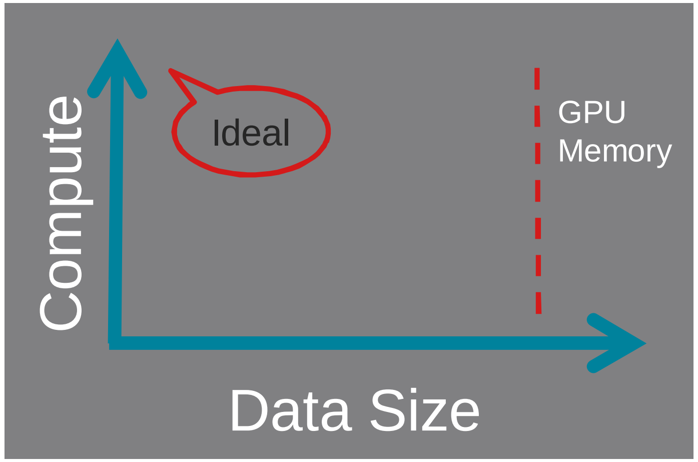
```
IntStream.range(0, in.length).forEach( p -> {
    out[p] = in[p] * in[p];
});
```

- Particularly if we can loop in any order and get same result

```
for (int i=99; i<= 0; i--)
    out[i] = in[i]*in[i];
```

CHARACTERISTICS OF AN IDEAL DISCRETE GPU WORKLOAD

- Each iteration contains sequential code
  - Modern GPU may have more than 1,500 stream cores
  - All GPU cores should be in “lock step” to get the best performance
  - Few divergent branches per wavefront
- Good balance between data size (low) and compute (high)
  - Data used in discrete GPU computation must be copied to/from card memory
- Transfer of data to/from the GPU can be costly
  - Trivial compute often not worth the transfer cost
  - May still benefit, by freeing up CPU for other work
- HSA will remove some of these limitations



WATCH OUT FOR DEPENDENCIES AND BOTTLENECKS

- Data dependencies can violate the "in any order" guideline

```
// for loop style
for (int i=1; i<100; i++) {
    out[i] = out[i-1] + in[i];
}
```

```
// stream style
IntStream.range(0, in.length).forEach( p -> {
    out[p] = out[p-1] * in[p];
});
```

- Mutating shared data can force use of atomic constructs
  - Note lambdas do not allow modifying captured values

```
for (int i=0; i< 100; i++)
    sum += in[i];
```

- Sometimes we can refactor to expose some parallelism

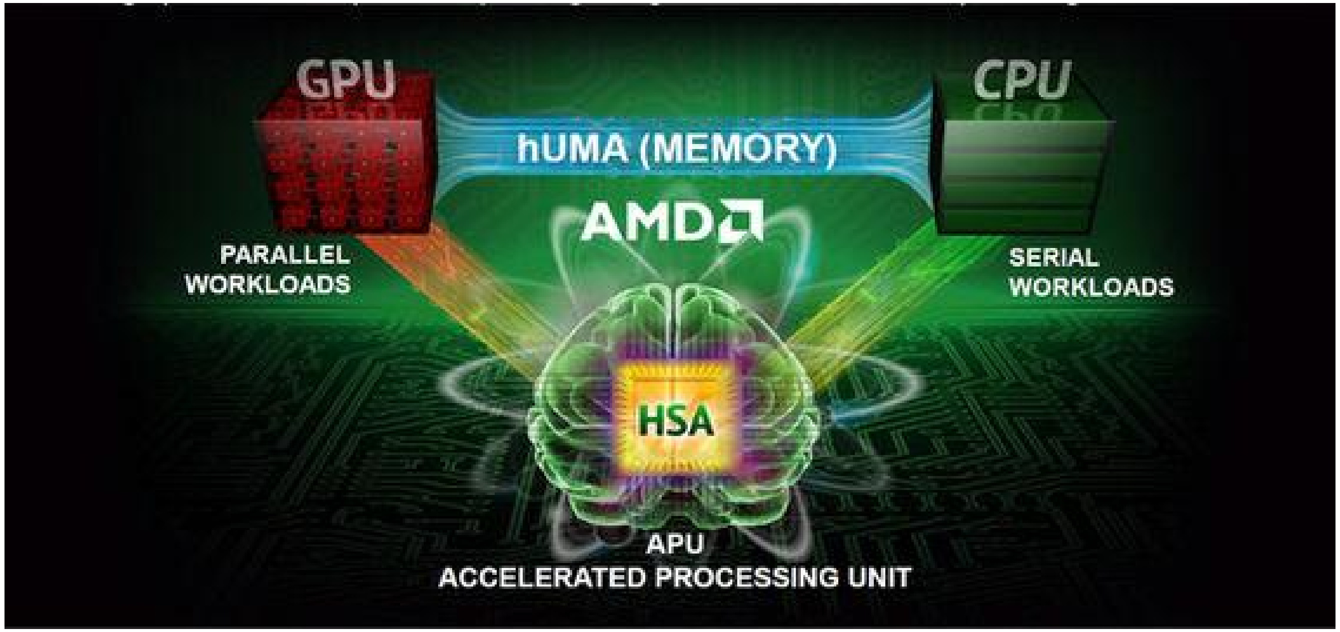
```
for (int n=0; n<10; n++)
   for (int i=0; i<10; i++)
     partial[n] += data[n*10+i];

for (int i=0; i< 10; i++)
     sum+=partial[i];
```

MEET HSA AND HSAIL

- Heterogeneous System Architecture standardizes CPU/GPU functionality
  - Be ISA-agnostic for both CPUs and accelerators
  - Support high-level programming languages
  - Provide the ability to access pageable system memory from the GPU
  - Maintain cache coherency for system memory between CPU and GPU
- Specifications and simulator from HSA Foundation
  - HSAIL portable ISA is "finalized" to particular hardware ISA at runtime
  - runtime specification for job launch and control
  - HSAIL simulator for development and testing before hardware availability

AMD ACCELERATED PROCESSING UNIT

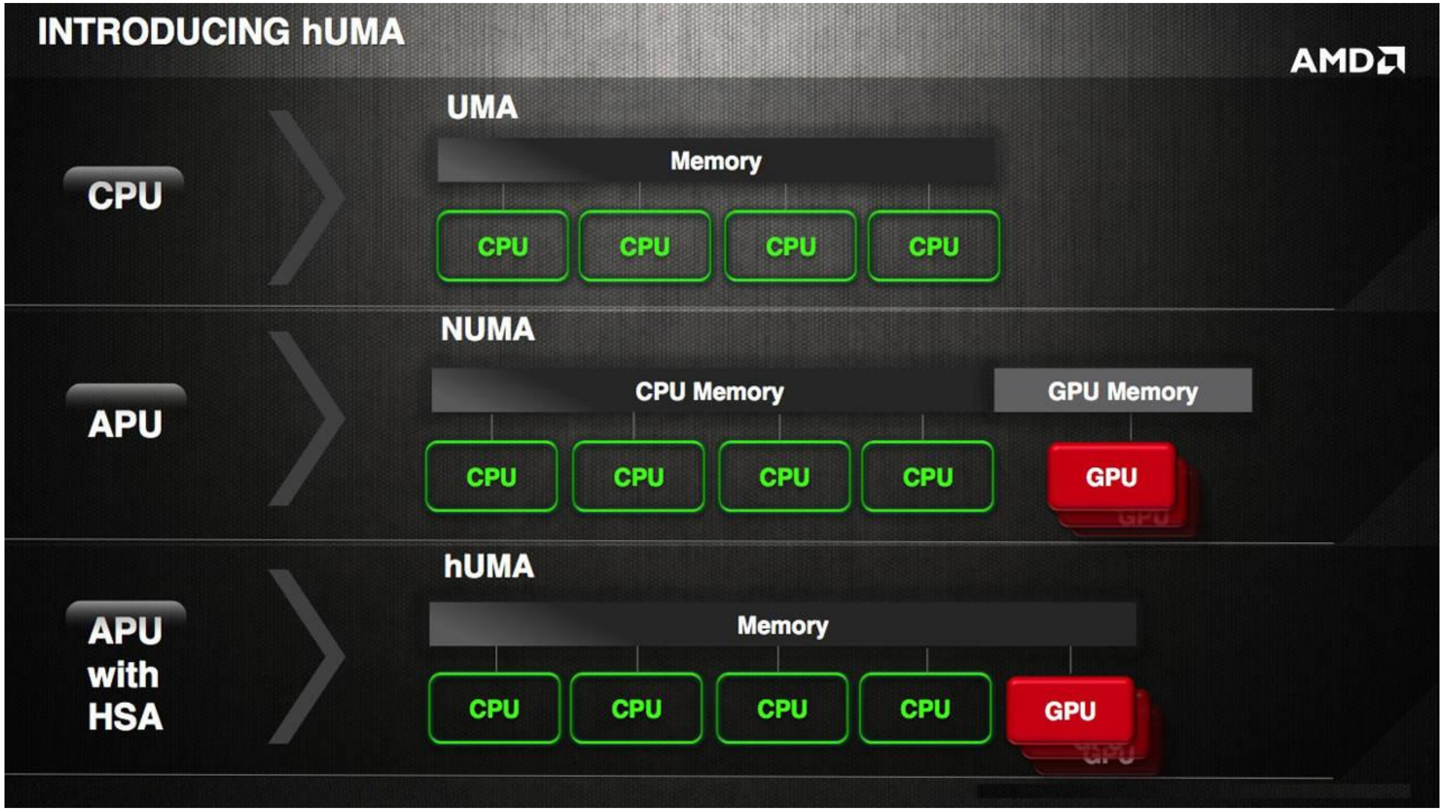
- AMD APU
  - CPU/GPU on one integrated chip
  - Various APU models shipping since June 2011
  - The upcoming Berlin APU will be the first to support HSA software stack
- HSA makes a great platform for Java offload
  - Direct access to Java heap objects in main memory from GPU cores
  - No extra copying over bus to discrete card
  - Pointer is a pointer from CPU or GPU application code



AMD hUMA ARCHITECTURE

AMD

- Upcoming AMD APUs feature heterogeneous Uniform Memory Access
  - Designed to work with HSA
  - Pointer is a pointer from CPU or GPU application code -- no copying over a bus



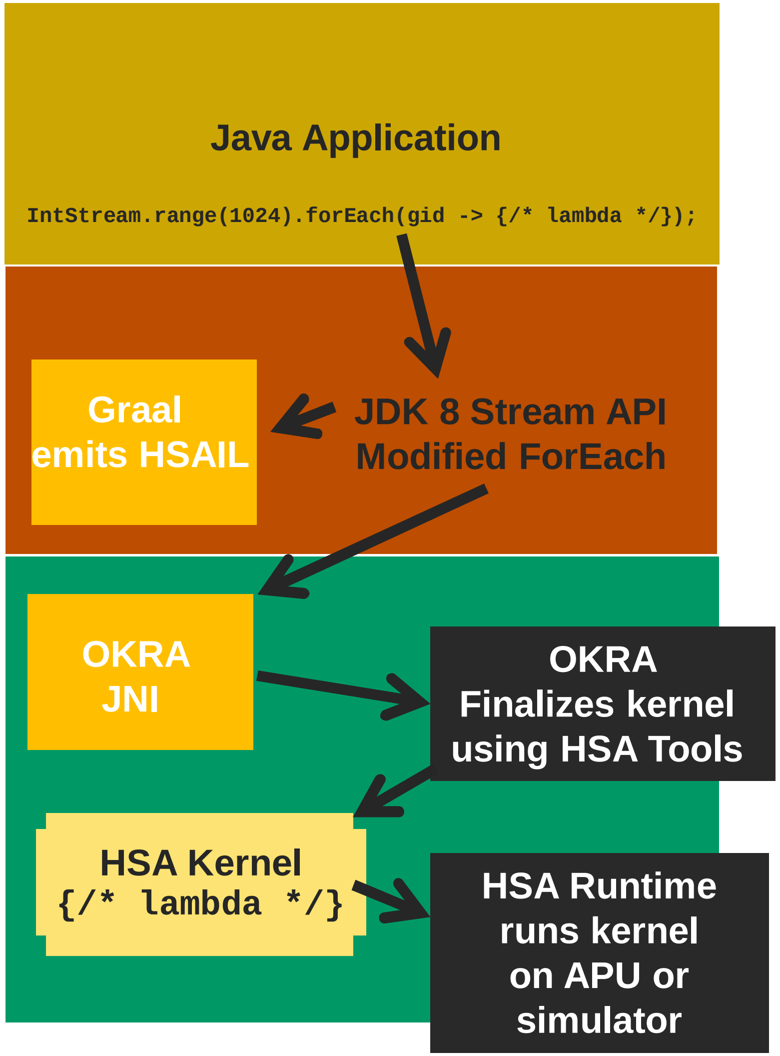
AMD SUMATRA PROTOTYPE: APU MEETS STREAM API

AMD

- Enables HSA APU offload of some JDK 8 parallel stream lambdas
  - Use of `parallel()` means developer thinks it's thread-safe
  - Immediate offload via flag or C2 compiler intrinsic to offload later
  - No special API or coding requirements for application developer
- We are adding HSAIL support to Graal
  - Basic HSAIL functionality already committed into Graal project
- We hook into `j.u.stream.ForEachOp` to redirect to our HSA offload code
  - `ForEach` "side effect" operation fits well with GPU data-parallel model
  - Do math, set field values, but no allocation or synchronization yet
  - Direct access to Java objects in the heap from GPU cores
- Seamless fallback to regular JDK code if code gen or offload fails
- This code available in Graal and a JDK webrev to be built together
- Can be easily run in open-source HSA simulator on regular systems

AMD SUMATRA PROTOTYPE: DIAGRAM

- Our JDK uses open-source HSAIL tools
- OKRA is a layer allowing easy use of the HSAIL tools from Java
- HSAIL tools assemble and finalize the HSAIL source emitted by Graal
- OKRA passes arguments to HSA Runtime and runs kernel



HOW IT WORKS

- APUs have dozens to hundreds of GPU cores
  - HSA workitem id is used as array index for each GPU core
  - Each core does one workitem per wavefront
  - Think of it as hundreds of threads, each running one function per invocation

- This JDK allows `IntStream` or `Object Array/Vector/ArrayList` stream offload
  - We added an extra class into `j.u.stream` to handle our extra stream processing
  - Stream source object array passed as hidden parameter to HSA
    - Object Stream kernel receives array ref and uses work item id as array index
    - Regular CPU lambda code receives Object as its parameter
  - `IntStream` range comes from HSA workitem id itself

- Collect the lambda target method at `ForEachOp` diversion point
  - Send lambda method to Graal HSAIL compiler
  - Graal emits HSAIL text then sent to HSA Finalizer for kernel creation
  - Kernel is cached for subsequent executions

MORE DETAILS

- Lambda arguments collected from consumer object created by stream API
  - Captured args passed as parameters to HSA kernel same as CPU code

- Referenced fields are accessed through memory ops like CPU-compiled methods
  - Offsets into objects computed by Graal same as CPU codegen

- Static fields accessed through JNI indirect reference
  - No finalized code patching at this time, so no GC-changeable embedded constants

- OKRA is a temporary interface to interact with HSA Runtime
  - Java thread calls our OKRA JNI code and blocks while kernel runs
  - OKRA is designed to work well with the HSA simulator

`IntStream` EXAMPLE

- Offload baseball statistics using `IntStream`
  - Player objects have accessors for various stat categories
  - Calculate the batting average for each player
  - `IntStream.forEach` lambda code in red is converted to HSA kernel

```
Player[] players = Arrays.stream(allHitters).map(objMapper).
        parallel().sorted().toArray(Player[]::new);

IntStream.range(0, players.length).parallel().forEach(n -> {
    Player p = players[n];
    if (p.getAb() > 0) {
        p.setBa((float)p.getHits() / (float)p.getAb());
    } else {
        p.setBa((float) 0.0);
    }
});
```

HSAIL FOR `IntStream` LAMBDA FROM GRAAL

```
version 0:95: $full : $large;
// static method HotSpotMethod<Main.lambda$7(Player[], int)>
kernel &run (
          kernarg_u64 %_arg0
          ) {
          ld_kernarg_u64  $d6, [%_arg0];          // Captured array ref
          workitemabsid_u32 $s2, 0;               // work item id is a gpu idiom

@L4:      ld_global_s32 $s0, [$d6 + 16];          // load array length
          cmp_ge_b1_u32 $c0, $s2, $s0;            // compare length to workitemid
          cbr $c0, @L5;                           // return if greater
@L6:      cvt_s64_s32 $d0, $s2;
          mul_s64 $d0, $d0, 8;                    // convert work item into array index
          add_u64 $d3, $d6, $d0;
          ld_global_u64 $d0, [$d3 + 24];          // load player object
          mov_b64 $d3, $d0;
          ld_global_s32 $s3, [$d0 + 20];          // this is inlined getAb()
          cmp_lt_b1_s32 $c0, 0, $s3;              // if (p.getAb() > 0)
          cbr $c0, @L7;
@L8:      mov_b32 $s16, 0.0f;
          st_global_f32 $s16, [$d0 + 76];          // p.setBa((float) 0.0);
@L9:      ret;
@L7:      ld_global_s32 $s1, [$d0 + 28];          // inlined getHits()
          cvt_f32_s32 $s16, $s1;                   // cast (float)p.getHits()
          cvt_f32_s32 $s17, $s3;                   // cast (float)p.getAb()
          div_f32 $s16, $s16, $s17;               // hits / ab
          st_global_f32 $s16, [$d0 + 76];         // inlined setBa()
          brn @L9;
@L5:      ret;
};
```

SMALL OBJECT STREAM EXAMPLE

- Same example as Object Stream
  - The `Stream.forEach` lambda is converted to an HSA kernel
  - Stream source array is passed as a hidden parameter to kernel

```
Stream<Player> s = Arrays.stream(allHitters).map(objMapper).parallel().sorted();

s.forEach(p -> {
    if (p.getAb() > 0) {
        p.setBa((float)p.getHits() / (float)p.getAb());
    } else {
        p.setBa((float)0.0);
    }
});
```

HSAIL FOR OBJECT STREAM LAMBDA

```
version 0:95: $full : $large;
// static method HotSpotMethod<Main.lambda$3(Player)>
kernel &run (
          kernarg_u64 %_arg0
          ) {
          ld_kernarg_u64  $d6, [%_arg0];          // Hidden stream source array ref
          workitemabsid_u32 $s2, 0;

          cvt_u64_s32 $d2, $s2;         // Convert work item id to long
          mul_u64 $d2, $d2, 8;          // Adjust index for sizeof ref
          add_u64 $d2, $d2, 24;         // Adjust for actual elements data start
          add_u64 $d2, $d2, $d6;        // Add to array ref ptr
          ld_global_u64 $d6, [$d2];     // Load from array element into parameter reg
@L0:
          ld_global_s32 $s0, [$d6 + 20];          // inlined getAb()
          cmp_lt_b1_s32 $c0, 0, $s0;              // if (p.getAb() > 0)
          cbr $c0, @L1;
@L2:
          mov_b32 $s16, 0.0f;
          st_global_f32 $s16, [$d6 + 76];        // p.setBa((float)0.0);
@L3:
          ret;
@L1:
          ld_global_s32 $s3, [$d6 + 28];         // load p.getHits()
          cvt_f32_s32 $s16, $s3;                 // (float) p.getHits()
          cvt_f32_s32 $s17, $s0;                 // (float) p.getAb()
          div_f32 $s16, $s16, $s17;
          st_global_f32 $s16, [$d6 + 76];        // inlined setBa()
          brn @L3;
};
```

CURRENT LIMITATIONS OF HSAIL OFFLOAD DEMO JDK

- Currently not allowed in an offloaded kernel
  - No heap allocation
  - No exception handling or try/catch inside a kernel
  - No calling methods that would be a JNI or runtime call
  - No synchronization in kernels
  - No method handles in target lambda methods

- Kernels are called by JNI code using JNI Critical
  - So no GC during kernel execution
  - No debug info or oop maps for kernels
  - No way to have embedded oops in finalized code like with `nmethods`

FEATURES HOPEFULLY STANDARDIZED IN SUMATRA

- What is the heuristic or coding model for offloading?
  - We chose parallel streams based on our experience with Aparapi and GPUs
  - This model does not require developers to learn new API, etc.
- GC interaction?
  - Possible or worthwhile to have safepoints during kernel execution?
- What runtime calls or allocation from a kernel can be supported?
  - Runtime calls imply pausing the GPU kernel and resuming on the CPU
- Exception handling?
  - Throw inside kernel with its own try-catch block handling it
  - Throw causing kernel abort and handled in runtime on CPU
- What synchronization can be supported in kernels?
  - Between GPU cores
  - Between CPU and GPU

FEATURES HOPEFULLY STANDARDIZED IN SUMATRA

- Details of HSA versus discrete card offload?
  - Copying/replacing buffers to card vs. direct heap access in HSA
  - Any difference in interaction with JVM runtime?
- How to detect and configure various offload runtime systems from Java?
  - HSAIL/BRIG, PTX, etc.
  - Select offload GPU(s) if more than one available

SUMMARY

- We can offload simple JDK 8 Stream API `forEach` lambdas to HSA systems
  – Seamlessly offload normal JDK 8 code
  – No special coding or API required

- Basic HSAIL code generation now in Graal repository

- HSAIL simulator is available and our HSAIL demo JDK supports it
  – Detailed check-out and build instructions on the Sumatra wiki: https://wiki.openjdk.java.net/display/Sumatra/Main

- GPU offload for Java is here
  – GPUs offer unprecedented performance for the appropriate workload
  – Don't assume everything can/should execute on the GPU
  – Look for "islands of parallel in a sea of sequential"

- Lots of work remains!

LINKS AND REFERENCES

- Sumatra OpenJDK GPU/APU offload project
  - Project home page: http://openjdk.java.net/projects/sumatra/
  - Wiki: https://wiki.openjdk.java.net/display/Sumatra/Main
- Graal JIT compiler and runtime project
  - Project home page: http://openjdk.java.net/projects/graal/
- HSA Foundation
  - Home page: http://hsafoundation.com/
  - Specifications at http://hsafoundation.com/standards/
- AMD Kaveri APU Overview
  - http://www.theregister.co.uk/2013/05/01/amd_huma/

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