LLVM Interpreter

a key component in validation of OpenCL™ compilers

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Intel
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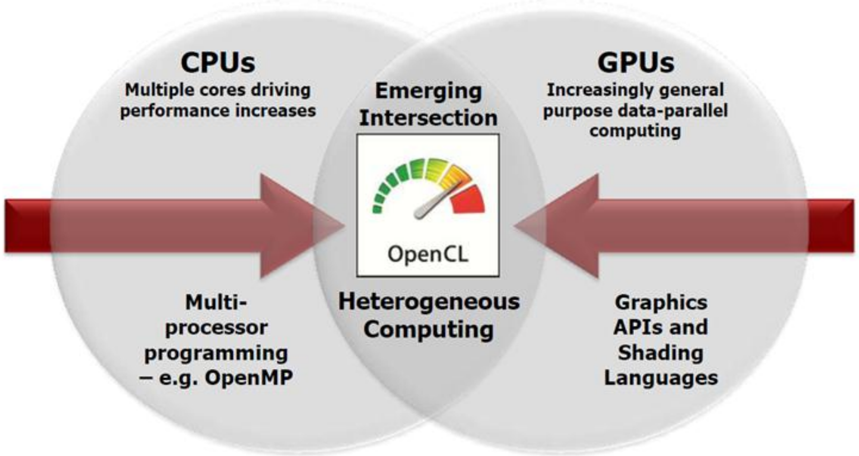
Agenda

- OpenCL™ standard overview
- OpenCL compiler standalone validation tool
- LLVM Interpreter
- Contribution to the LLVM community

Optimization Notice

OpenCL™ Standard

OpenCL™ - Open Standard for Parallel Computing



- Open standard driven by Khronos*
- Royalty-free
- First spec in 2009
- Cross-platform

Diagram based on PDF OpenCL overview available at http://www.khronos.org/opencl/

OpenCL™ Standard Overview

- Portable C code for all architectures
- Derived from ISO C99
  - Few restrictions, e.g. recursion, function pointers
  - Short vector types e.g., float4, short2, int16
  - Built-in functions: math (e.g., sin), geometric, common (e.g., min, clamp)
- Configurable N-dimensional computation domain
- Barriers and memory fences within workgroups
- Extensive list of optimized built-in functions

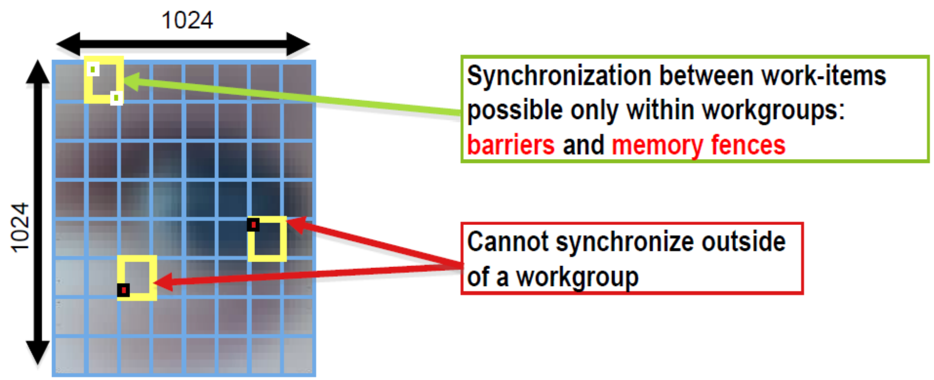


Diagram based on the PDF OpenCL™ overview available at http://www.khronos.org/opencl/

Intel® SDK for OpenCL™ Applications 2013

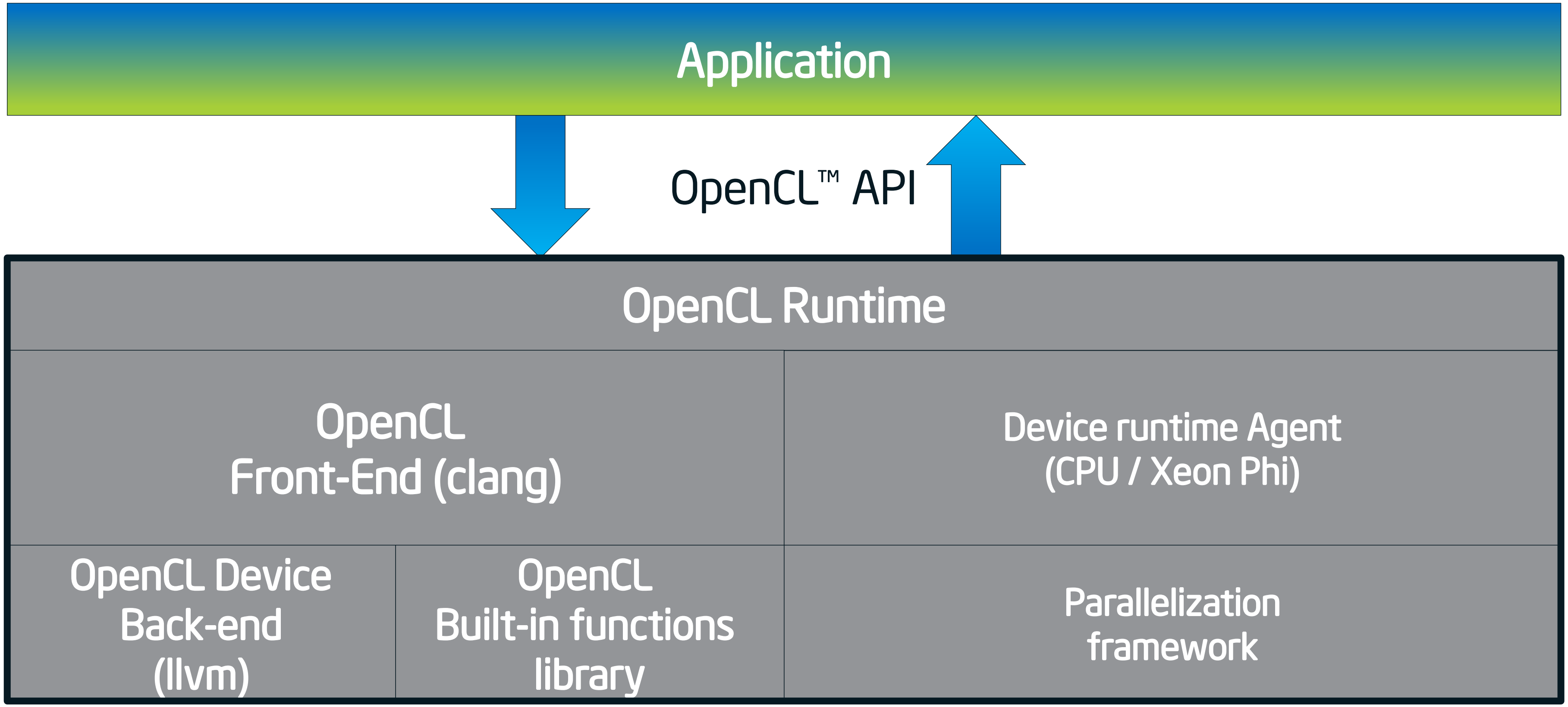
A Comprehensive Software Development Environment for OpenCL™ Applications

	Target Processors	Target Operating System	OpenCL Spec Version	Target SDK	Developer Benefits
Visual Computing Domain		Windows 7 Windows 8	OpenCL 1.2	(Version 2013)	Develop and deploy visual computing applications for 3rd and 4th Generation Intel® Core™ Processors Get ready for next generations
Data Center Domain		(Red Hat*, SUSE*)	OpenCL 1.2	(Version XE 2013)	Preserve your investment when developing high performance compute applications

OpenCL compiler validation Standalone Tool

Intel OpenCL™ implementation architecture

Running on Intel® CPU and Intel Xeon Phi™ Coprocessor



OpenCL is multicomponent system challenging to validate

Conformance Tests
OpenCL™ Implementation validation

- Provided and maintained by Khronos*
- A compliance test for OpenCL™ specification
- System level tests
  - Tests OpenCL implementation as whole entity
  - All components should be functional

Validation on component level is not trivial

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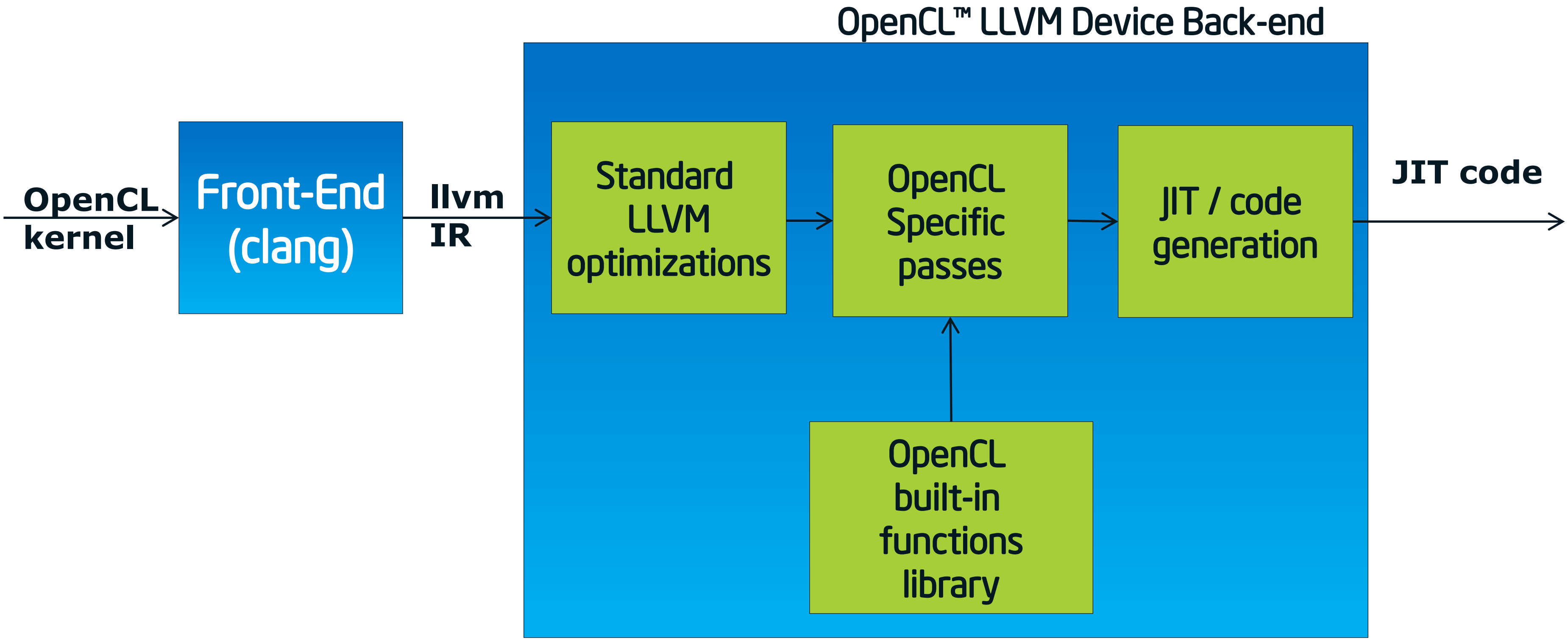
OpenCL™ Standard
Supporting Intel® Many Integrated Core Architecture

- Simultaneous development of multiple components
  - Runtime
  - Device agent
  - Device Back-end
  - OpenCL™ built-in functions library
  - …
- Conformance tests
  - Not functional until all components are ready
- Early testing is highly needed
  - Boosts development speed

How to validate device backend?

OpenCL™ Compiler for Intel® CPU and Intel Xeon Phi™ Coprocessors
Zoom in



How to validate device backend?

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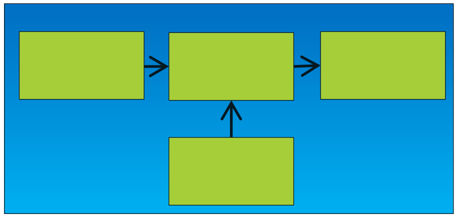
Standalone compiler validation tool

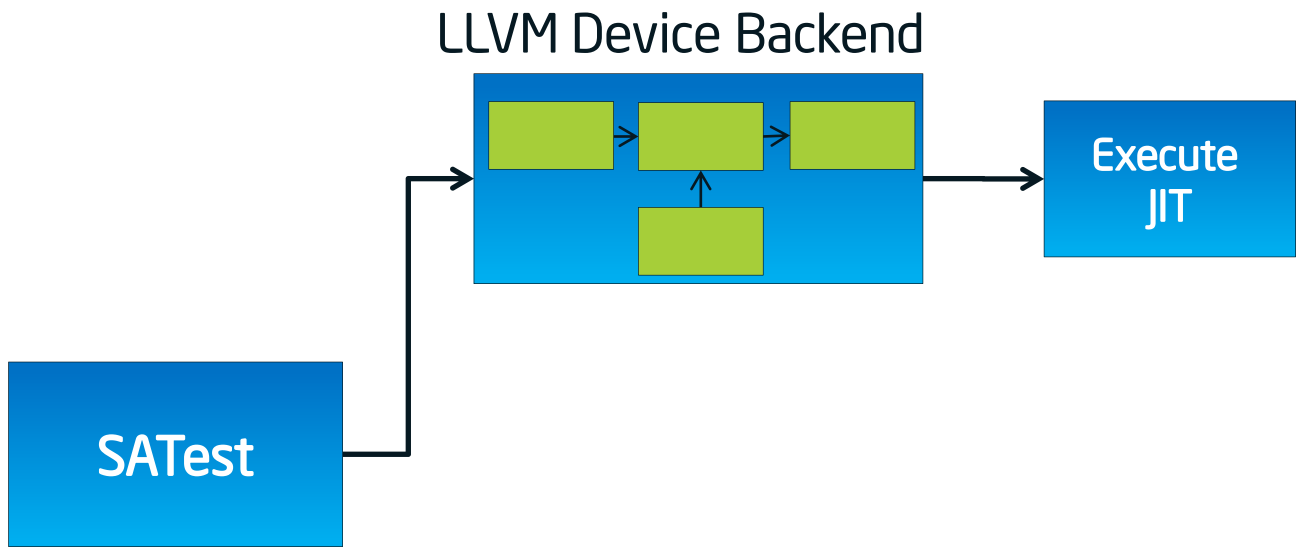
LLVM Device Backend



IDEA!!!

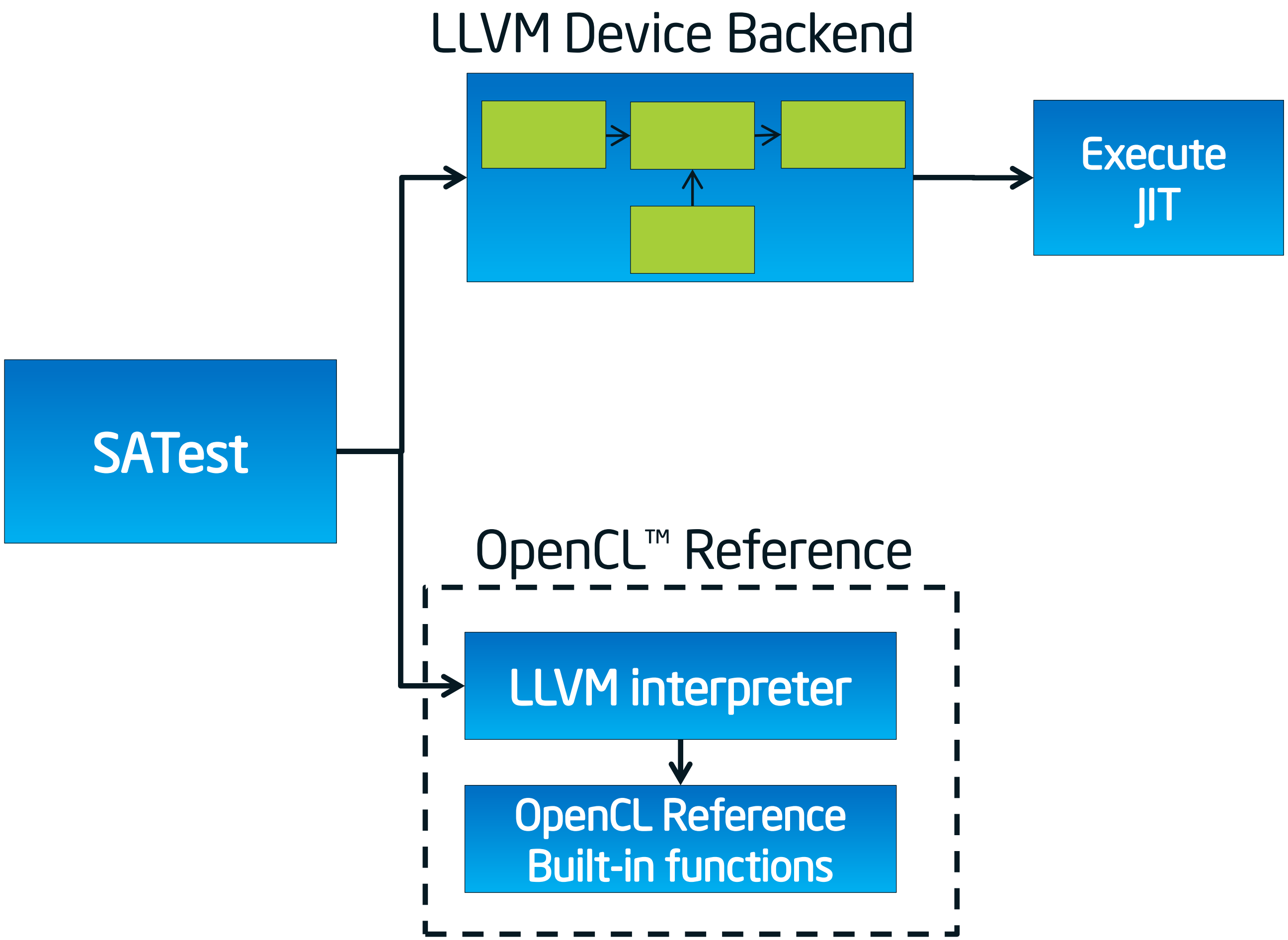
Isolate testing device backend from other components

Standalone compiler validation tool



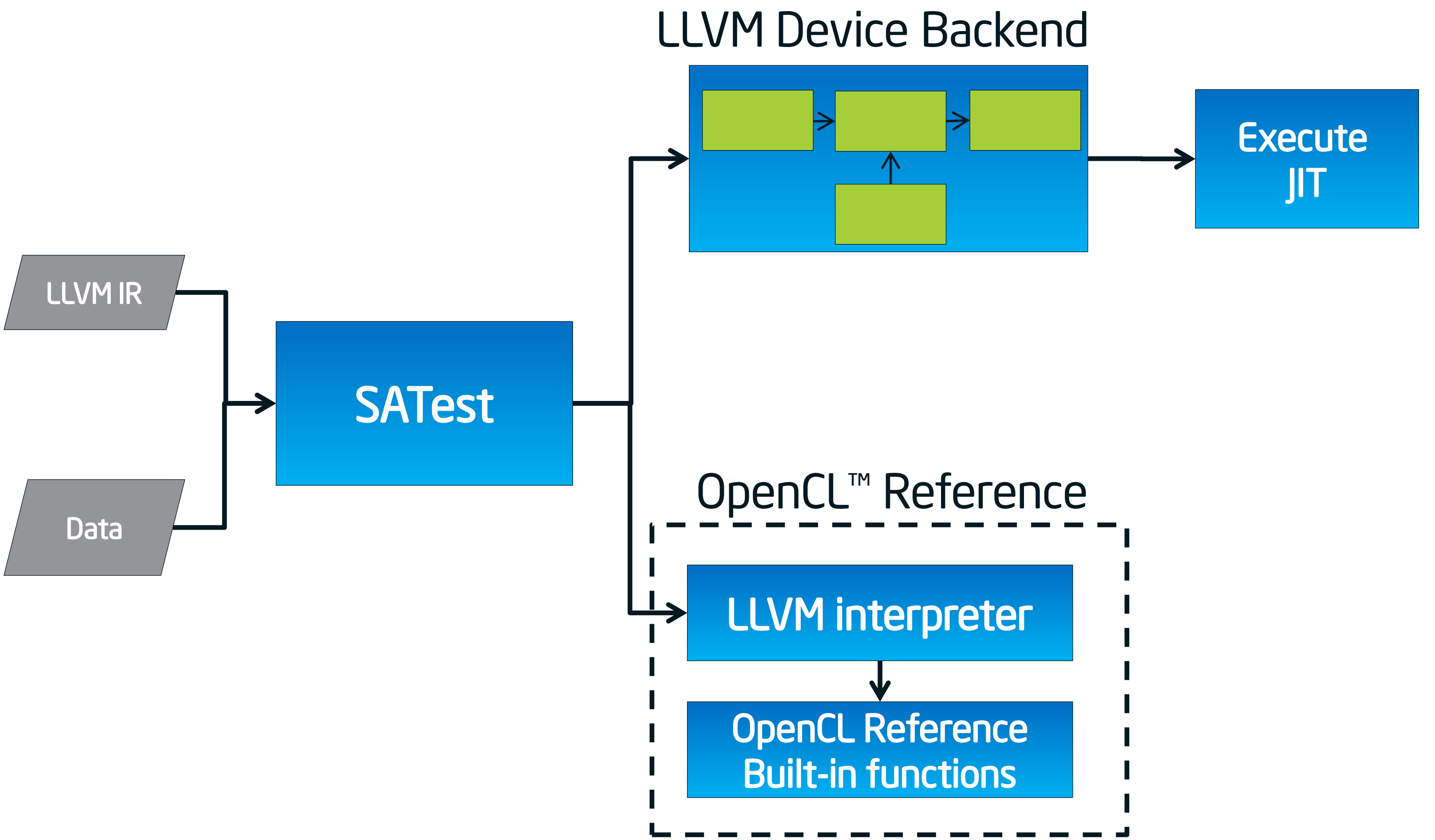
Implement standalone tool to work with device back-end

Standalone compiler validation tool



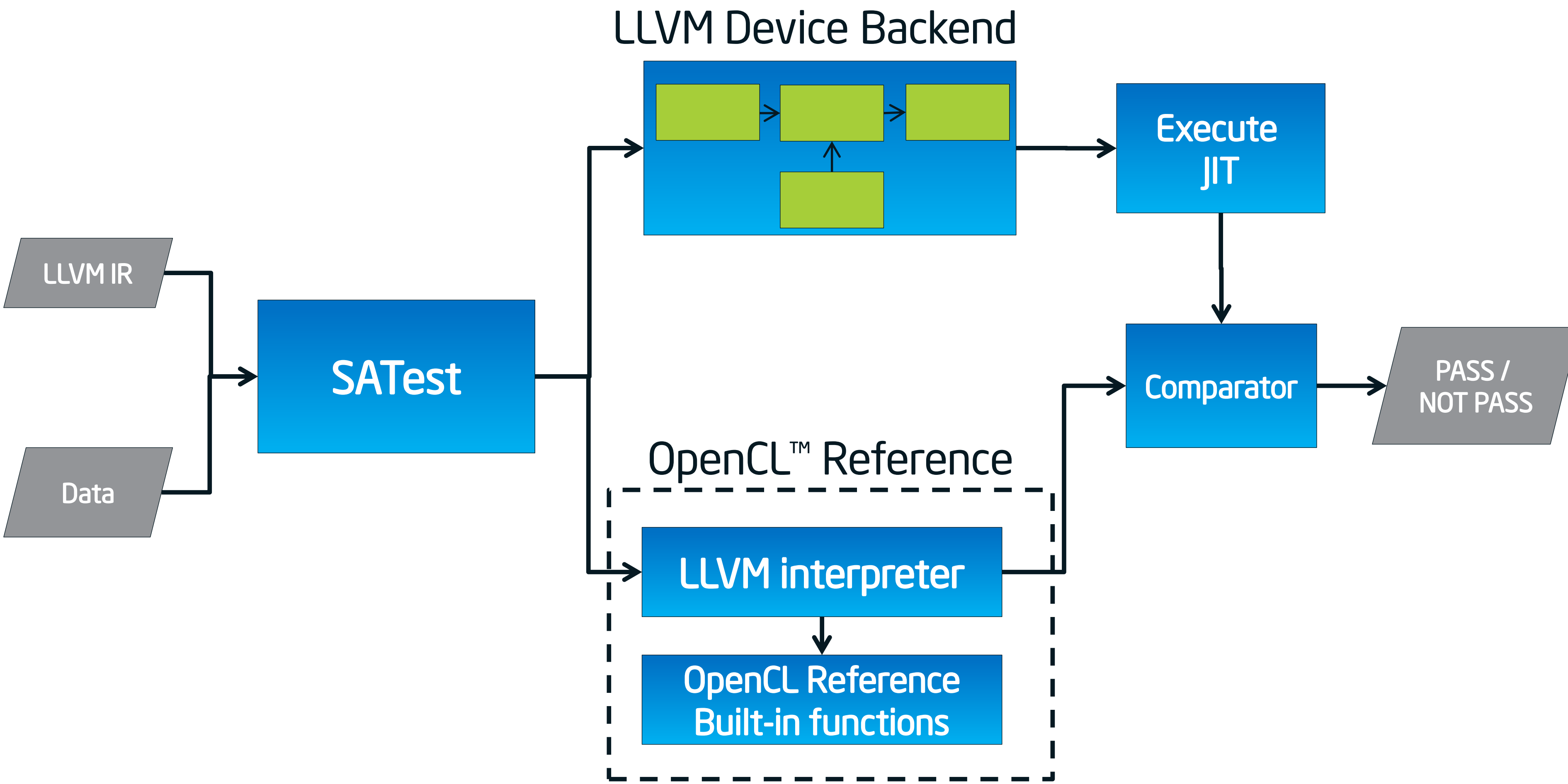
Implement OpenCL Reference to obtain reference results
Share the same build/execute interface with back-end

Standalone compiler validation tool



Import LLVM kernel compiled from OpenCL
Import data recorded from running OpenCL kernel

Standalone compiler validation tool



Compare Reference and Back-end outputs
Report PASS/NOT PASS

Standalone compiler validation tool
Features

Several modes of operation

- Functional Validation
  - Check device back-end produces OpenCL™ 1.2 conformant results
  - Real life kernels and data
- Performance
  - Compile time
  - Kernel execution time
  - Single thread execution
  - Isolate and Detect issues coming from backend
- Build
  - Dump LLVM IR and JIT code on specified pass
  - Directly track/debug optimizations

Tool for backend developers

LLVM Interpreter

LLVM Interpreter

- MUST have component for OpenCL™ Reference
- Executes LLVM bytecode directly
- Produces bitwise accurate results
- Slow
- No optimizations
- LLVM trunk version lacks vector and aggregate types support. Need to implement them

Produces reference results of running OpenCL kernel

Missing pieces in LLVM interpreter

OpenCL™

```
kernel void cl_exp(global const float4 *a,
                   global float4 *result) {

    int id = get_global_id(0);
    result[id] = exp(a[id]);
}
```

LLVM IR

```
define void @cl_exp(<4 x float> addrspace(1)* %a, <4 x float>
addrspace(1)* %result) nounwind {

  %1 = call i64 @get_global_id(i32 0) nounwind readnone
  %sext = shl i64 %1, 32
  %2 = ashr exact i64 %sext, 32
  %3 = getelementptr inbounds <4 x float> addrspace(1)* %a,
i64 %2
  %4 = load <4 x float> addrspace(1)* %3, align 16
  %5 = call <4 x float> @_Z3expDv4_f(<4 x float> %4)
nounwind readnone
  %sext1 = shl i64 %1, 32
  %6 = ashr exact i64 %sext1, 32
  %7 = getelementptr inbounds <4 x float>
addrspace(1)* %result, i64 %6
  store <4 x float> %5, <4 x float> addrspace(1)* %7, align 16
  ret void
}
```

Not supported in LLVM interperter

LLVM Interpreter: Current State
Essential Methods of Interpreter

```
class Interpreter : public ExecutionEngine, public
InstVisitor<Interpreter> {

  …

  // The runtime stack of executing code.
  // current function record.
  std::vector<ExecutionContext> ECStack;

  …
}
```

All interpreter logic encapsulated into 'Interpreter' class

LLVM Interpreter: Current State
Essential Methods of Interpreter

```
class Interpreter : public ExecutionEngine, public
InstVisitor<Interpreter> {

 …

  /// run - Start execution with the specified function and
arguments.

 virtual GenericValue runFunction(Function *F, const
                          std::vector<GenericValue> &ArgValues);


 /// Opcode Implementations(e.g. void visitLoadInst(LoadInst &I))

 void visit*();

 …

}
```

visit*() methods execute instructions

LLVM Interpreter: Current State
Execution Context

```
struct ExecutionContext {
  …
  /// LLVM values used in this invocation
  std::map<Value *, GenericValue> Values;
  /// Values passed …
  std::vector<GenericValue>  VarArgs;
  …
};
```

Local variables and arguments container

Stores current basic block, function and next instruction

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GenericValue Structure

```
struct GenericValue {
  union {
    double          DoubleVal;
    float           FloatVal;
    PointerTy       PointerVal;
    struct { unsigned int first; unsigned int second; } UIntPairVal;
    unsigned char   Untyped[8];
  };
  APInt IntVal;   // also used for long doubles
    ...

};
```

Universal container for variable values

GenericValue Structure

```
struct GenericValue {
  union {
    double          DoubleVal;
    float           FloatVal;
    PointerTy       PointerVal;
    struct { unsigned int first; unsigned int second; } UIntPairVal;
    unsigned char   Untyped[8];
  };
  APInt IntVal;   // also used for long doubles
    ...
  std::vector<GenericValue> AggregateVal;

...

};
```

Stores missing vector and aggregate type

Adding new single field covers vector and aggregate types

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Example of New visit* Method

Typical visit* method

```
void visit*(Instruction& I)
{
  ExecutionContext &SF = ECStack.back();
  const Type *Ty    = I.getType();
  GenericValue Src1 = getOperandValue(I.getOperand(0), SF);
  GenericValue Src2 = getOperandValue(I.getOperand(1), SF);
  GenericValue R;   // Result
  switch (Ty->getTypeID())
  {
    case: Type::IntegerTyID: // R.IntVal = Src1.IntVal OP Src2.IntVal;
    case: Type::FloatTyID:   // R.FloatVal = Src1.FloatVal OP Src2.FloatVal;
    …
}
```

Example of New visit* Method

Typical visit* method

```
void visit*(Instruction& I)
{
  ExecutionContext &SF = ECStack.back();
  const Type *Ty    = I.getType();
  GenericValue Src1 = getOperandValue(I.getOperand(0), SF);
  GenericValue Src2 = getOperandValue(I.getOperand(1), SF);
  GenericValue R;   // Result
  switch (Ty->getTypeID())
  {
    case: Type::IntegerTyID: // R.IntVal = Src1.IntVal OP Src2.IntVal;
    case: Type::FloatTyID:   // R.FloatVal = Src1.FloatVal OP Src2.FloatVal;
    …
    case: Type::VectorTyID:
       // set vector size
       R.AggregateVal.resize(Src1.AggregateVal.size());

       if (cast<VectorType>(Ty)->getElementType()->isFloatTy())
       // process R.FloatVecVal
       …
       if (cast<VectorType>(Ty)->getElementType()->isIntegerTy())
       // process R.IntVecVal

  }
```

Processing vectors

Interpreter
Operations implemented

Group	Number of operations
Vector Memory Access and Addressing	4
Vector binary	12
In-vector	3
Vector comparison	3
Vector bitwise binary	6
Vector conversion	10
Aggregate	2

OpenCL™ Reference Tool
Built-in Functions Implemented

- High-precision reference implementation
- Full support of OpenCL™ 1.2 standard
- Over 3000 functions
  - Math
  - Geometric
  - Common
  - Image
  - Conversions between types (~2000)
  - etc

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Demo

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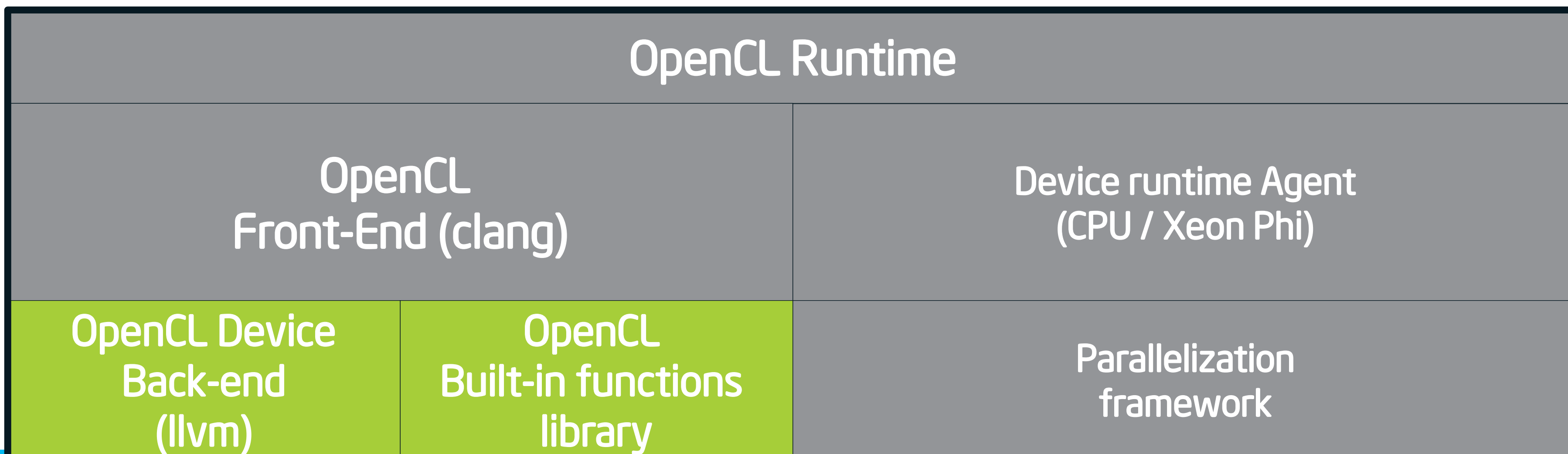
OpenCL™ Back-end Validation for Intel® Xeon Phi™ Coprocessor Summary

- Enabled validation at early stage
  - At 1st stages on functional simulator
  - Other components of OpenCL™ infrastructure not yet ready
  - Before hardware was ready
- Saved time on isolated backend development



Contribution to the LLVM Community

Interpreter
Summary of our Modifications

- Added Vector and aggregate types to Execution Context
- Added Vector operations
  - Memory access and addressing
  - Binary
  - In-vector
  - Comparison
  - Constant
- Added Aggregate types operations
  - 'extractvalue'
  - 'insertvalue'

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Contribution to the LLVM Community

- Uploading interpreter changes to LLVM repository
- Incremental commits adding new features to interpreter
- Vectors and aggregate types will be supported in interpreter

Wish list for the Interpreter

- Add standard C LLVM intrinsics support
- Enhance processing of constant expressions

- Multiple components are developed simultaneously
- Existing tests work only after all components are ready
- **Lack of Early validation**
- We provide early validation infrastructure using LLVM interpreter

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Thank you

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