Modular

Mojo GPU Compilation 🔥

Weiwei Chen
weiwei.chen@modular.com

Abdul Dakkak
adakkak@modular.com

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GPU Programming in Mojo🔥

- Pythonic **systems programming** language
  - Generic programming, type system, and memory safety
  - Blazing fast
  - Best way to extend Python to CPUs and GPUs
  - Bedrock for Modular's MAX inference engine.
- **Unified programming** for CPU + GPU
  - The full power of standard CUDA/ROCm, but without "CUDA"
    - Threads, warps, sync primitives, WMMA instructions
    - Generate executables **without** using vendor toolkits or libraries
  - All GPU kernels for Nvidia, AMD, Apple written in Mojo
- **Library driven** with **simple** compiler support

```
from math import ceildiv
from sys import has_accelerator
from gpu import global_idx
from gpu.host import DeviceContext
from layout import Layout, LayoutTensor

alias float_dtype = DType.float32
alias VECTOR_WIDTH = 10
alias BLOCK_SIZE = 5
alias layout = Layout.row_major(VECTOR_WIDTH)

fn vector_addition(
    lhs_tensor: LayoutTensor[float_dtype, layout, MutableAnyOrigin],
    rhs_tensor: LayoutTensor[float_dtype, layout, MutableAnyOrigin],
    out_tensor: LayoutTensor[float_dtype, layout, MutableAnyOrigin],
    size: Int,
):
    """The calculation to perform across the vector on the GPU."""
    var global_tid = global_idx.x
    if global_tid < UInt(size):
        out_tensor[global_tid] = lhs_tensor[global_tid] + rhs_tensor[global_tid]

def main():
    constrained[has_accelerator(), "This example requires a supported GPU"]()

    # Get context for the attached GPU
    var ctx = DeviceContext()

    # Allocate data on the GPU address space
    var lhs_buffer = ctx.enqueue_create_buffer[float_dtype](VECTOR_WIDTH)
    var rhs_buffer = ctx.enqueue_create_buffer[float_dtype](VECTOR_WIDTH)
    var out_buffer = ctx.enqueue_create_buffer[float_dtype](VECTOR_WIDTH)

    # Fill in values across the entire width
    _ = lhs_buffer.enqueue_fill(1.25)
    _ = rhs_buffer.enqueue_fill(2.5)

    # Wrap the device buffers in tensors
    var lhs_tensor = LayoutTensor[float_dtype, layout](lhs_buffer)
    var rhs_tensor = LayoutTensor[float_dtype, layout](rhs_buffer)
    var out_tensor = LayoutTensor[float_dtype, layout](out_buffer)

    # Calculate the number of blocks needed to cover the vector
    var grid_dim = ceildiv(VECTOR_WIDTH, BLOCK_SIZE)

    # Launch the vector_addition function as a GPU kernel
    ctx.enqueue_function_checked[vector_addition, vector_addition](
        lhs_tensor,
        rhs_tensor,
        out_tensor,
        VECTOR_WIDTH,
        grid_dim=grid_dim,
        block_dim=BLOCK_SIZE,
    )

    # Map to host so that values can be printed from the CPU
    with out_buffer.map_to_host() as host_buffer:
        var host_tensor = LayoutTensor[float_dtype, layout](host_buffer)
        print("Resulting vector:", host_tensor)
```

GPU kernel

CPU driver code

GPU device context

GPU buffers

compile and launch GPU kernel

device buffer to host

https://github.com/modular/modular/blob/main/examples/mojo/gpu-functions/vector_addition.mojo

Mojo GPU Compilation Flow

```
def main():
    constrained[has_accelerator(), "This example requires a supported GPU"]()

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    )

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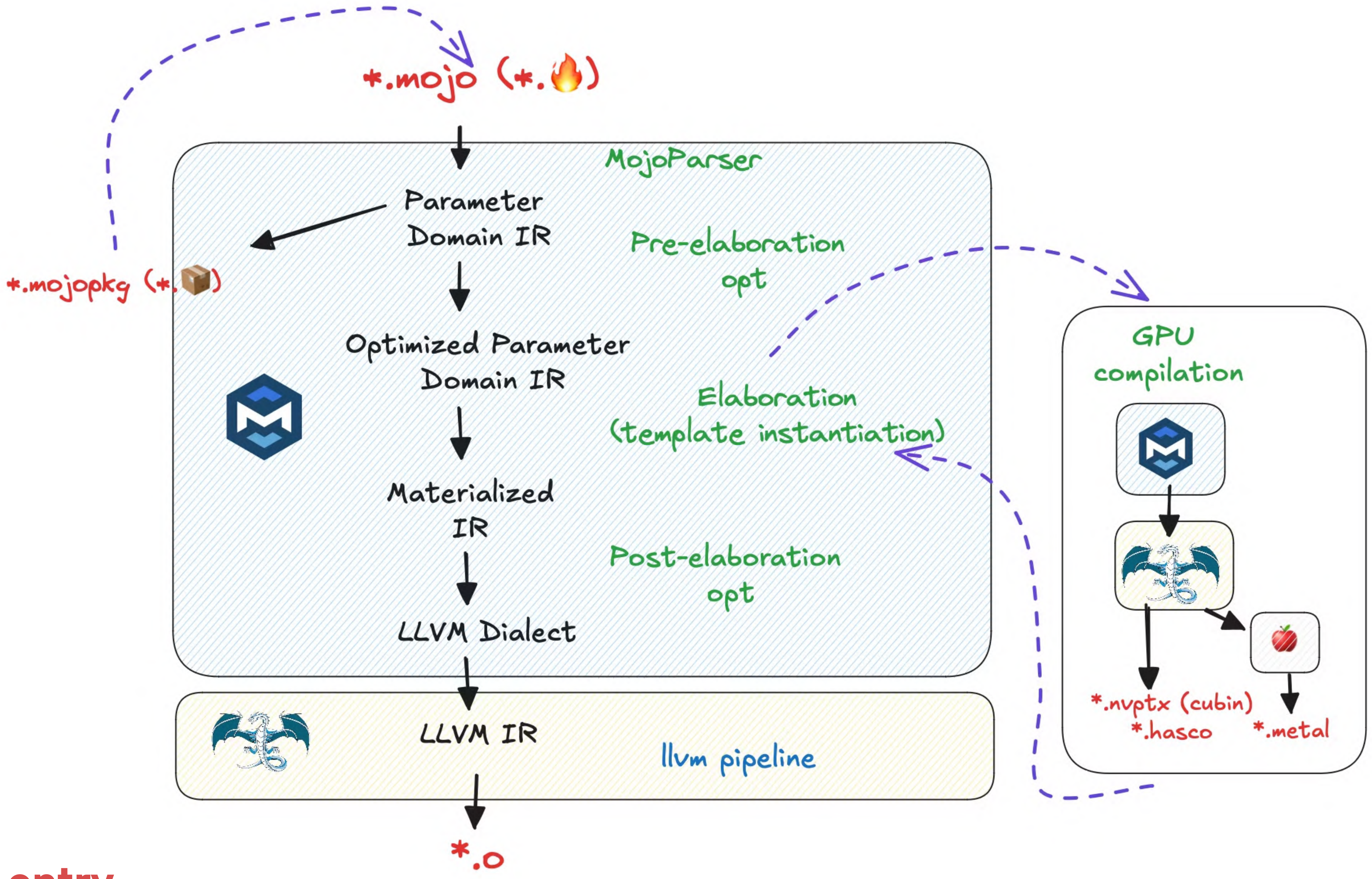
        print("Resulting vector:", host_tensor)
```

GPU entry function as a parameter

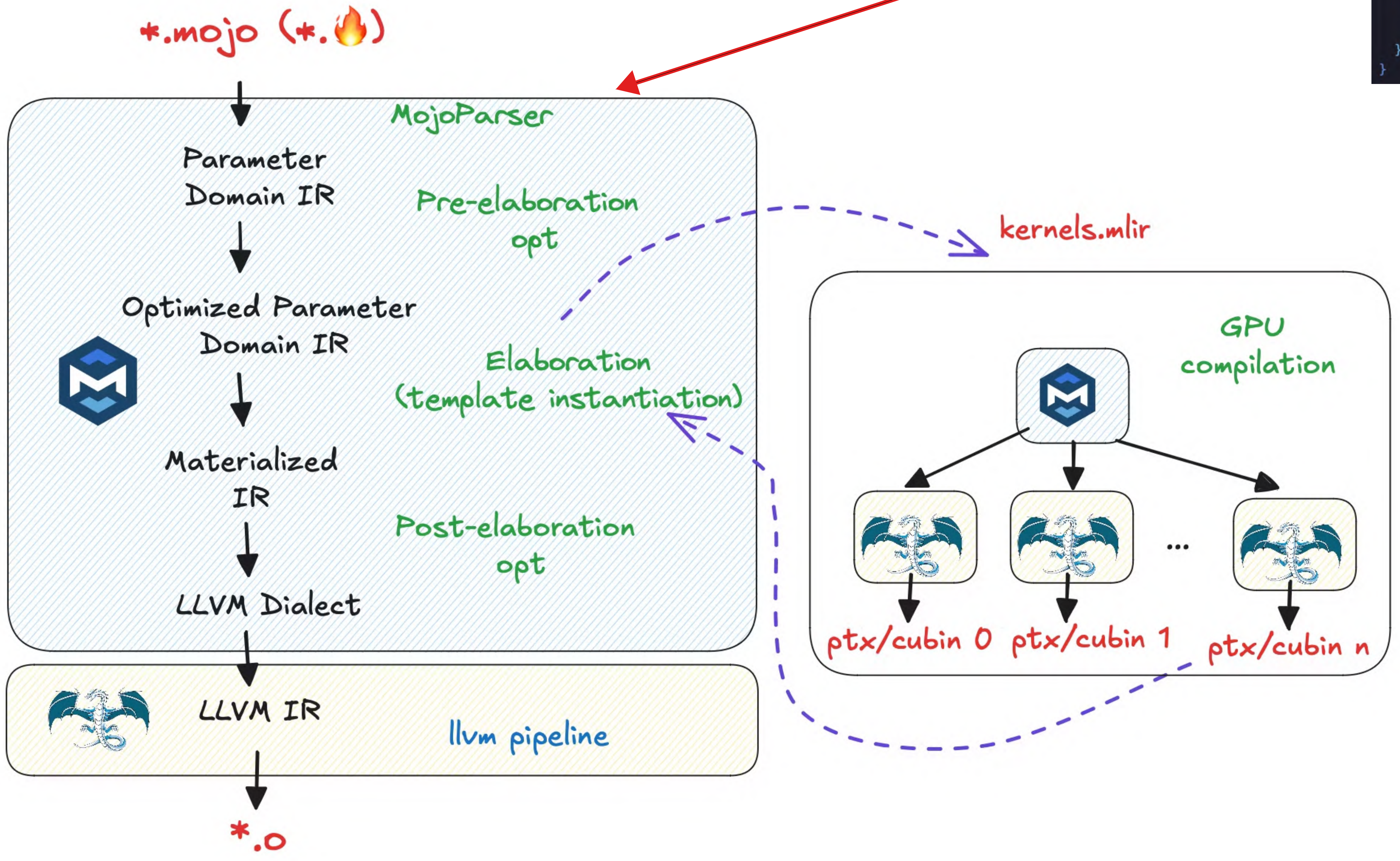


Mojo GPU Compilation Flow

```
module attributes {M.target_info = #M.target<triple = "arm64-apple-darwin23.6.0", arch = "apple-m2", features = "+aes,+bf16,+complxnum,+crc,
+dotprod,+fp-armv8,+fp16fml,+fpac,+fullfp16,+i8mm,+jsconv,+lse,+neon,+pauth,+perfmon,+ras,+rcpc,+rdm,+sha2,+sha3,+ssbs", data_layout =
"e-m:o-p270:32:32-p271:32:32-p272:64:64-i64:64-i128:128-n32:64-S128-Fn32", relocation_model = "pic", simd_bit_width = 128, index_bit_width =
64>, kgen.env = #kgen.env<{}>} {
  kgen.generator @kernel1() -> !kgen.none {
    %none = kgen.param.constant: none = <#kgen.none>
    kgen.return %none : !kgen.none
  }
  kgen.generator @kernel2() -> !kgen.none {
    %none = kgen.param.constant: none = <#kgen.none>
    kgen.return %none : !kgen.none
  }
  kgen.generator export @entry(%arg0: !kgen.pointer<none>) {
    kgen.param.declare nvptx: target = <#kgen.target<triple = "nvptx64-nvidia-cuda",
                                        arch = "sm_80",
                                        simd_bit_width = 128,
                                        index_bit_width = 64,
                                        tune_cpu = "sm_80">>

    %0:2 = kgen.compile_offload<nvptx, 0, "", :() -> !kgen.none @kernel1> -> string, index
    %1:2 = kgen.compile_offload<nvptx, 0, "", :() -> !kgen.none @kernel2> -> string, index
    kgen.call @launch_kernel(%0#0, %0#1) : (!kgen.string, index) -> !kgen.none
    kgen.call @launch_kernel(%1#0, %1#1) : (!kgen.string, index) -> !kgen.none
    kgen.return
  }
}
```

Input Mojo program
Host + GPU



Mojo GPU Compilation Flow

Input Mojo program
Host + GPU

```
module attributes {M.target_info = #M.target<triple = "arm64-apple-darwin23.6.0", arch = "apple-m2", features = "+aes,+bf16,+complxnum,+crc,
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    %none = kgen.param.constant: none = <#kgen.none>
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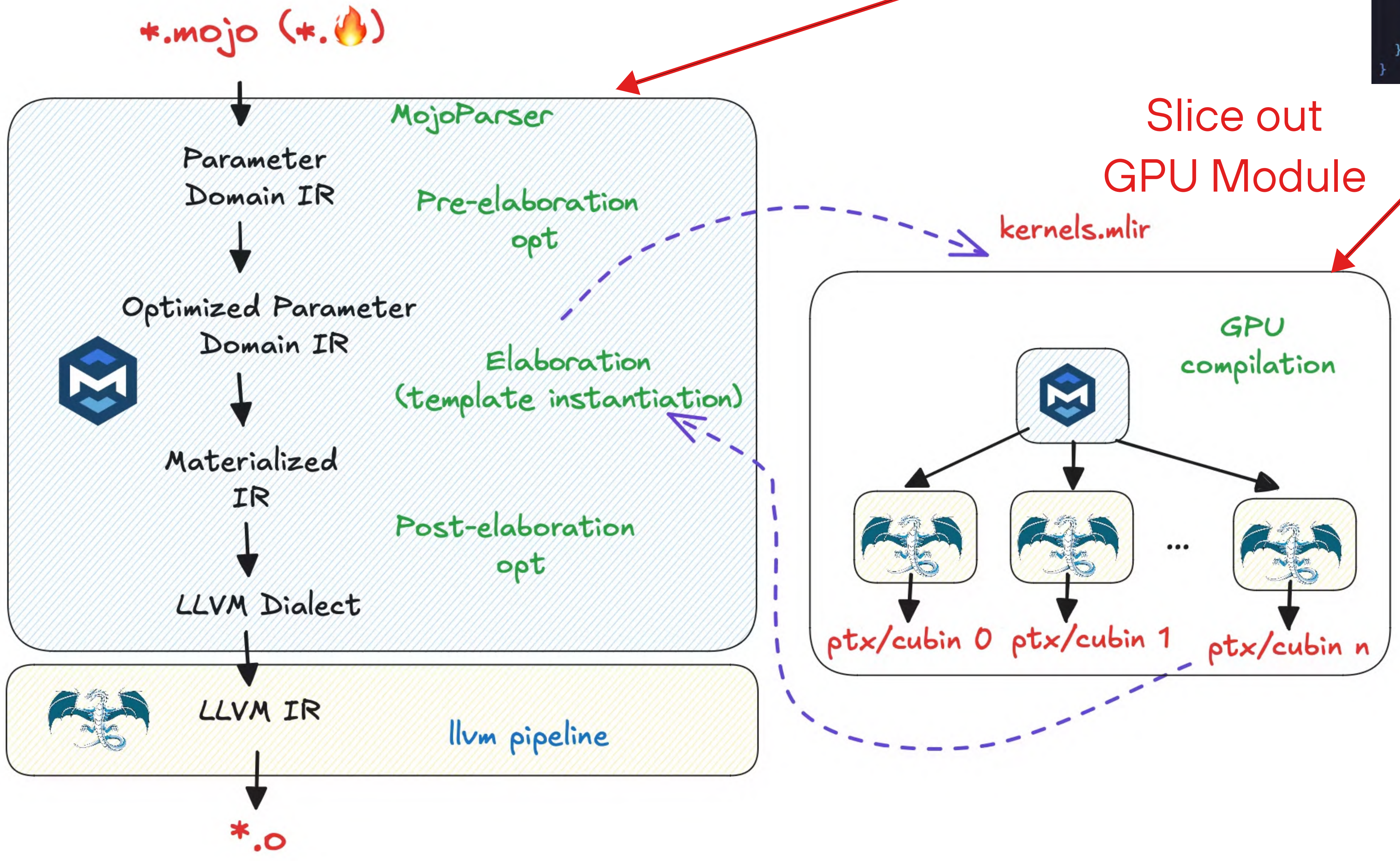
  }
  kgen.generator export @entry(%arg0: !kgen.pointer<none>) {
    kgen.param.declare nvptx: target = <#kgen.target<triple = "nvptx64-nvidia-cuda",
                                       arch = "sm_80",
                                       simd_bit_width = 128,
                                       index_bit_width = 64,
                                       tune_cpu = "sm_80">>

    %0:2 = kgen.compile_offload<nvptx, 0, "", :() -> !kgen.none @kernel1> -> string, index
    %1:2 = kgen.compile_offload<nvptx, 0, "", :() -> !kgen.none @kernel2> -> string, index
    kgen.call @launch_kernel(%0#0, %0#1) : (!kgen.string, index) -> !kgen.none
    kgen.call @launch_kernel(%1#0, %1#1) : (!kgen.string, index) -> !kgen.none
    kgen.return
  }
}
```



Slice out
GPU Module

```
module attributes {M.target_info = #M.target<triple = "nvptx64-nvidia-cuda", arch = "sm_80", simd_bit_width = 128, index_bit_width = 64, tune_cpu
= "sm_80">, kgen.env = #kgen.env<{}>} {
  kgen.generator export @kernel1() -> !kgen.none attributes {LLVMMetadataArray = ["kgen.offload.kernelid", 0 : index]} {
    %none = kgen.param.constant: none = <#kgen.none>
    kgen.return %none : !kgen.none
  }
  kgen.generator export @kernel2() -> !kgen.none attributes {LLVMMetadataArray = ["kgen.offload.kernelid", 1 : index]} {
    %none = kgen.param.constant: none = <#kgen.none>
    kgen.return %none : !kgen.none
  }
}
```

Mojo GPU Compilation Flow

Input Mojo program
Host + GPU

```
module attributes {M.target_info = #M.target<triple = "arm64-apple-darwin23.6.0", arch = "apple-m2", features = "+aes,+bf16,+complxnum,+crc,
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    %none = kgen.param.constant: none = <#kgen.none>
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  }
  kgen.generator export @entry(%arg0: !kgen.pointer<none>) {
    kgen.param.declare nvptx: target = <#kgen.target<triple = "nvptx64-nvidia-cuda",
                                       arch = "sm_80",
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                                       index_bit_width = 64,
                                       tune_cpu = "sm_80">>

    %0:2 = kgen.compile_offload<nvptx, 0, "", :() -> !kgen.none @kernel1> -> string, index
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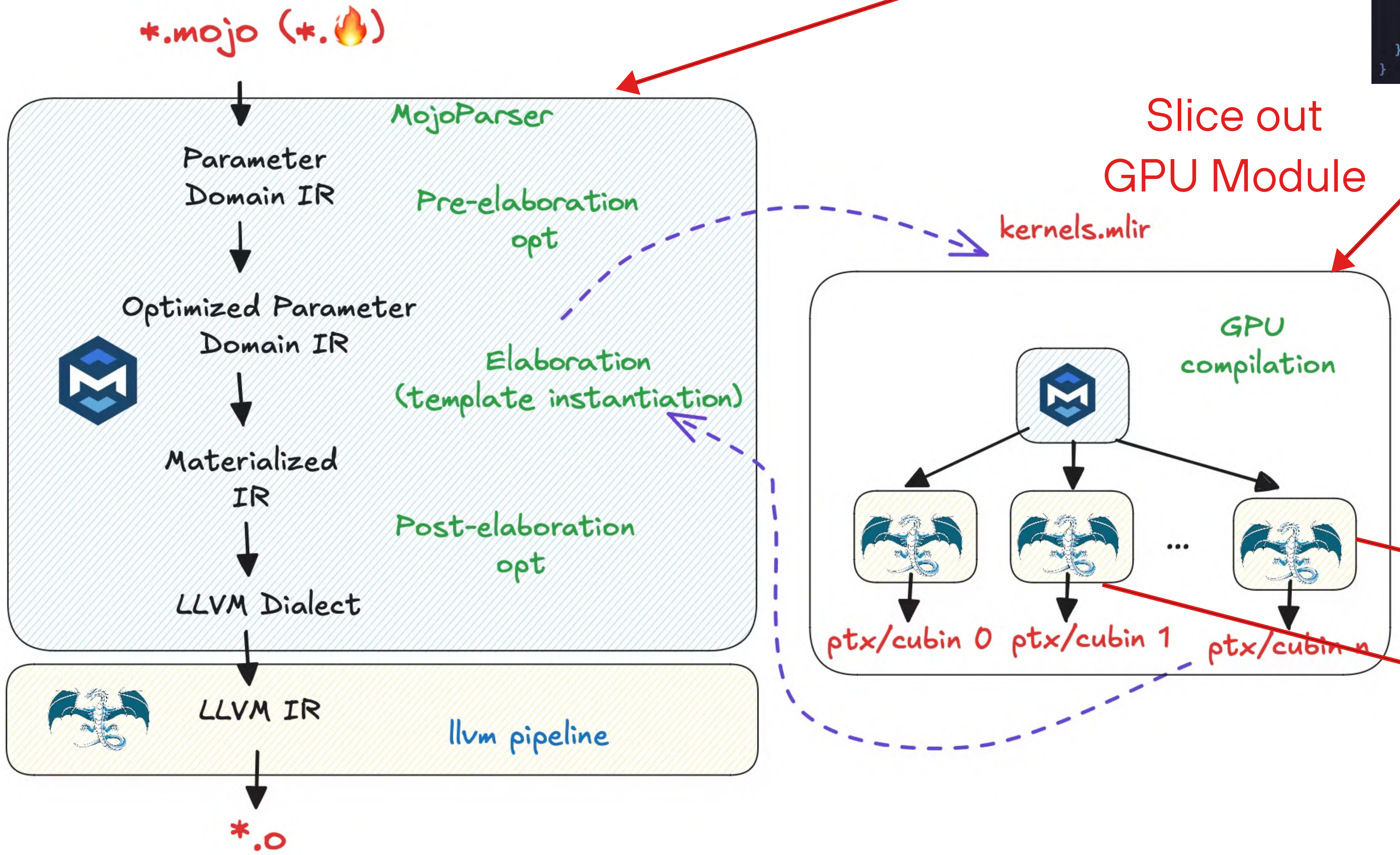
    kgen.call @launch_kernel(%0#0, %0#1) : (!kgen.string, index) -> !kgen.none
    kgen.call @launch_kernel(%1#0, %1#1) : (!kgen.string, index) -> !kgen.none
    kgen.return
  }
}
```



Slice out
GPU Module

```
module attributes {M.target_info = #M.target<triple = "nvptx64-nvidia-cuda", arch = "sm_80", simd_bit_width = 128, index_bit_width = 64, tune_cpu
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    kgen.return %none : !kgen.none
  }
  kgen.generator export @kernel2() -> !kgen.none attributes {LLVMMetadataArray = ["kgen.offload.kernelid", 1 : index]} {
    %none = kgen.param.constant: none = <#kgen.none>
    kgen.return %none : !kgen.none
  }
}
```

PTX outputs

```
"//\0A// Generated by LLVM NVPTX Back-End\0A//\0A\0A.version 7.0\0A.target sm_80\0A.address_size 64\0A\0A\09// .globl\09kernel1\0A\0A.
visible .entry kernel1()\0A{\0A\0A\0A\09ret;\0A\0A}\0A"
```

```
"//\0A// Generated by LLVM NVPTX Back-End\0A//\0A\0A.version 7.0\0A.target sm_80\0A.address_size 64\0A\0A\09// .globl\09kernel2\0A\0A.
visible .entry kernel2()\0A{\0A\0A\0A\09ret;\0A\0A}\0A"
```

Mojo GPU Compilation Flow

Input Mojo program
Host + GPU

```
module attributes {M.target_info = #M.target<triple = "arm64-apple-darwin23.6.0", arch = "apple-m2", features = "+aes,+bf16,+complxnum,+crc,
+dotprod,+fp-armv8,+fp16fml,+fpac,+fullfp16,+i8mm,+jsconv,+lse,+neon,+pauth,+perfmon,+ras,+rcpc,+rdm,+sha2,+sha3,+ssbs", data_layout =
"e-m:o-p270:32:32-p271:32:32-p272:64:64-i64:64-i128:128-n32:64-S128-Fn32", relocation_model = "pic", simd_bit_width = 128, index_bit_width =
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    %none = kgen.param.constant: none = <#kgen.none>
    kgen.return %none : !kgen.none
  }
  kgen.generator export @entry(%arg0: !kgen.pointer<none>) {
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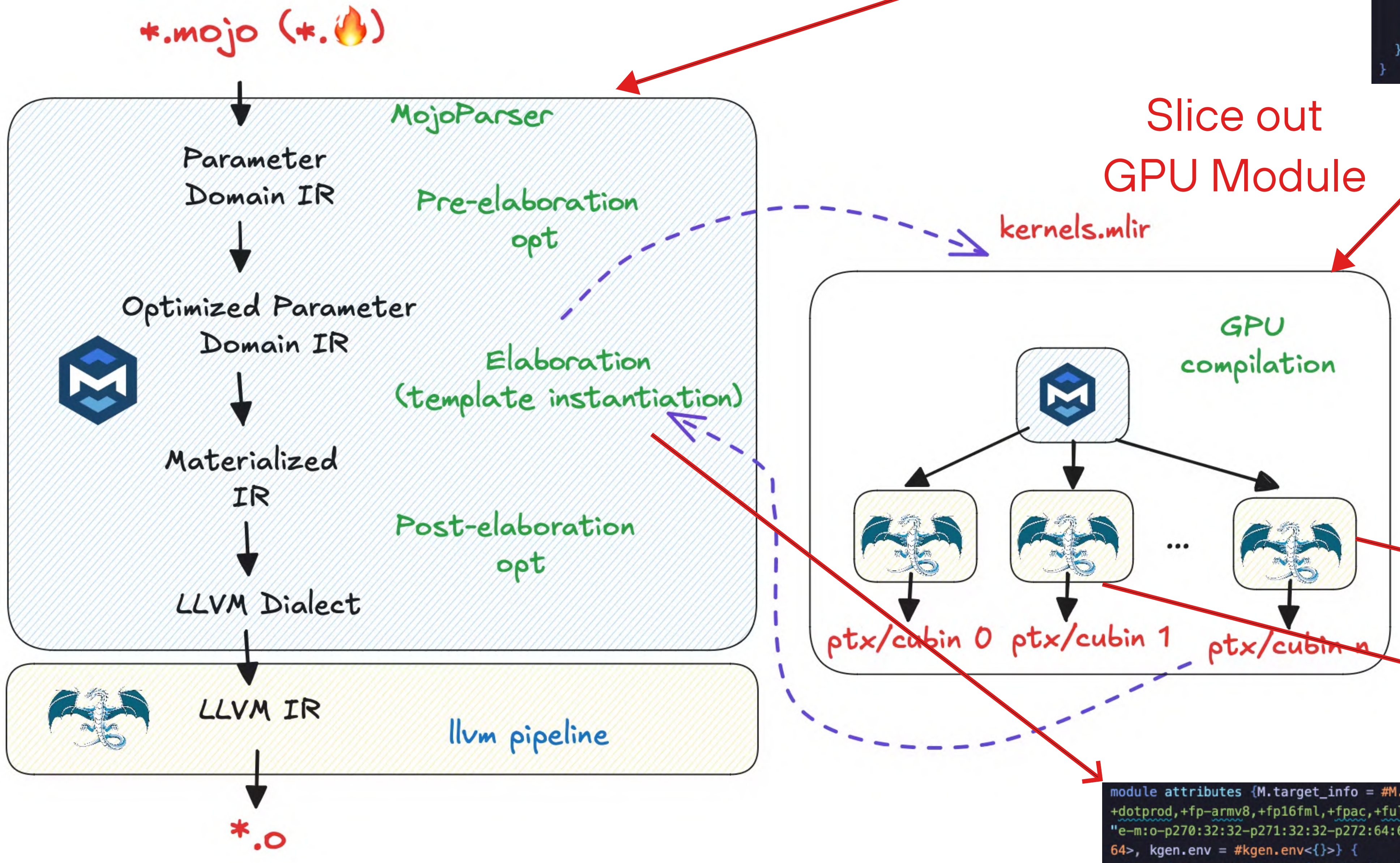
                                        arch = "sm_80",
                                        simd_bit_width = 128,
                                        index_bit_width = 64,
                                        tune_cpu = "sm_80">>

    %0:2 = kgen.compile_offload<nvptx, 0, "", :() -> !kgen.none @kernel1> -> string, index
    %1:2 = kgen.compile_offload<nvptx, 0, "", :() -> !kgen.none @kernel2> -> string, index
    kgen.call @launch_kernel(%0#0, %0#1) : (!kgen.string, index) -> !kgen.none
    kgen.call @launch_kernel(%1#0, %1#1) : (!kgen.string, index) -> !kgen.none
    kgen.return
  }
}
```



Slice out
GPU Module

```
module attributes {M.target_info = #M.target<triple = "nvptx64-nvidia-cuda", arch = "sm_80", simd_bit_width = 128, index_bit_width = 64, tune_cpu
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  kgen.generator export @kernel1() -> !kgen.none attributes {LLVMMetadataArray = ["kgen.offload.kernelid", 0 : index]} {
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```
"//\0A// Generated by LLVM NVPTX Back-End\0A//\0A\0A.version 7.0\0A.target sm_80\0A.address_size 64\0A\0A\09// .globl\09kernel1\0A\0A.
visible .entry kernel1()\0A{\0A\0A\0A\09ret;\0A\0A}\0A"
```

```
"//\0A// Generated by LLVM NVPTX Back-End\0A//\0A\0A.version 7.0\0A.target sm_80\0A.address_size 64\0A\0A\09// .globl\09kernel2\0A\0A.
visible .entry kernel2()\0A{\0A\0A\0A\09ret;\0A\0A}\0A"
```

Host code with
compiled offload PTX

```
module attributes {M.target_info = #M.target<triple = "arm64-apple-darwin23.6.0", arch = "apple-m2", features = "+aes,+bf16,+complxnum,+crc,
+dotprod,+fp-armv8,+fp16fml,+fpac,+fullfp16,+i8mm,+jsconv,+lse,+neon,+pauth,+perfmon,+ras,+rcpc,+rdm,+sha2,+sha3,+ssbs", data_layout =
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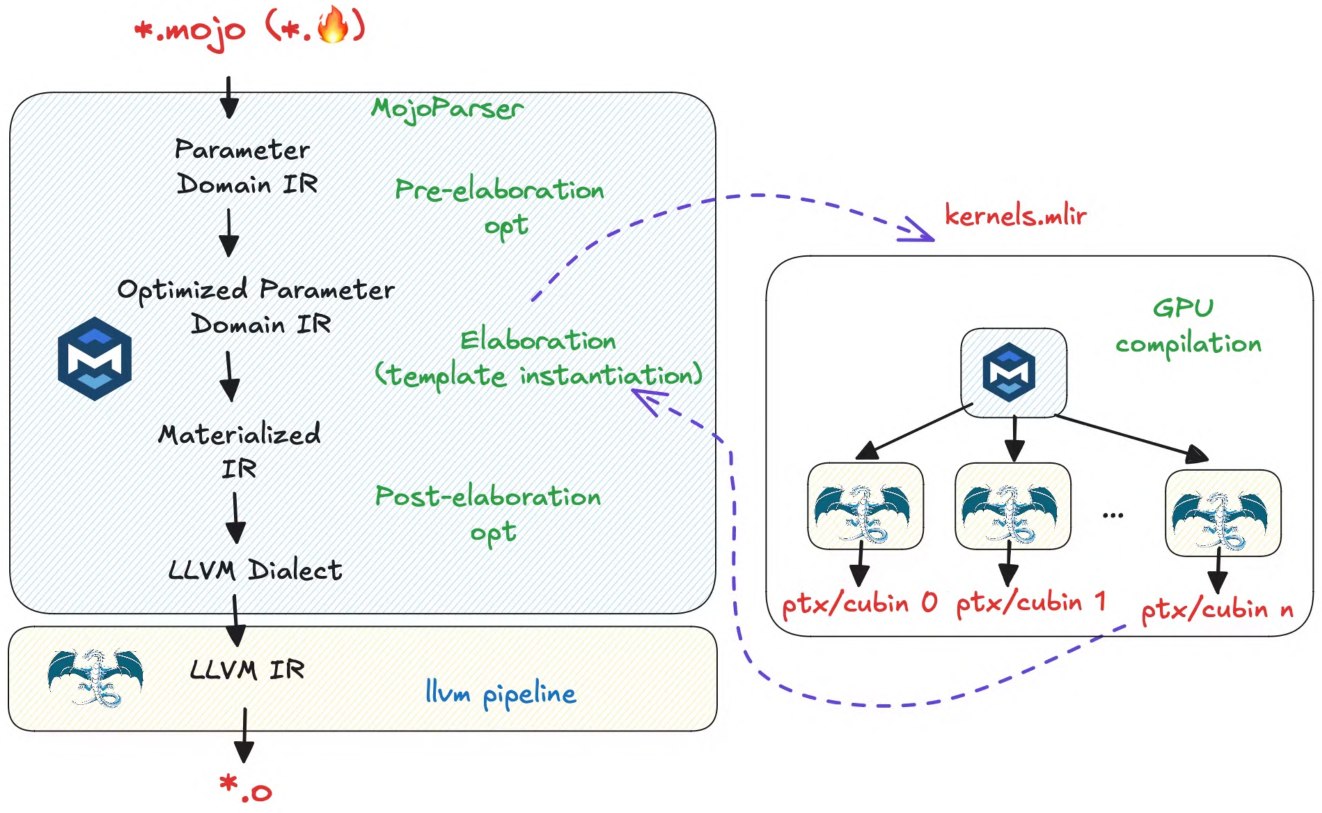
64>, kgen.env = #kgen.env<{}>} {
  kgen.func export @entry(%arg0: !kgen.pointer<none>) {
    %string = kgen.param.constant: string = <"//\0A// Generated by LLVM NVPTX Back-End\0A//\0A\0A.version 7.0\0A.target sm_80\0A.address_size
    64\0A\0A\09// .globl\09kernel1\0A\0A.visible .entry kernel1()\0A{\0A\0A\0A\09ret;\0A\0A}\0A">
    %index0 = kgen.param.constant = <0>
    kgen.call @launch_kernel(%string, %index0) : (!kgen.string, index) -> !kgen.none
    %string_1 = kgen.param.constant: string = <"//\0A// Generated by LLVM NVPTX Back-End\0A//\0A\0A.version 7.0\0A.target sm_80\0A.
    address_size 64\0A\0A\09// .globl\09kernel2\0A\0A.visible .entry kernel2()\0A{\0A\0A\0A\09ret;\0A\0A}\0A">
    %index0_1 = kgen.param.constant = <0>
    kgen.call @launch_kernel(%string_1, %index0_1) : (!kgen.string, index) -> !kgen.none
    kgen.return
  }
}
```

Compiler support for Debugging Kernels 🔎

- Inspecting Mojo GPU kernel in LLVM IR, assembly (PTX), or object file (cubin, hsaco)
- Same GPU compilation flow, just change what the pipeline produces.
- Plug the result as string to host code.



asm

```
//
// Generated by LLVM NVPTX Back-End
//
.version 8.1
.target sm_80
.address_size 64

        // .globl       compile_offload_hello6A6AoApA

.visible .entry compile_offload_hello6A6AoApA()
{
        ret;
}
```

llvm IR

```
; ModuleID = 'compile_offload.mojo'
source_filename = "compile_offload.mojo"
target datalayout =
"e-p3:32:32-p4:32:32-p5:32:32-p6:32:32-p7:32:32-i64:64-i128:128-i256:256-v16:16-v32:32-n16:32:64"
target triple = "nvptx64-nvidia-cuda"

; Function Attrs: norecurse
define dso_local ptx_kernel void @compile_offload_hello6A6AoApA() #0 {
  ret void
}

attributes #0 = { norecurse "target-cpu"="sm_80" "target-features"="+ptx81,+sm_80" "tune-cpu"="sm_80" }

!llvm.module.flags = !{!0}

!0 = !{i32 2, !"Debug Info Version", i32 3}
```

```
; ModuleID = 'compile_offload.mojo'
source_filename = "compile_offload.mojo"
target datalayout = "e-m:o-p270:32:32-p271:32:32-p272:64:64-i64:64-i128:128-n32:64-S128-Fn32"
target triple = "arm64-apple-darwin23.6.0"

; Function Attrs: mustprogress nofree norecurse nosync nounwind willreturn memory(none)
define dso_local void @"compile_offload::hello()"() #0 {
  ret void
}

attributes #0 = { mustprogress nofree norecurse nosync nounwind willreturn memory(none) "target-cpu"="apple-m2"
"target-features"="+aes,+bf16,+complxnum,+crc,+dotprod,+fp-armv8,+fp16fml,+fpac,+fullfp16,+i8mm,+jsconv,+lse,
+neon,+pauth,+perfmon,+ras,+rcpc,+rdm,+sha2,+sha3,+ssbs" }

!llvm.module.flags = !{!0}

!0 = !{i32 2, !"Debug Info Version", i32 3}
```

opt llvm IR

```
@fieldwise_init
@register_passable("trivial")
struct _Info:
    var kernel: __mlir_type.`!kgen.string`
    var name: __mlir_type.`!kgen.string`
    var num_captures: __mlir_type.index


@fieldwise_init
@register_passable("trivial")
struct Info:
    var kernel: StaticString
    var name: StaticString
    var num_captures: Int


@always_inline
fn _compile_info[
    func_type: AnyTrivialRegType, //,
    func: func_type,
    /,
    emission_kind: StaticString = "asm",
    target: _TargetType = A100.target(),
    compile_options: StaticString = CompilationTarget[
        target
    ].default_compile_options(),
]() -> Info:
    var info = __mlir_op.`kgen.compile_offload`[
        target_type=target,
        emission_kind = _get_emission_kind_id[emission_kind]()._mlir_value,
        emission_option = _get_kgen_string[compile_options](),
        func=func,
        _type=_Info,
    ]()

    return Info(
        StaticString(info.kernel),
        StaticString(info.name),
        Int(mlir_value=info.num_captures),
    )

fn hello():
    pass

fn main():
    # compile kernel to asm.
    t1 = _compile_info[hello, emission_kind="asm"]()
    print(t1.kernel)

    # compile kernel to llvm ir.
    t2 = _compile_info[hello, emission_kind="llvm"]()
    print(t2.kernel)

    # compile kernel to optimized llvm ir.
    t3 = _compile_info[hello, emission_kind="llvm-opt"]()
    print(t3.kernel)
```

https://github.com/modular/modular/blob/main/mojo/stdlib/test/compile/test_compile.mojo

Conclusions

- Mojo provides a unified way to write CPU+GPU code => **one MLIR module**
- Library driven GPU feature implementation for different vendors => **simple compiler, no heroic magic**
- MLIR unlocks seamless compiler integration:
    - Native compiler support to know what to slice into GPU mlir modules during elaboration.
    - Add an mlir op kgen.compile_offload.
    - Mojo has support as MLIR sugar:
        - No need to change the parser to extend syntax.
        - Ease of writing library code that uses architecture specific dialects (nvvm, rocdl) and low-level intrinsics (llvm).
- Compiling multiple kernels in one MLIR module and split for LLVM pipeline => **fast compilation**
- **Generally applicable** to compile other accelerator offloads built on top of LLVM/MLIR framework.
- Mojo GPU kernels are all open-sourced
  https://github.com/modular/modular/tree/main/max/kernels

Thank you!
Hope to see you at the poster session!

Acknowledgement:
The Mojo Language Team at Modular