Response-Time Analysis of a Soft Real-time NVIDIA Holoscan Application

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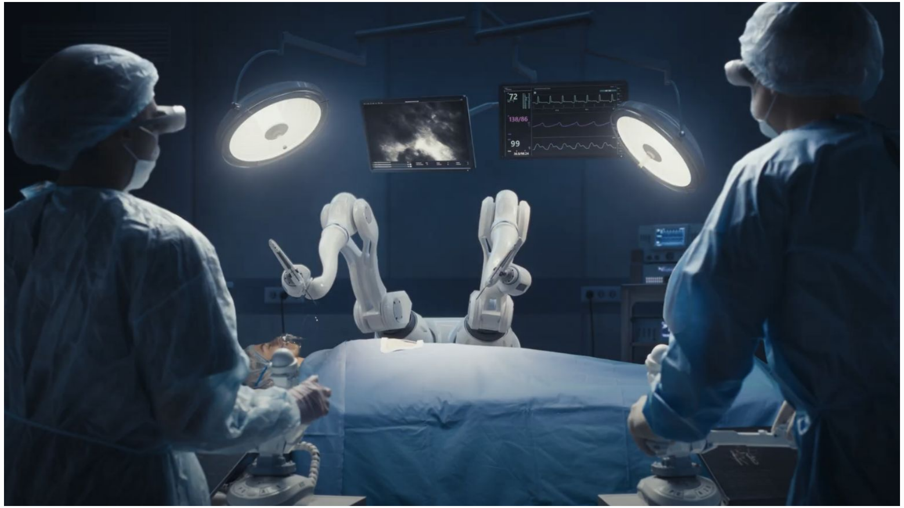
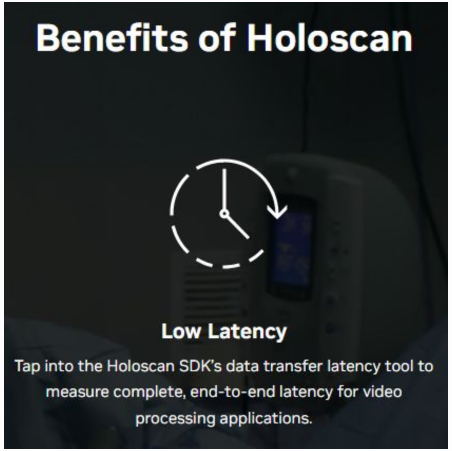
Edge Computing

- AI is fueling resource-intensive applications on the edge
- Embedded platforms become more complex
  - Harder to develop apps



Frameworks and Limitations

- Development frameworks built with latency in mind
- **NVIDIA Holoscan** promises low latency SDK for medical devices
- But what about guarantees?
    - Holoscan relies on profiling...



What's wrong with profiling?

- Profiling to learn timing properties has many issues
  - **The response time bound may be unsafe**
  - **Application development must be finished**
  - **Profiling can be costly in time and compute**

Research Question:

Can we develop a response time bound for any Holoscan application, given information about it?

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Holoscan

Holoscan Basics

Operator

(Assume execution time known)

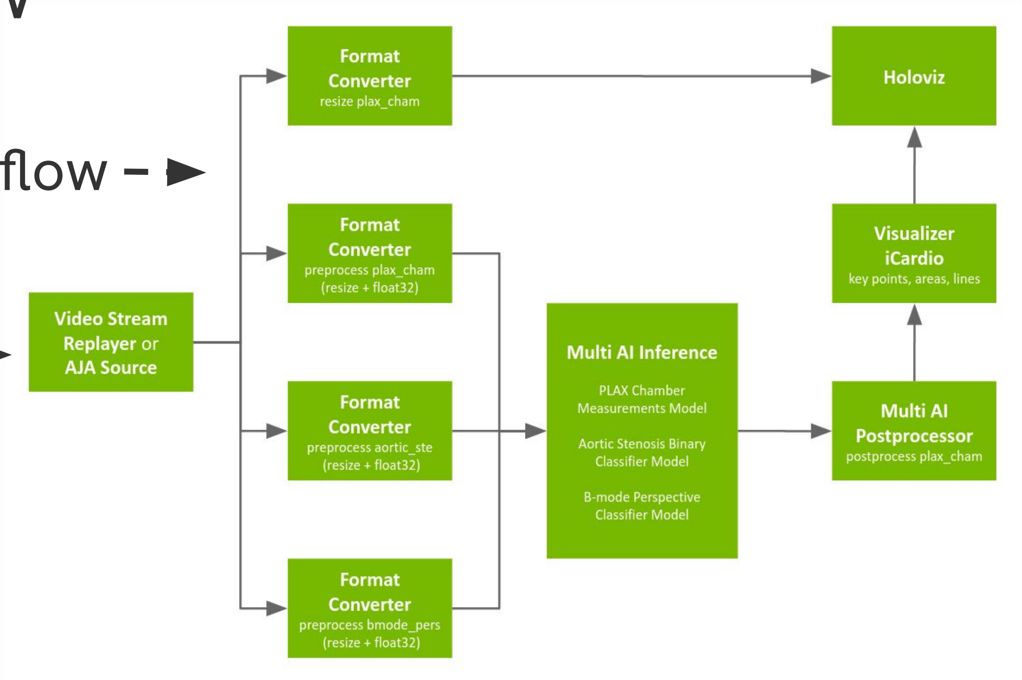
- Holoscan apps are made up of ***operators***
  - Blocks of code that run on CPU threads
  - Can call on the GPU
- Operators scheduled by an executor

```cpp
void FormatConverterOp::compute(InputContext& op_input, OutputContext& op_output,
                                ExecutionContext& context) {

  // Process input message
  auto in_message = op_input.receive<gxf::Entity>("source_video").value();

  // get the CUDA stream from the input message
  gxf_result_t stream_handler_result =
      cuda_stream_handler_.from_message(context.context(), in_message);
  if (stream_handler_result != GXF_SUCCESS) {
    throw std::runtime_error("Failed to get the CUDA stream from incoming messages");
  }

  // assign the CUDA stream to the NPP stream context
  npp_stream_ctx_.hStream = cuda_stream_handler_.get_cuda_stream(context.context());

  nvidia::gxf::Shape out_shape{0, 0, 0};
  void* in_tensor_data = nullptr;
  nvidia::gxf::PrimitiveType in_primitive_type = nvidia::gxf::PrimitiveType::kCustom;
  nvidia::gxf::MemoryStorageType in_memory_storage_type = nvidia::gxf::MemoryStorageType::kHost;
  int32_t rows = 0;
  int32_t columns = 0;
  int16_t in_channels = 0;
  int16_t out_channels = 0;
  std::vector<nvidia::gxf::ColorPlane> in_color_planes;

  // get Handle to underlying nvidia::gxf::Allocator from std::shared_ptr<holoscan::Allocator>
  auto pool =
      nvidia::gxf::Handle<nvidia::gxf::Allocator>::Create(context.context(), pool_->gxf_cid());

  // Get either the Tensor or VideoBuffer attached to the message
  bool is_video_buffer;
  nvidia::gxf::Handle<nvidia::gxf::VideoBuffer> video_buffer;
  try {
    video_buffer = holoscan::gxf::get_videobuffer(in_message);
    is_video_buffer = true;
  } catch (const std::runtime_error& r_) {
    HOLOSCAN_LOG_TRACE("Failed to read VideoBuffer with error: {}", std::string(r_.what()));
    is_video_buffer = false;
  }

  if (is_video_buffer) {
    // Convert VideoBuffer to Tensor
    auto frame = video_buffer.get();
```

What do Holoscan Applications Look Like? REDRAW

Data flow – ►

Operator – ►



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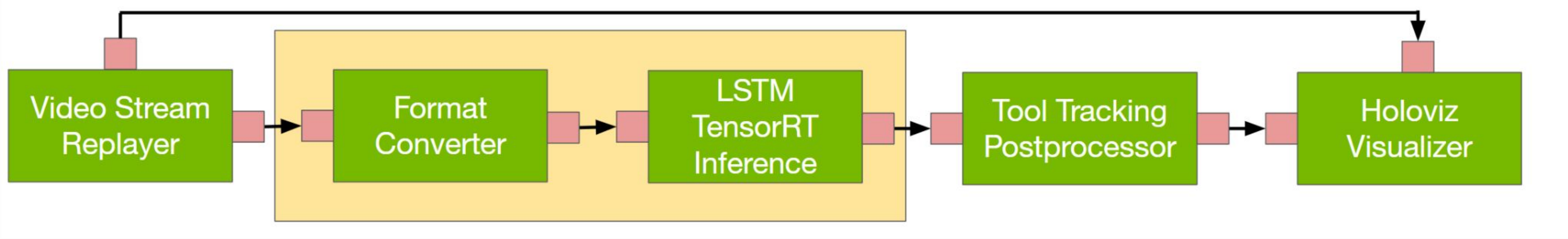

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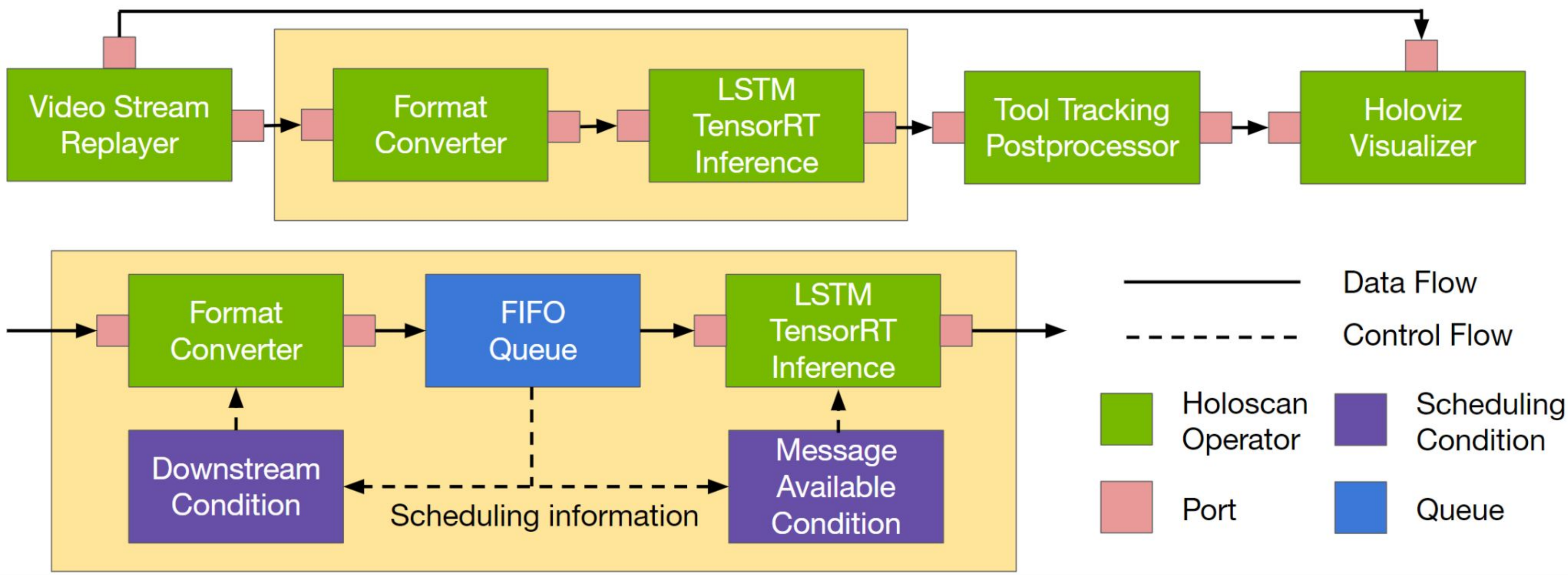
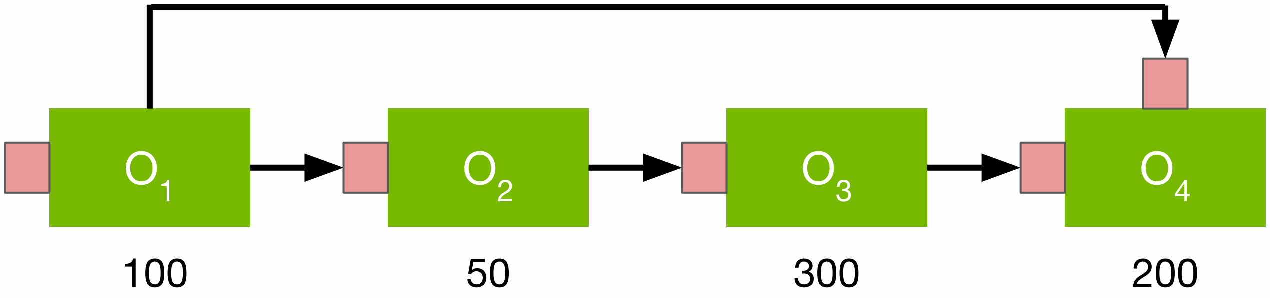


Downstream Examples

Example 1

Why do we need the downstream condition?

Why Downstream?



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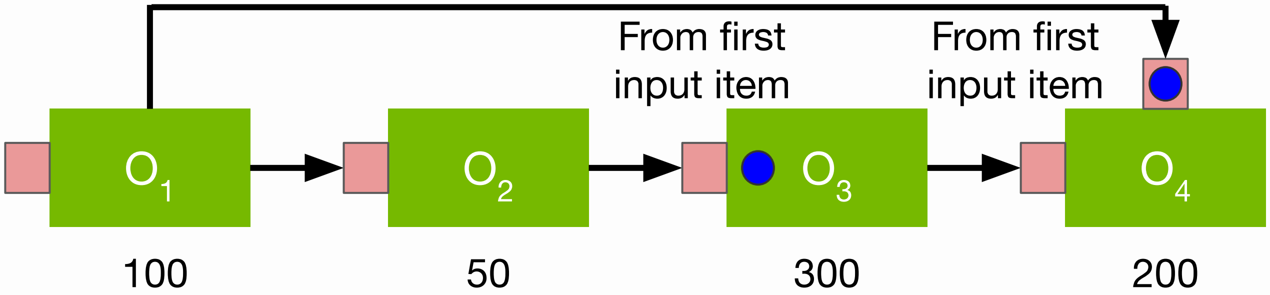

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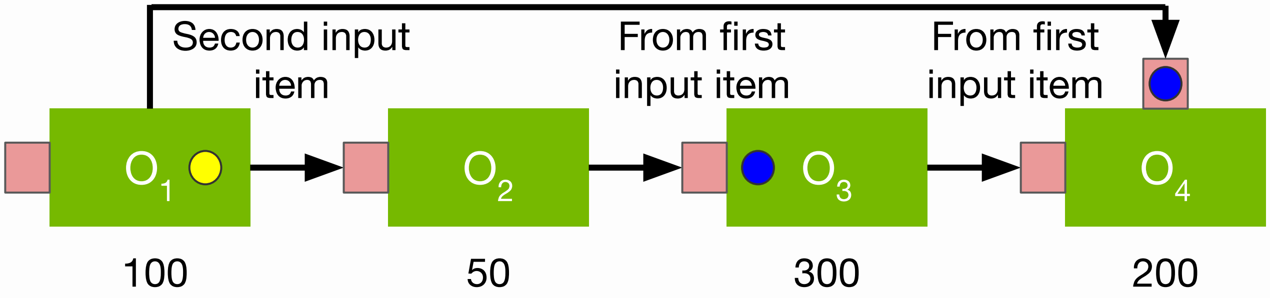

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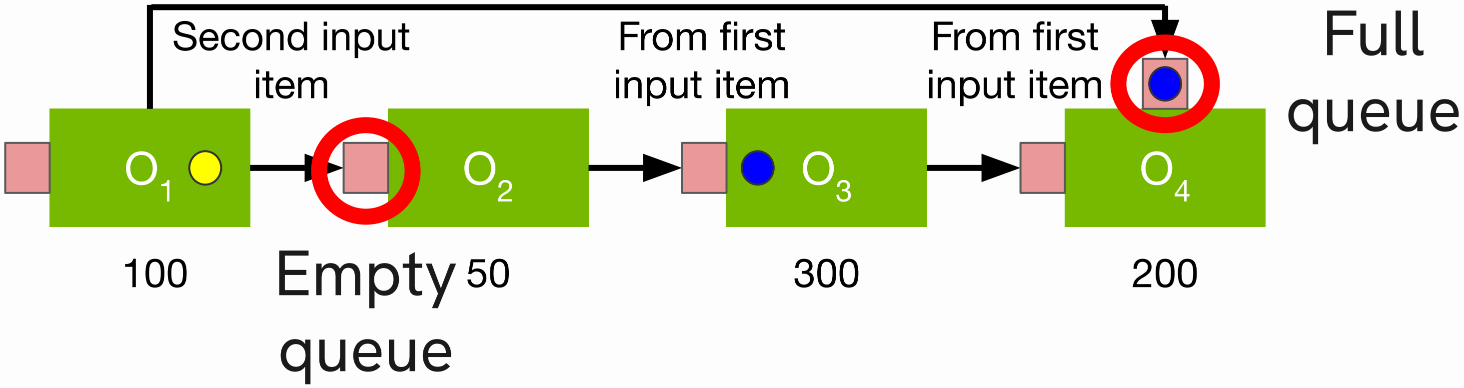

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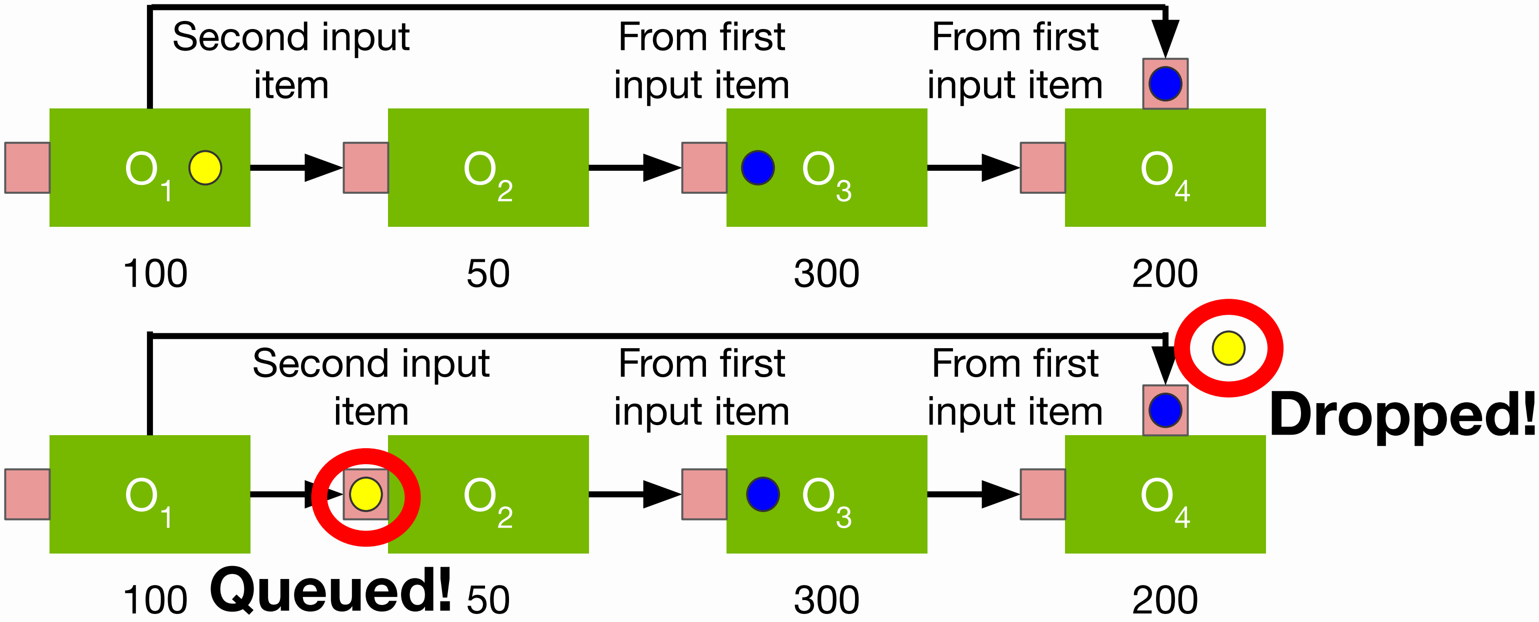

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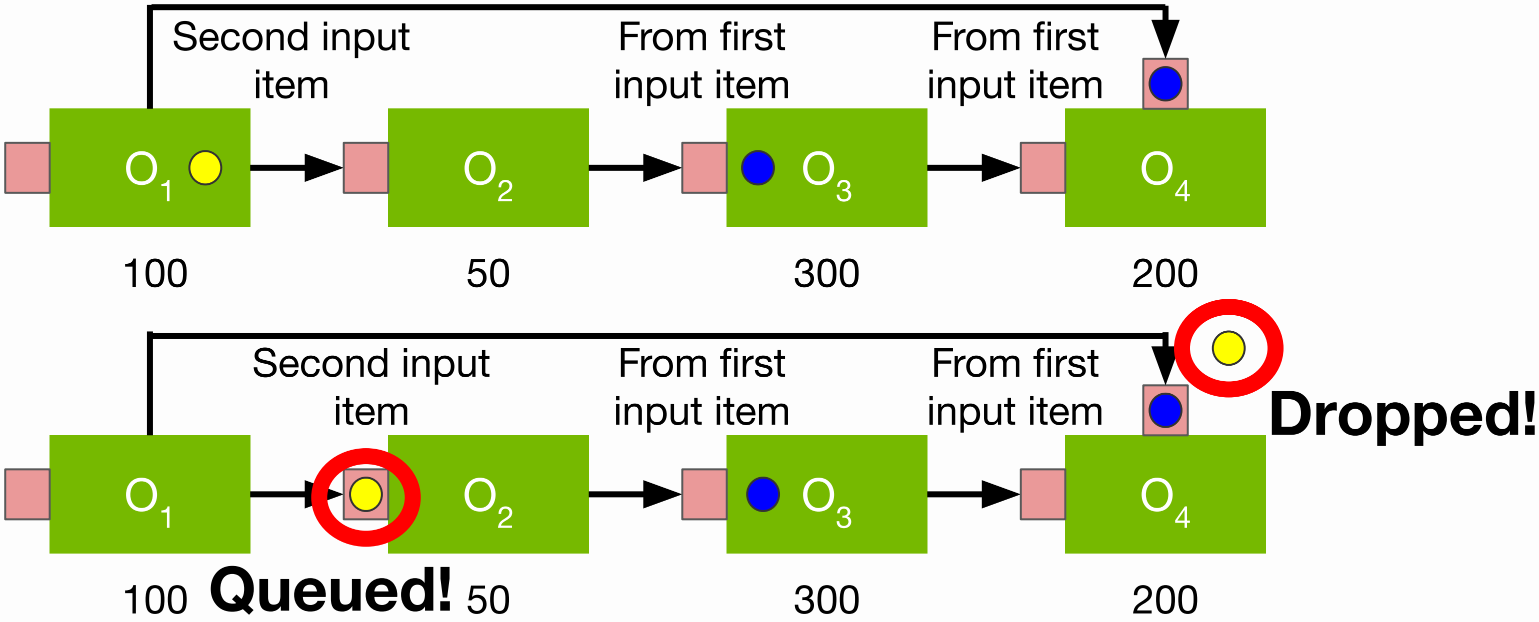


Takeaway: Violates correctness condition

Downstream Examples

Example 1

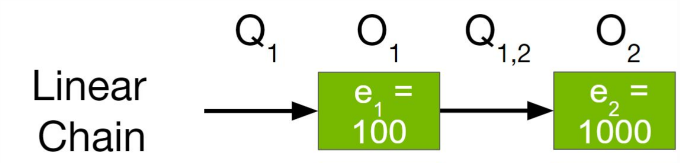
Why do we need the downstream condition?

Example 2

How does downstream affect response times?

Downstream and Response Times

Let's assume...



- Linear chain of length 2
- Period = 100
- Queue size = 1
- No overheads

Downstream and Response Times

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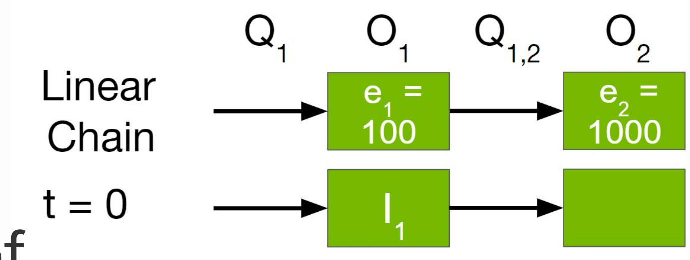

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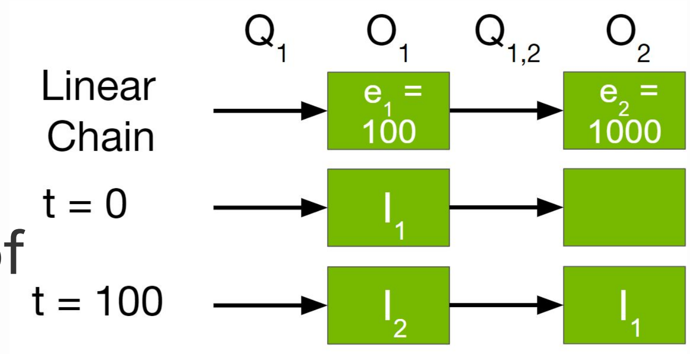

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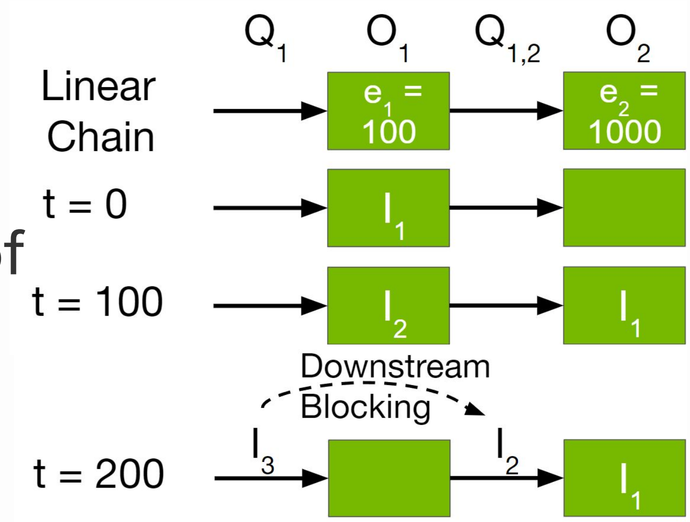

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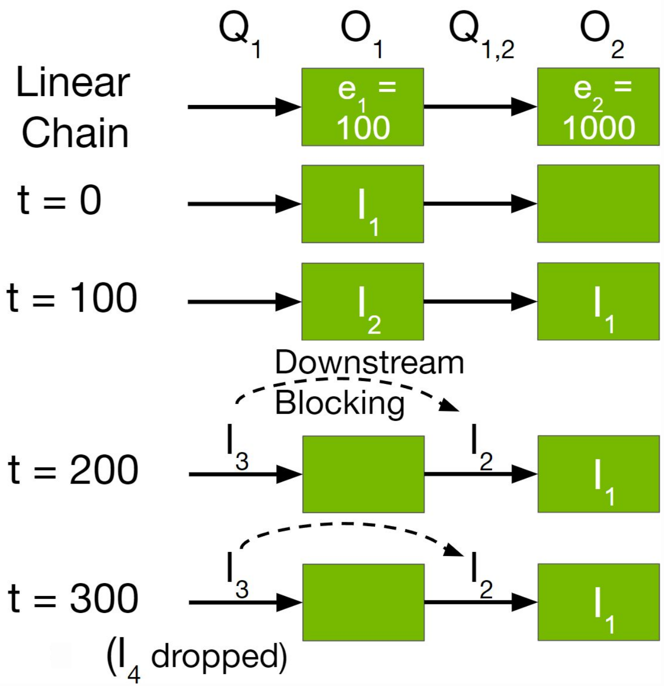

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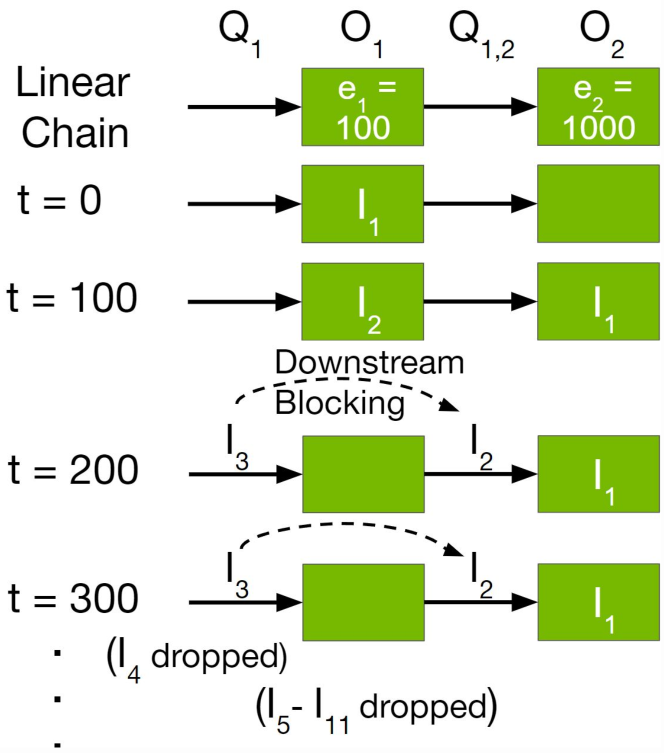

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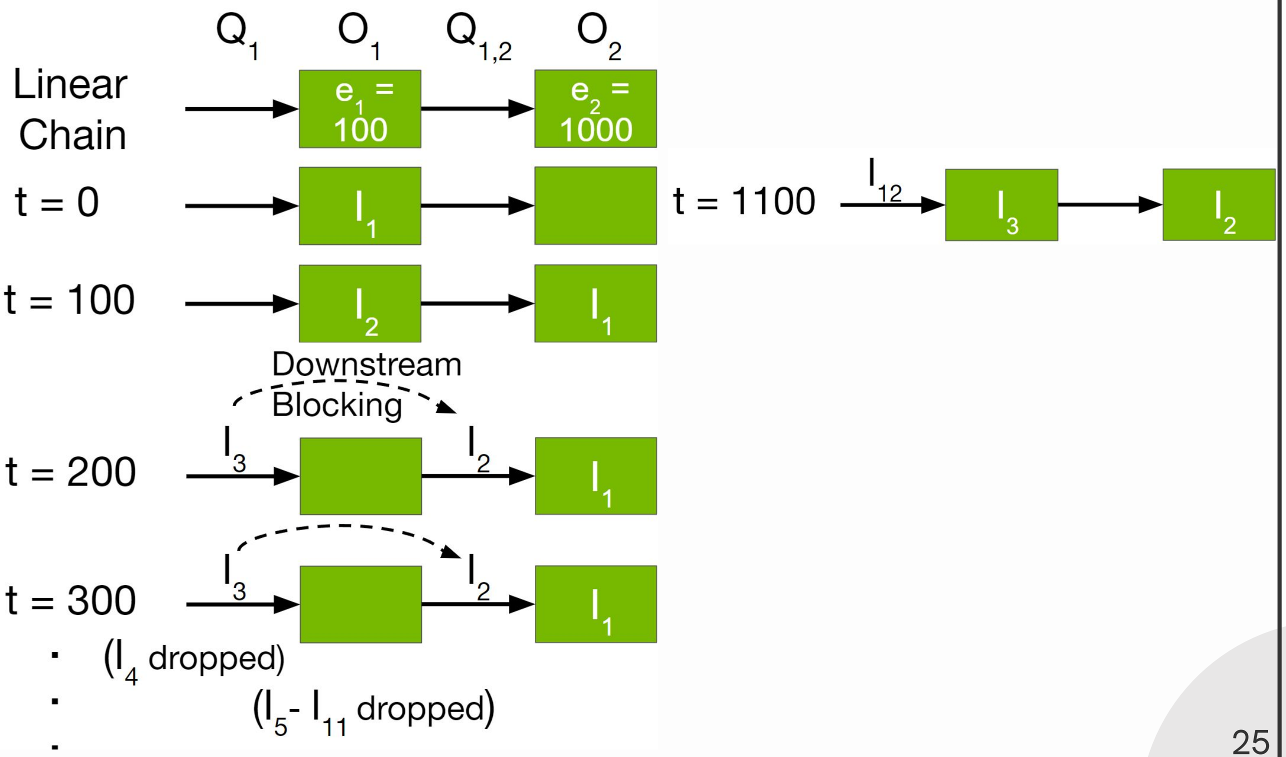

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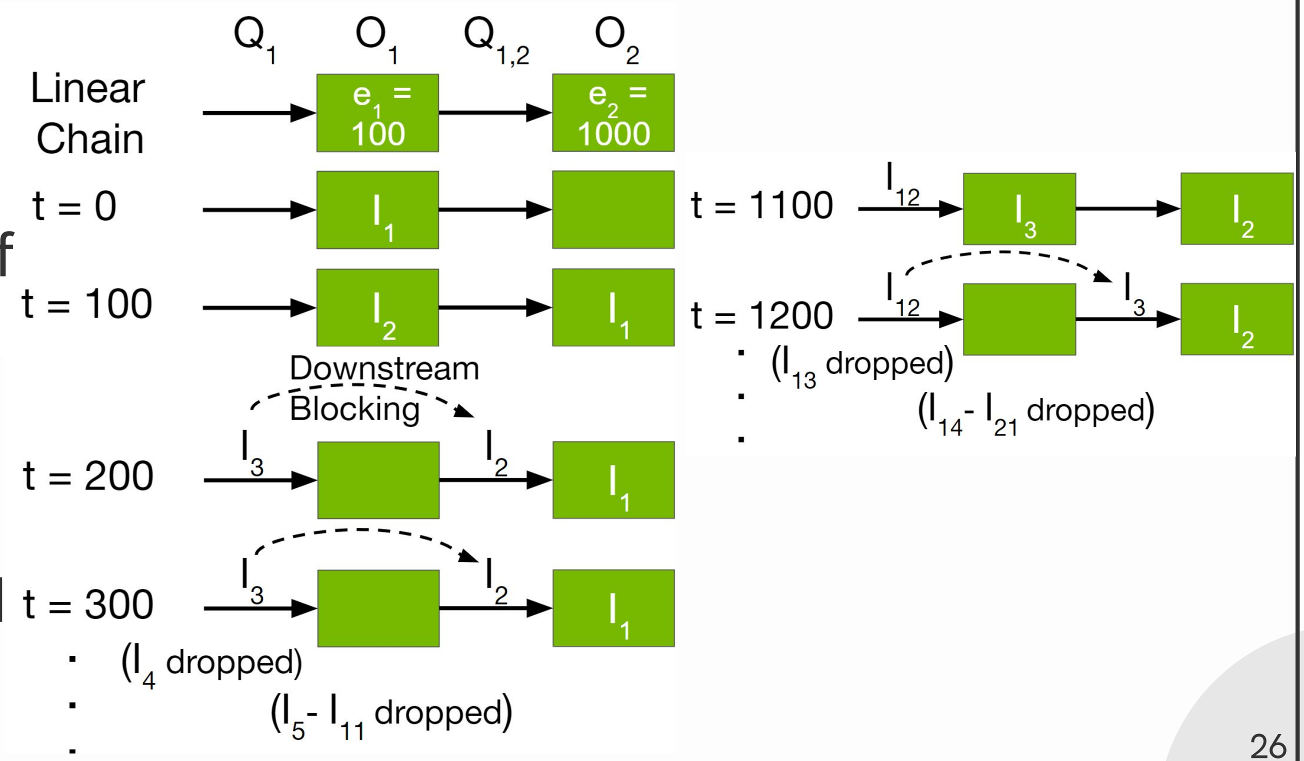

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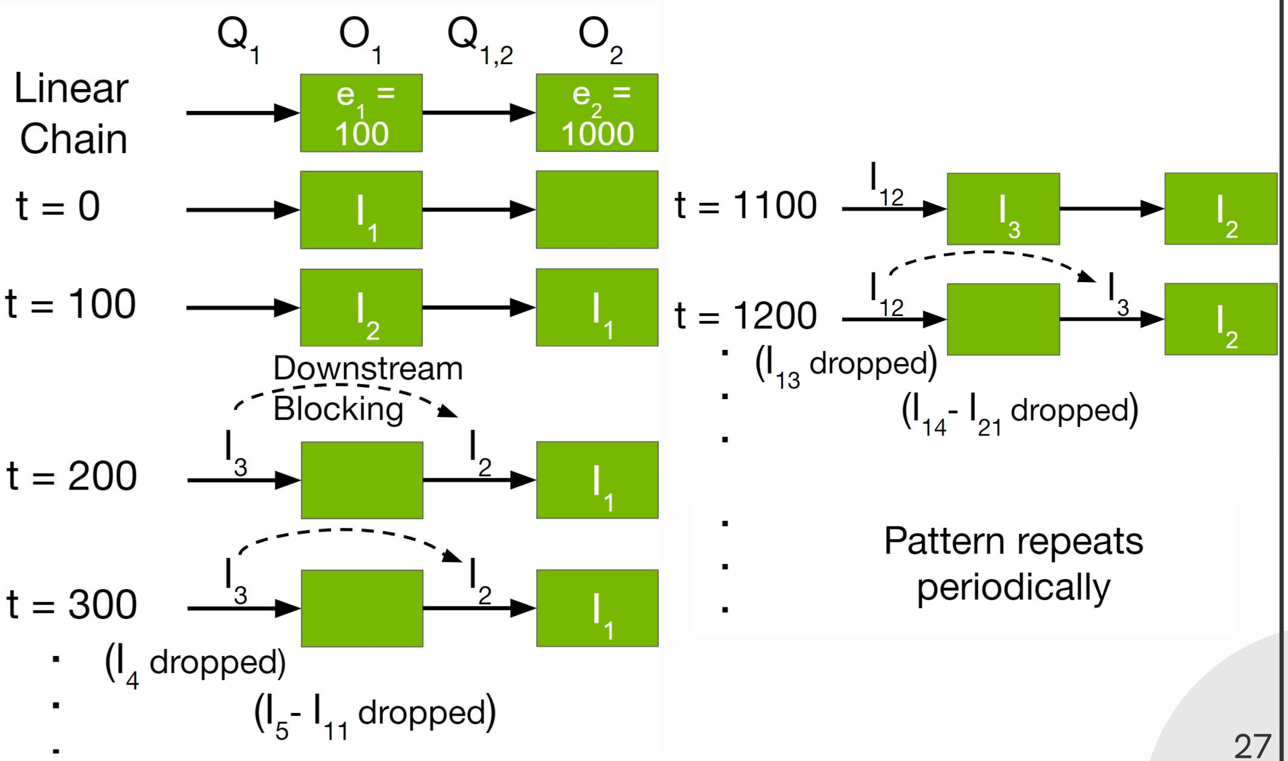

Downstream and Response Times

Takeaway: WCRT of 2900 with total operator execution time of just 1100

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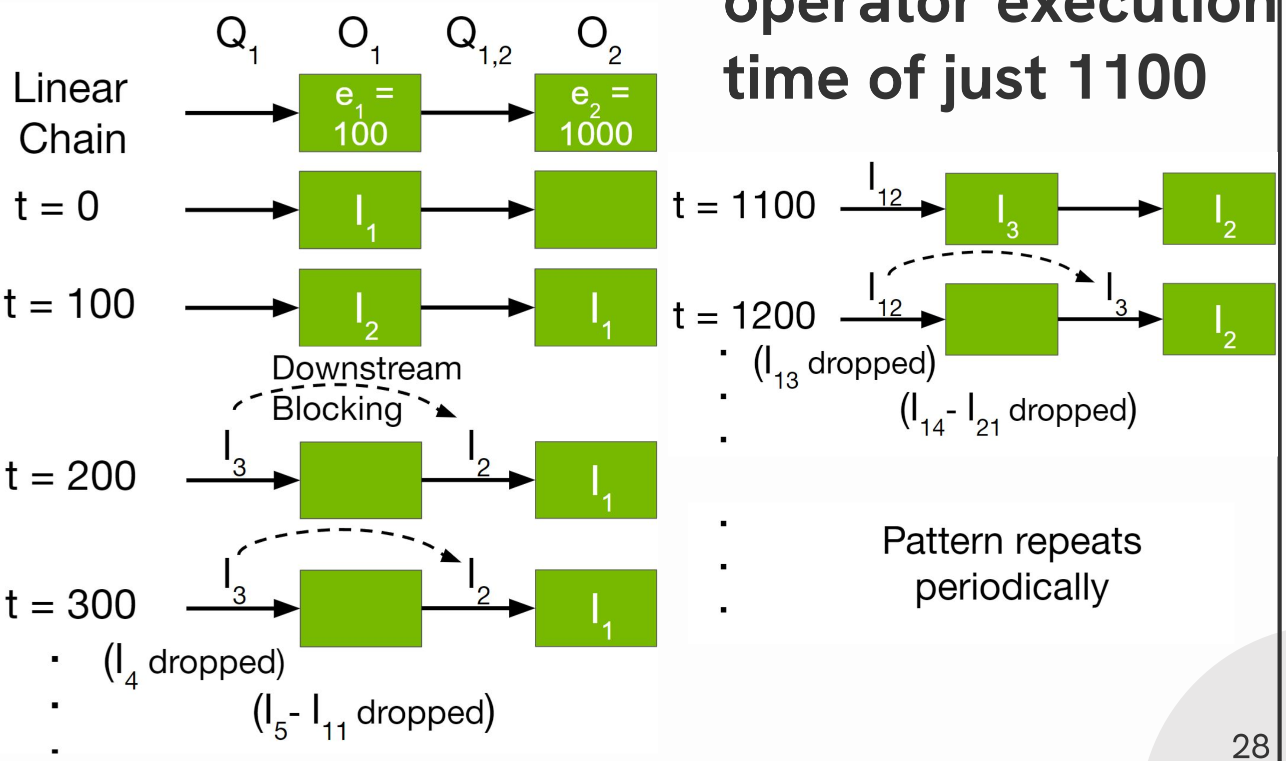

Downstream Examples

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Why do we need the downstream condition?

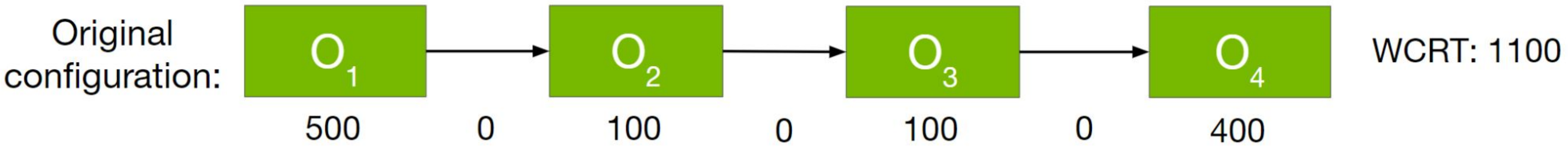
Example 2

How does downstream affect response times?

Example 3

How downstream can cause timing anomalies

Downstream Blocking Causes Timing Anomalies



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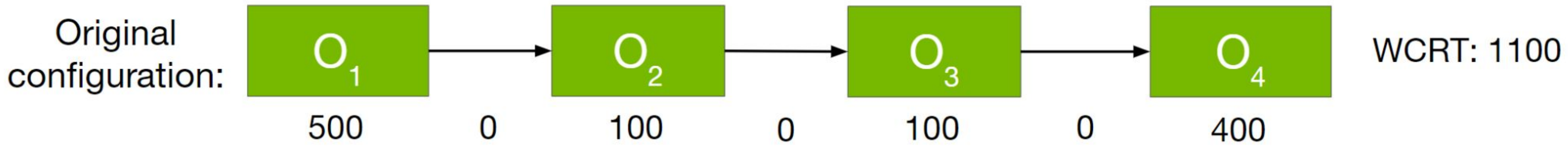
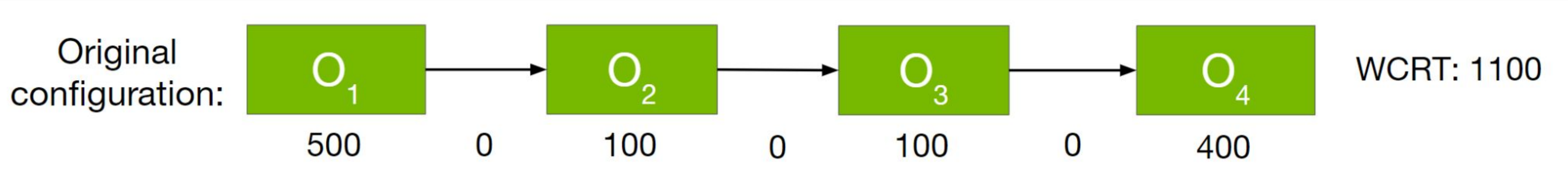


Work hard optimizing O_1 to lower execution time…

Downstream Blocking Causes Timing Anomalies



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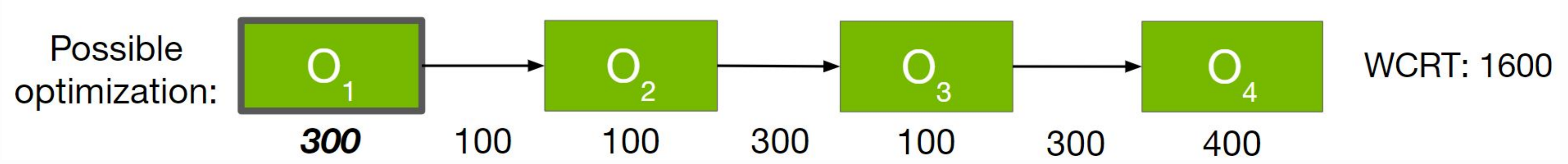

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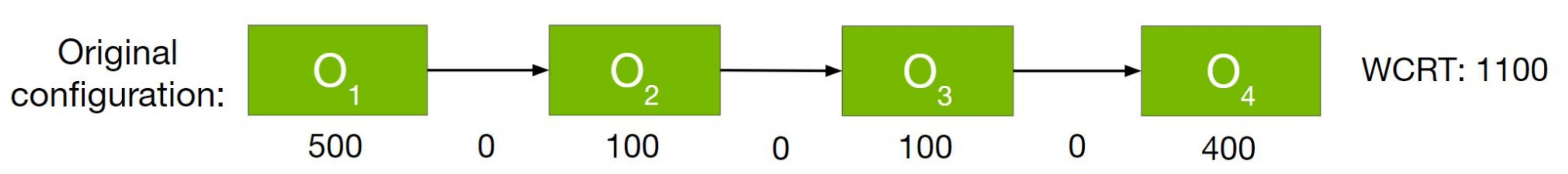

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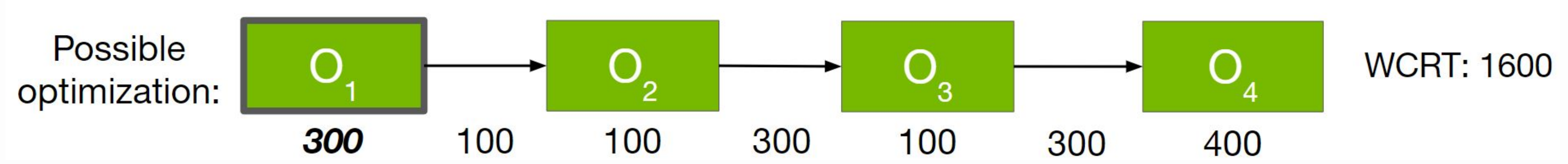

…but we encounter a timing anomaly!

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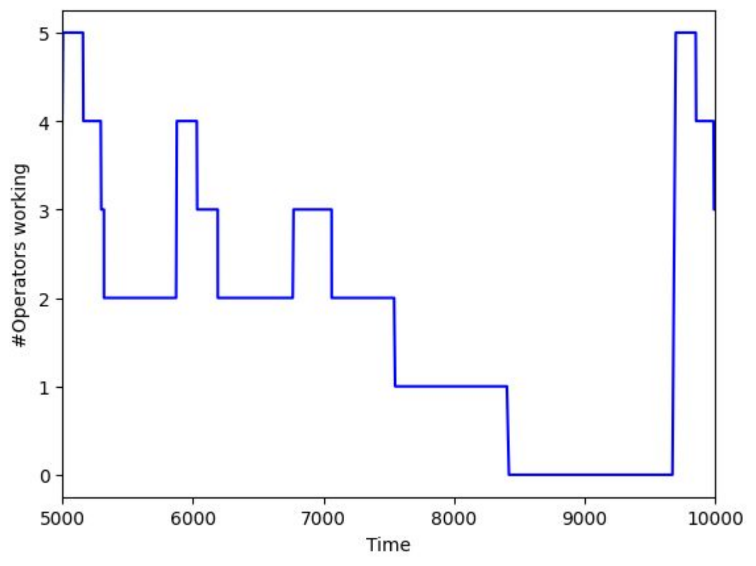
Response-Time Analysis

Approaches to RTA

- Many DAG response-time analyses already exist
  - Why not employ them?
- Consider a period T and relative deadline D…
  - Analyses commonly assume $T \geq D$
- But Holoscan wants to leverage parallelism
  - No hard deadline, maximizing throughput (T is small)

Leverage Parallelism

- Can process the first, second, third inputs simultaneously
- Holoscan geared to pipelined execution
  - Multiple jobs in same DAG



Operator parallelism over time

RTA Strategy

1. Response time bound for a linear chain
2. Why chain analysis insufficient for DAGs
3. Generalize response time bound for any arbitrary DAG

Assumptions

- Queue size = 1
  - Holoscan default
- All operators can run in parallel
  - NVIDIA embedded platforms have enough cores to do this
- Inputs arrive with a period as low as 0
- Operator execution time fixed throughout entire run

Assumptions

Ours is the first timing analysis of Holoscan

- Queue size = 1
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Assumptions

Ours is the first timing analysis of Holoscan

These match how the system is used

- Queue size = 1
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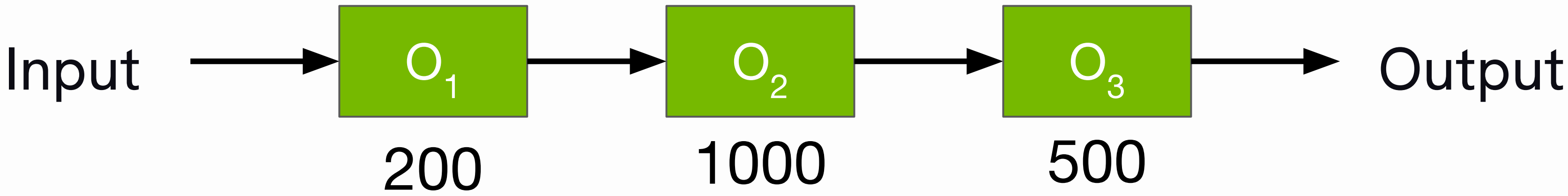
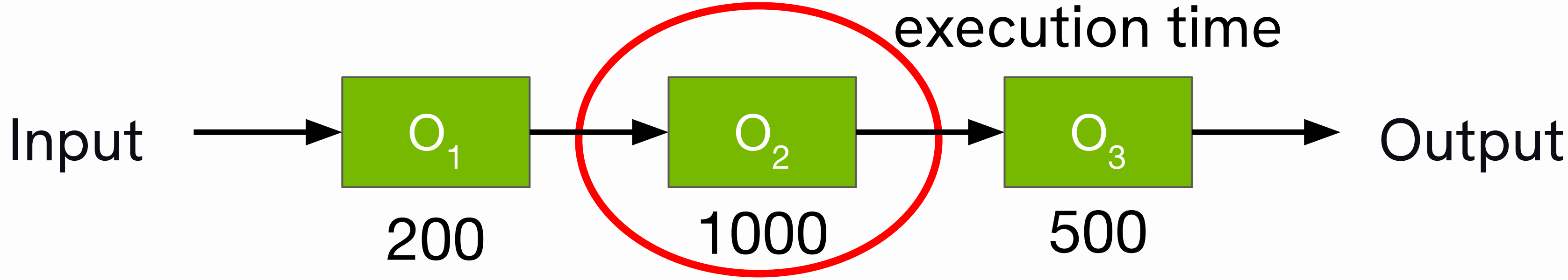
Linear Chain Response Time Bound



Linear Chain Response Time Bound

Key idea: Bottleneck is operator with greatest execution time



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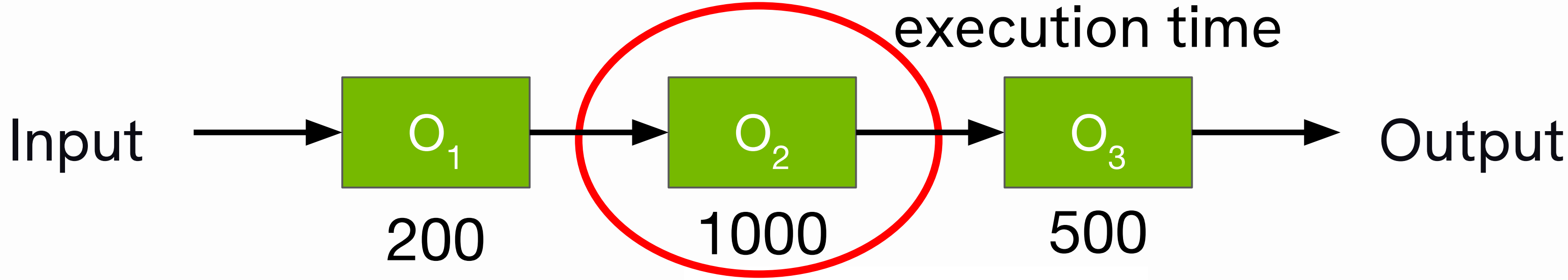

Upper bound: $e_b^{ub} \cdot b + \sum_{i=b+1}^{n} e_i^{ub}$

Linear Chain Response Time Bound

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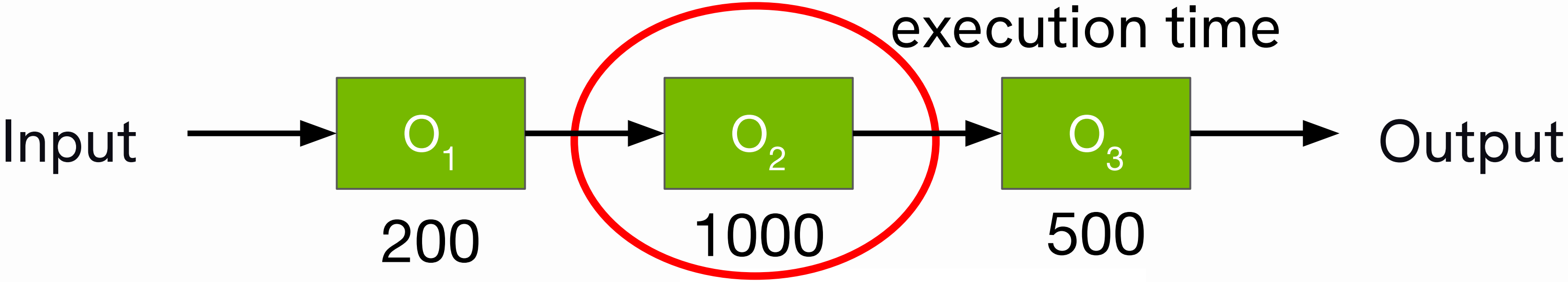


Upper bound: $$\underbrace{e_b^{ub} \cdot b}_{\text{Bottleneck worst-case execution time multiplied by its index}} + \underbrace{\sum_{i=b+1}^{n} e_i^{ub}}_{\text{Sum of worst-case execution times of operators following bottleneck}}$$

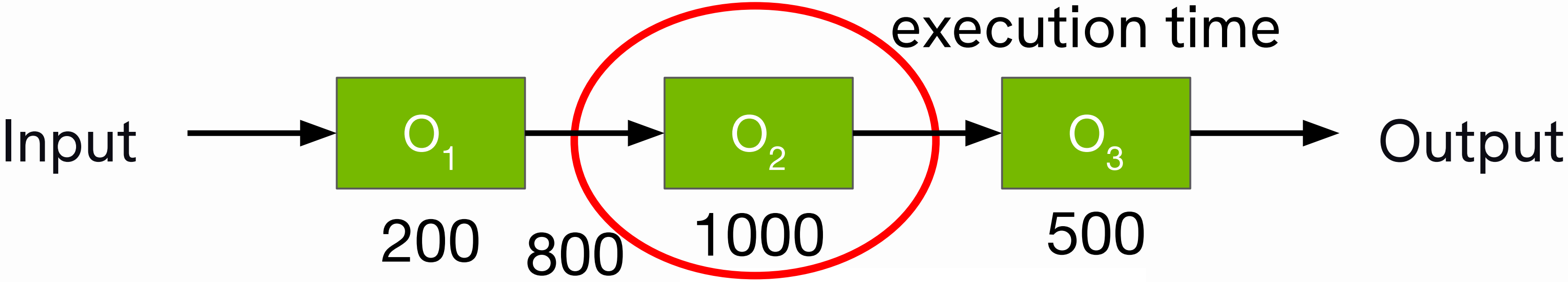
Bottleneck worst-case execution time multiplied by its index

Sum of worst-case execution times of operators following bottleneck

Linear Chain Response Time Bound

2*1000 + 500 = 2500

Key idea: Bottleneck is operator with greatest execution time



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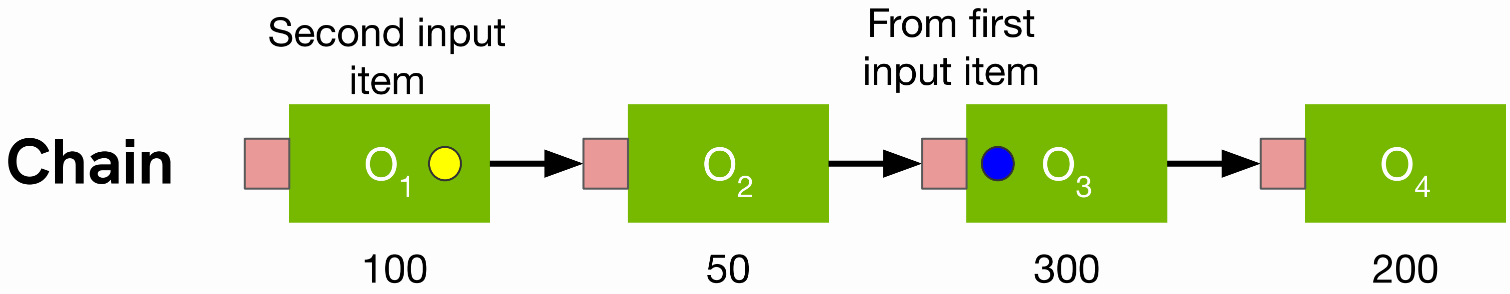
Bottleneck worst-case execution time multiplied by its index

Sum of worst-case execution times of operators following bottleneck

Chains vs DAGs



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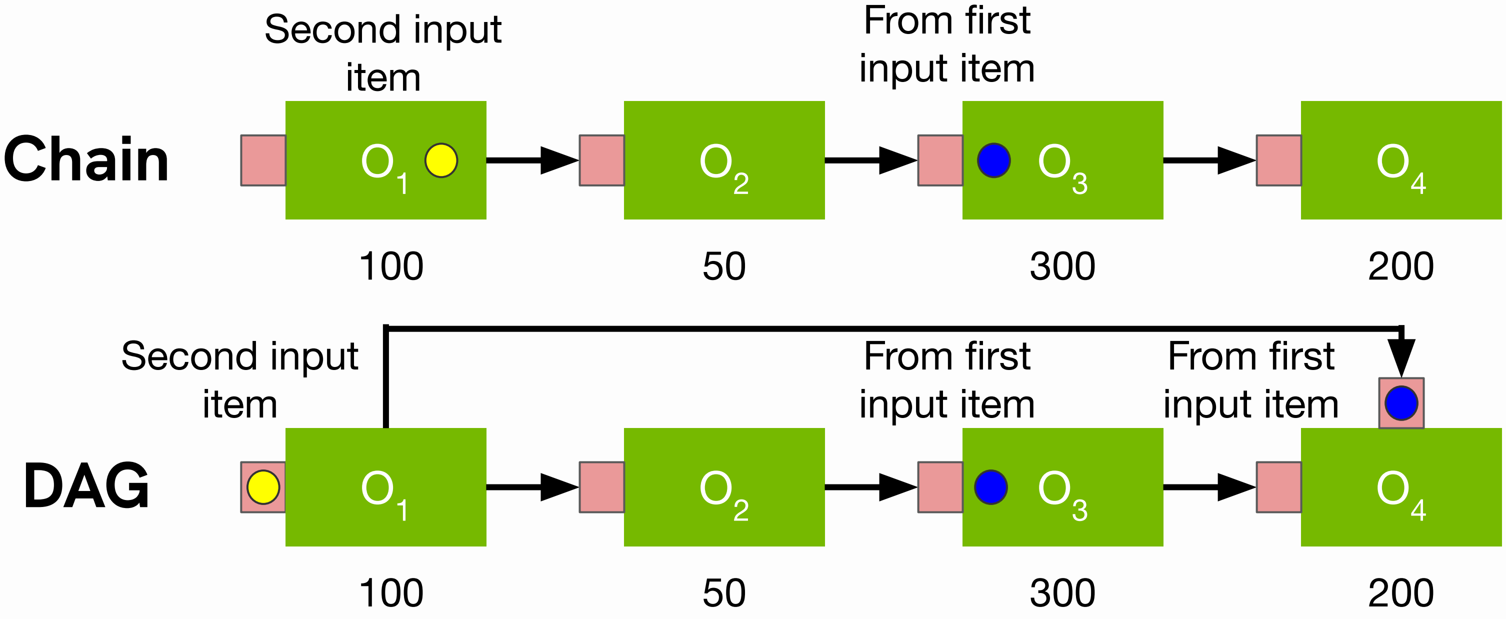

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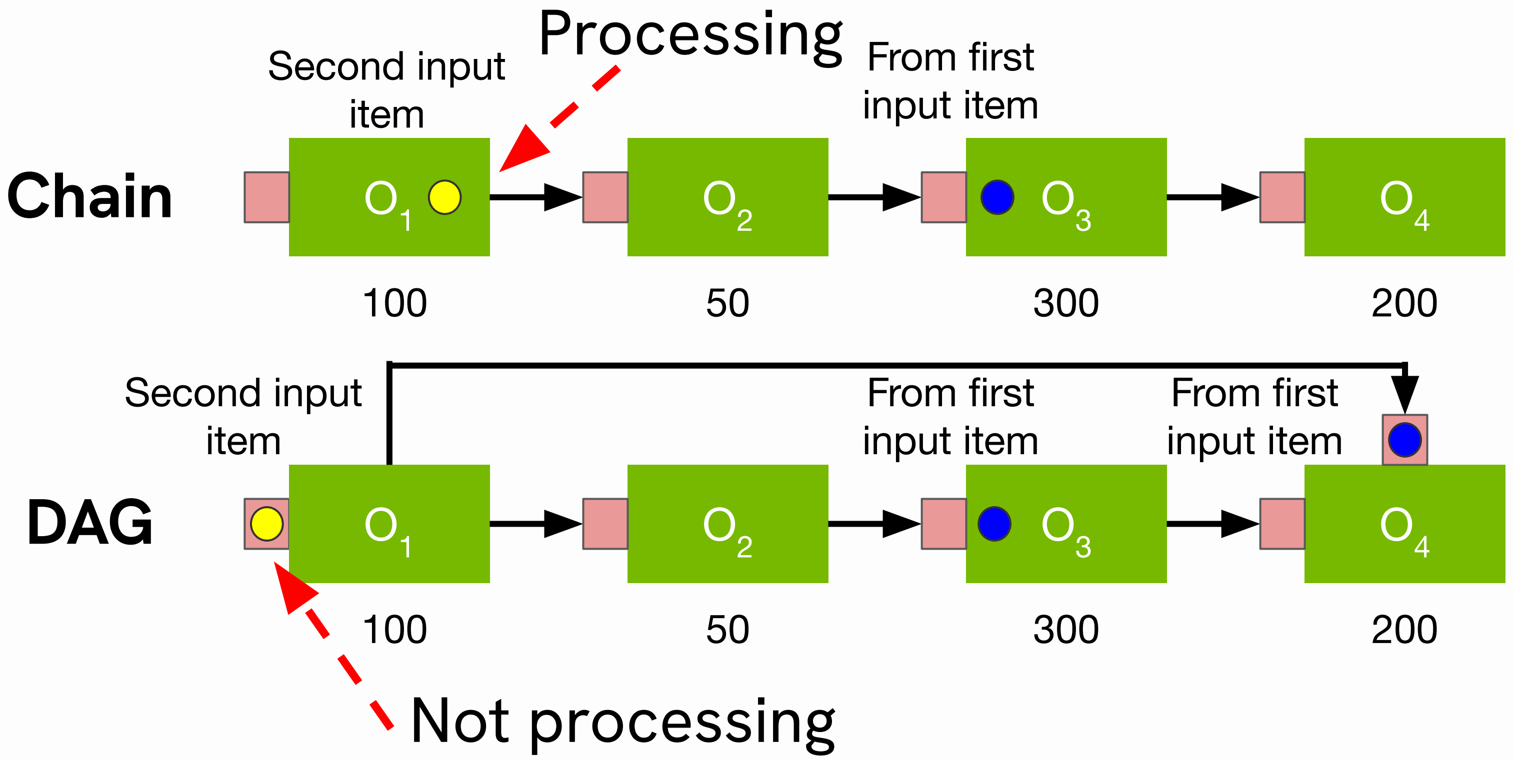

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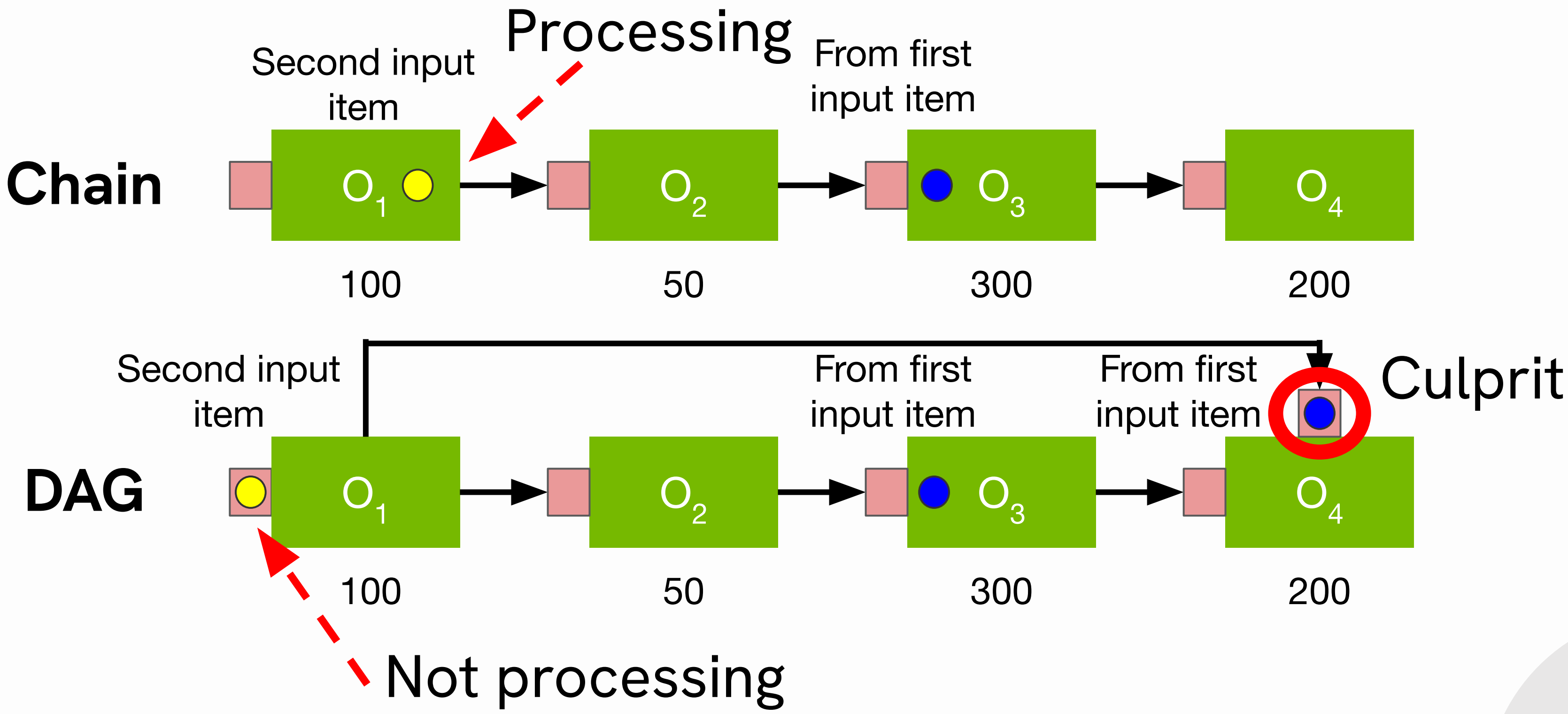

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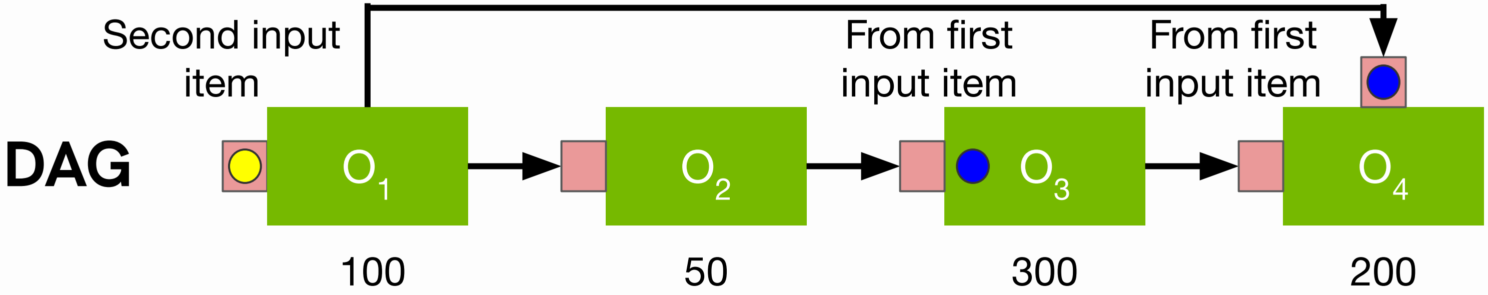

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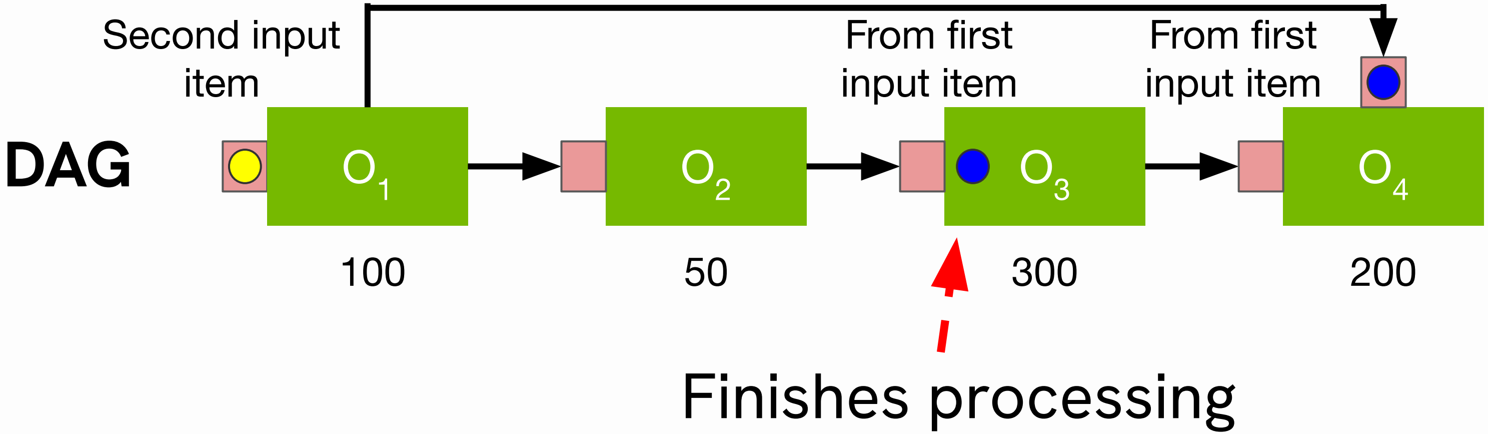

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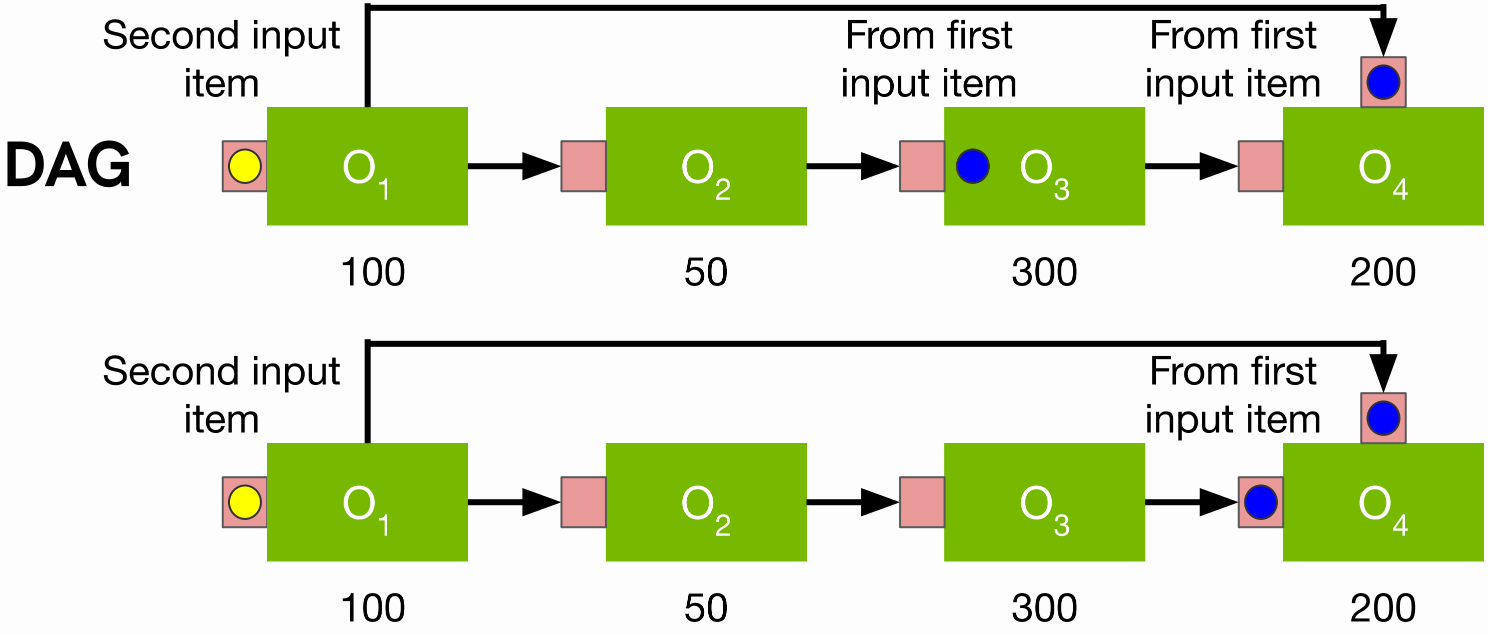

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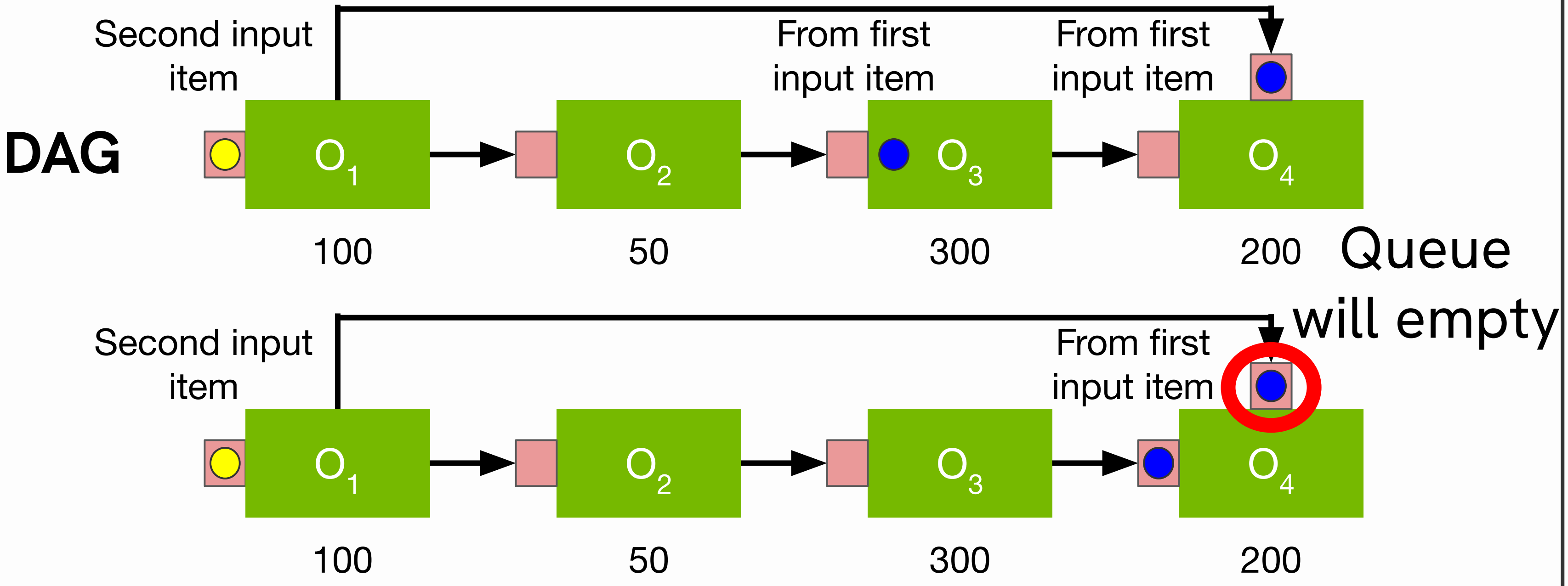

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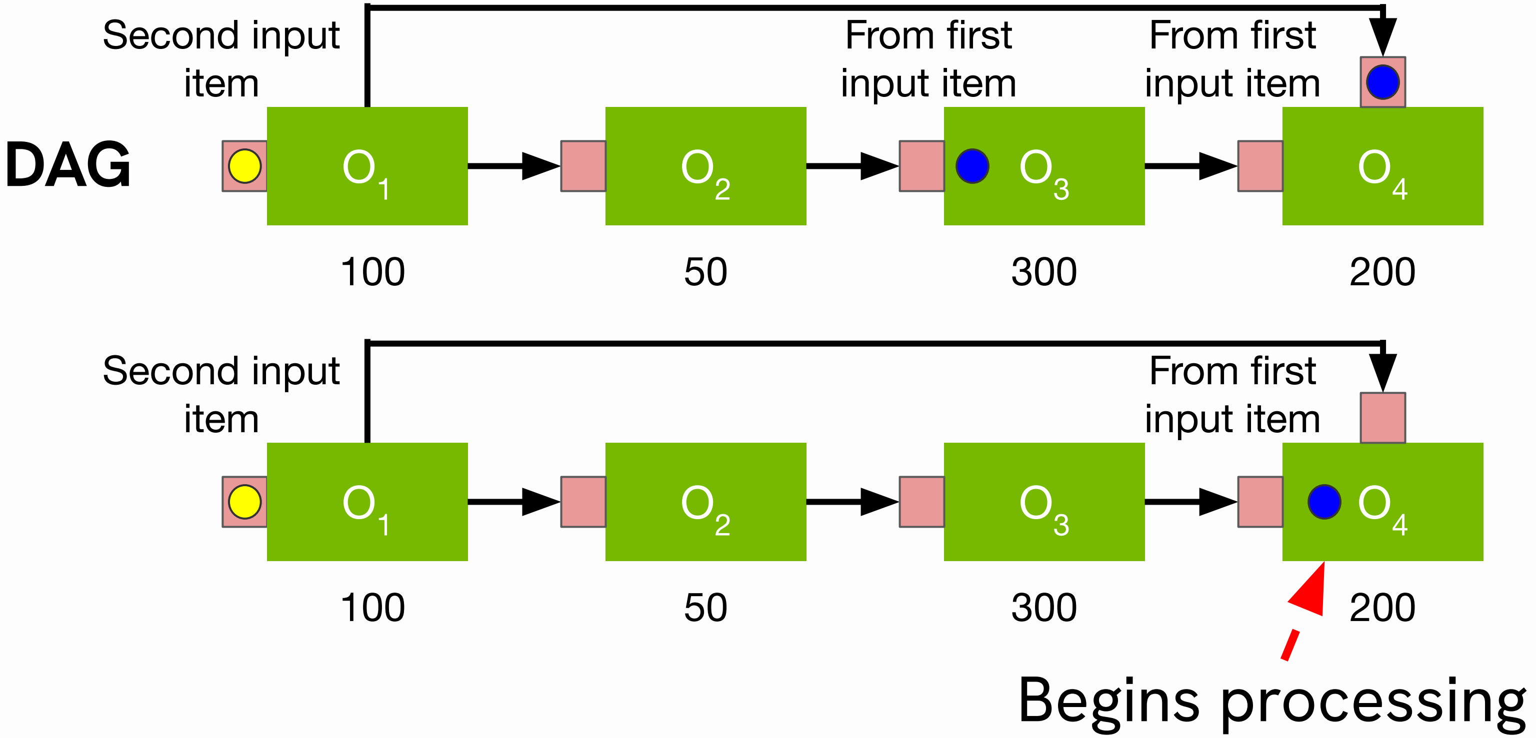

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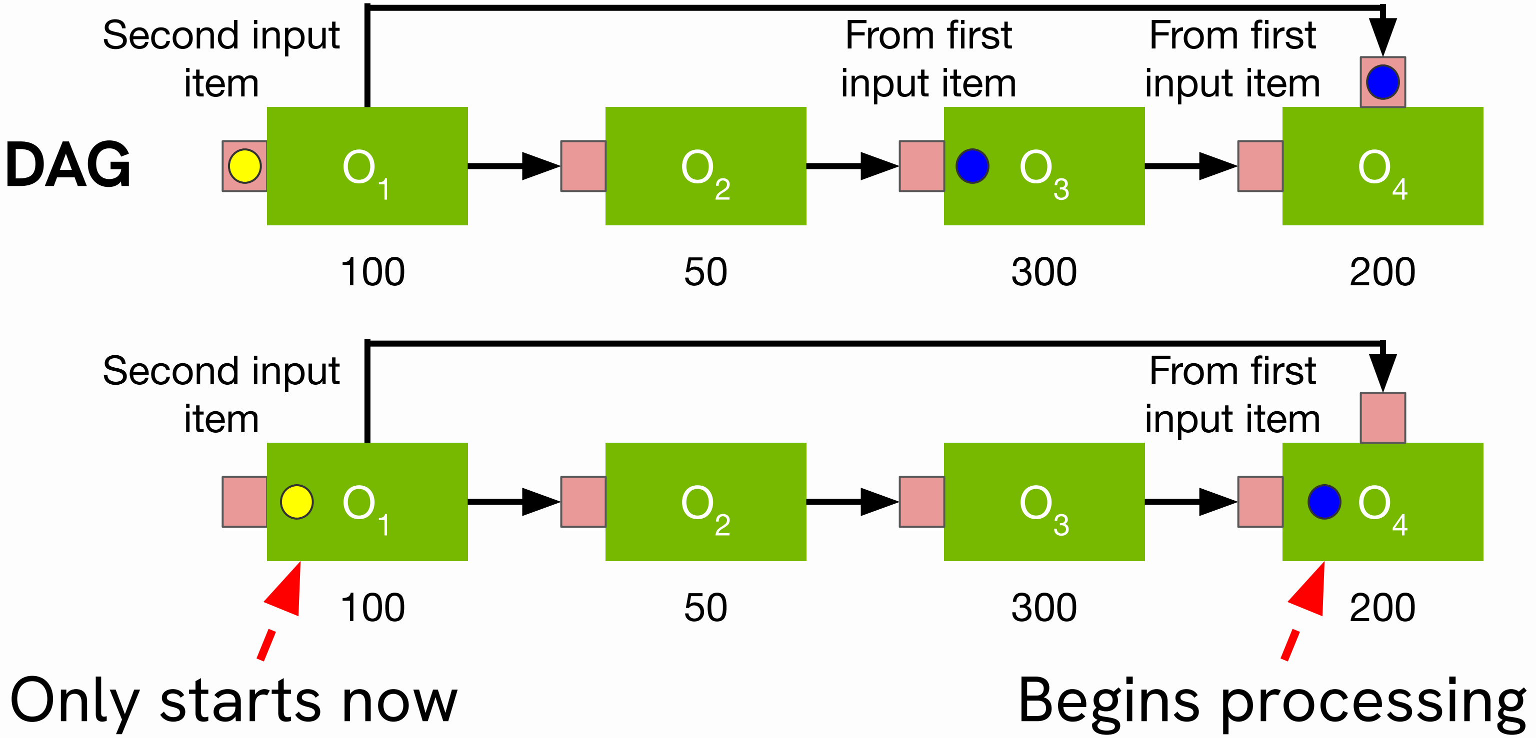

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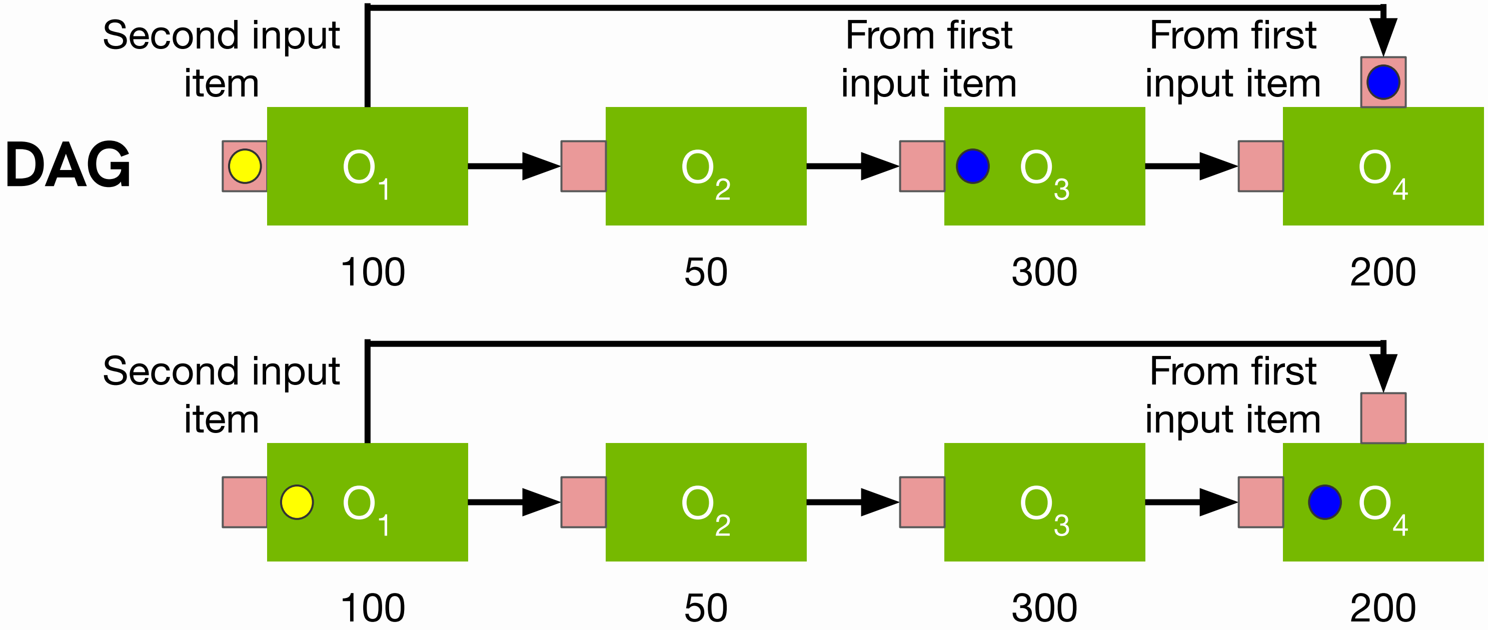
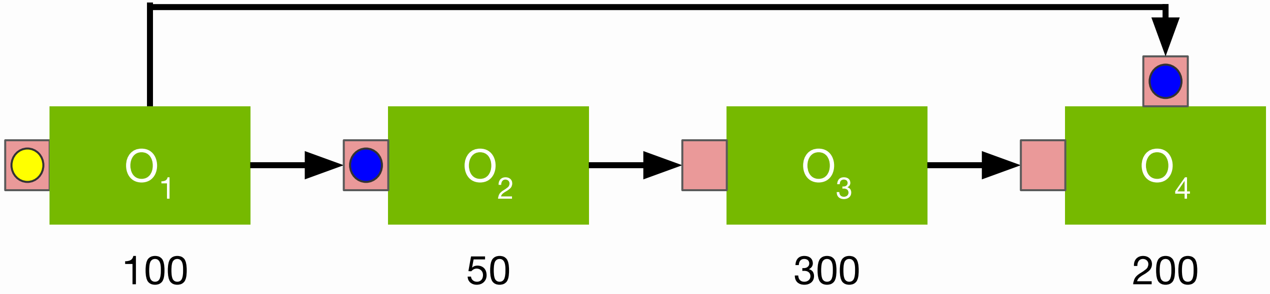


Takeaway: DAG had to wait longer than chain!

Inter-processing Delay

- The maximum time that can pass between two of an operator’s consecutive outputs.



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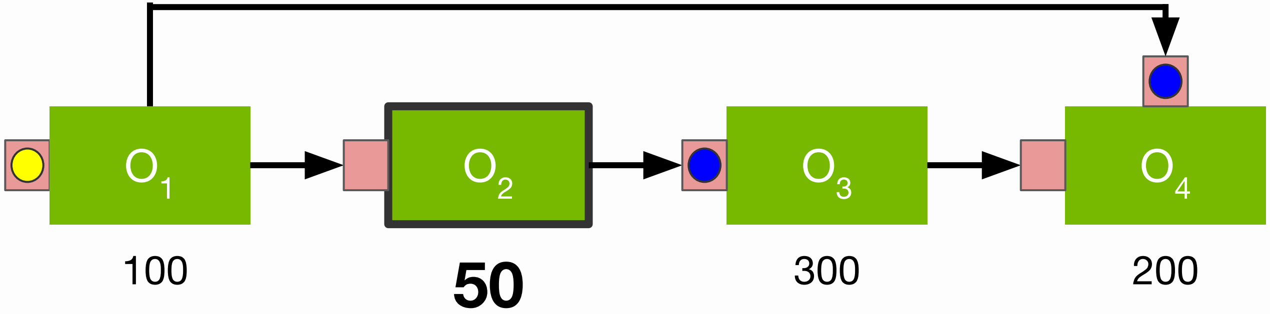

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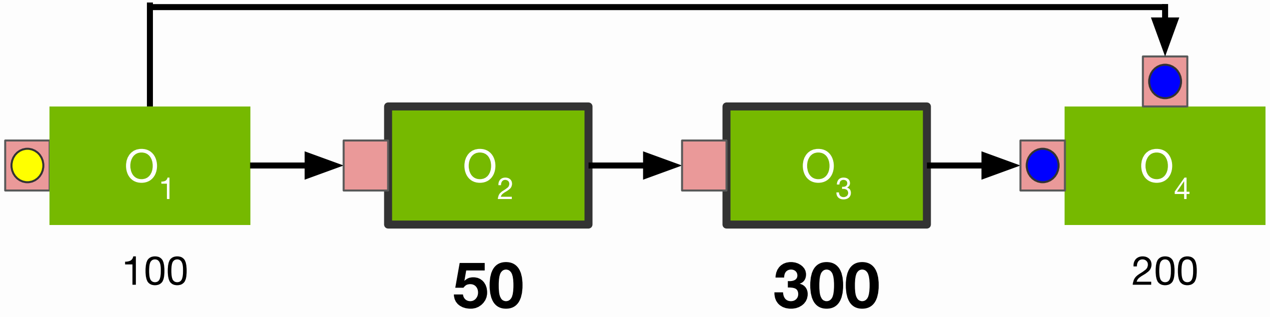

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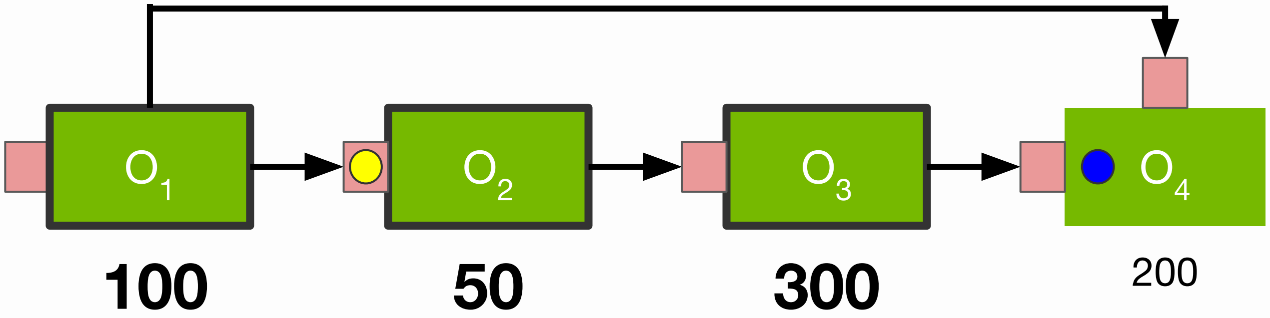

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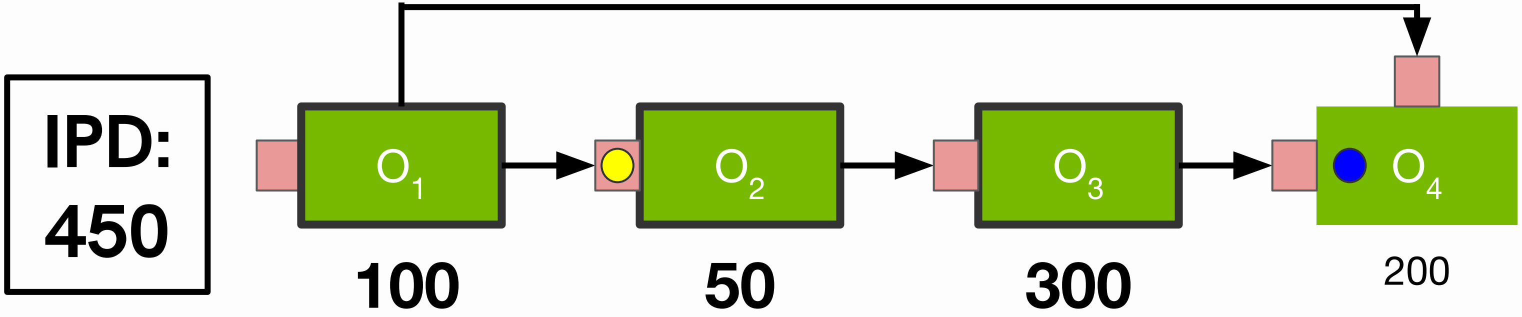

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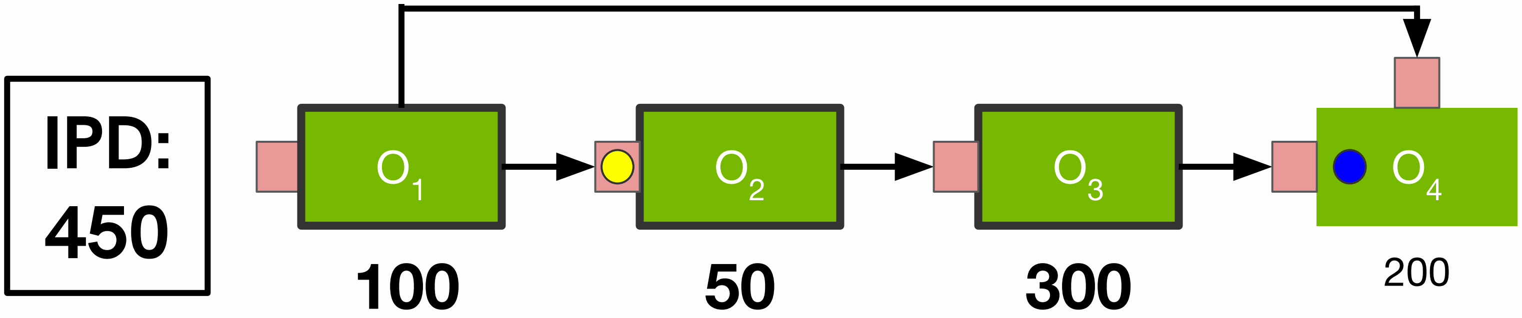

Key idea: use inter-processing delay term to generalize our linear chain bound to DAGs

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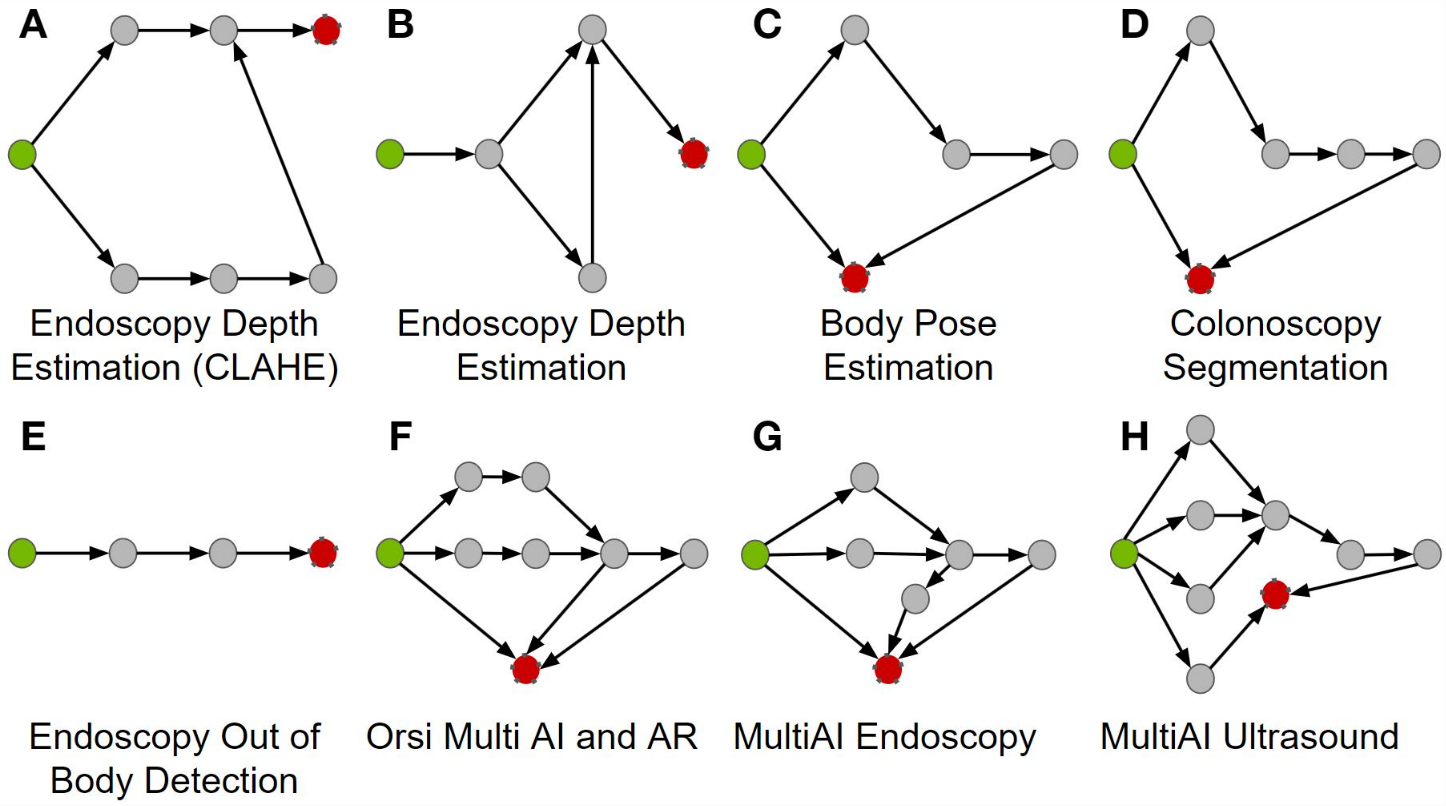
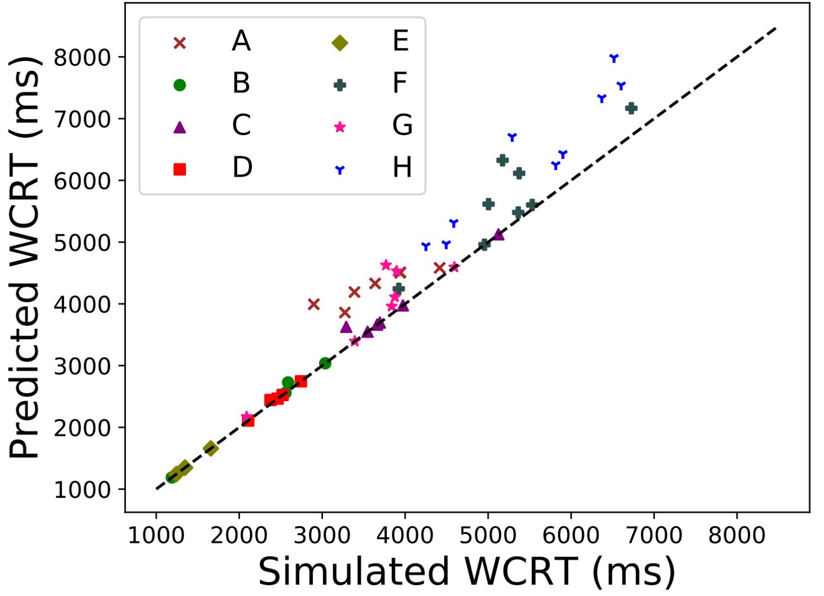
Evaluation

Evaluation: HoloHub Graph Structures



Evaluation: Bounds vs Sim and Profiled



- Compare theoretical WCRT to simulated and real executions
- Pessimism: The IPD we calculate may not be possible in practice

Takeaway: Closely bound most graph variations

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Conclusion

What's wrong with profiling?

- Profiling to learn timing properties has many issues
  - **The response time bound may be unsafe**
  - **Application development must be finished**
  - **Profiling can be costly in time and compute**

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  - **~~The response time bound may be unsafe~~**
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Takeaways

- First safe response-time bound for NVIDIA Holoscan
- Is applicable to arbitrary DAGs
  - Scalability experiments in paper
- Can help developers account for timing anomalies!
  - Observe directly how change in execution time corresponds to increase or decrease in response time

Future Research Areas

- Relax fixed execution time assumption
- Extend to core-constrained setting
- Fine-grained GPU-aware execution time analysis
- Independent applications running in parallel
- Transferring RTA results across different hardware

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UBC Systems Lab is Looking for New Students!

https://systopia.cs.ubc.ca

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Thank you for listening! Questions?

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