Variable Capacity Scheduling

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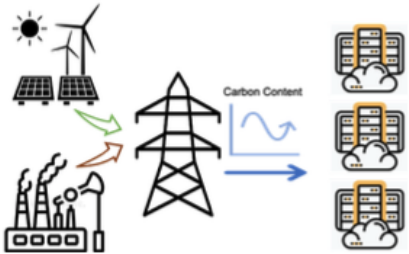
October 29, 2024 – Humboldt University Seminar – Berlin

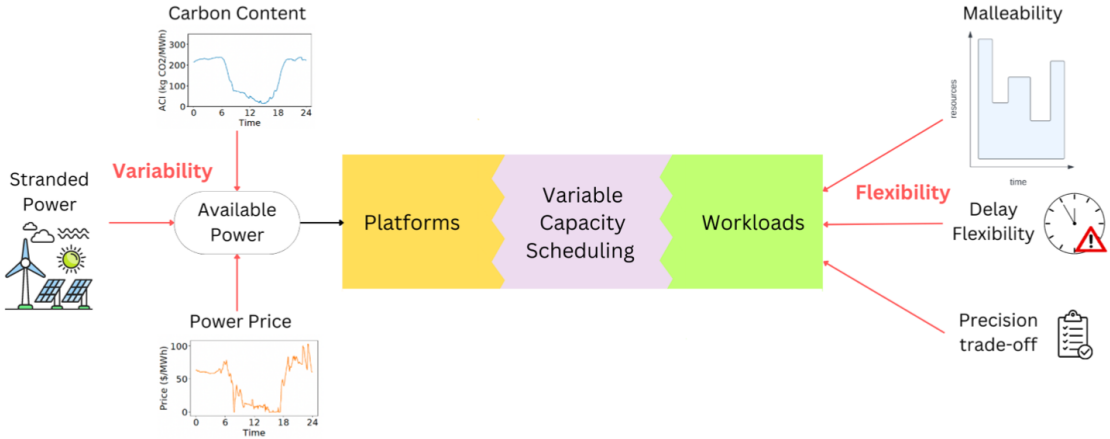
Variable power



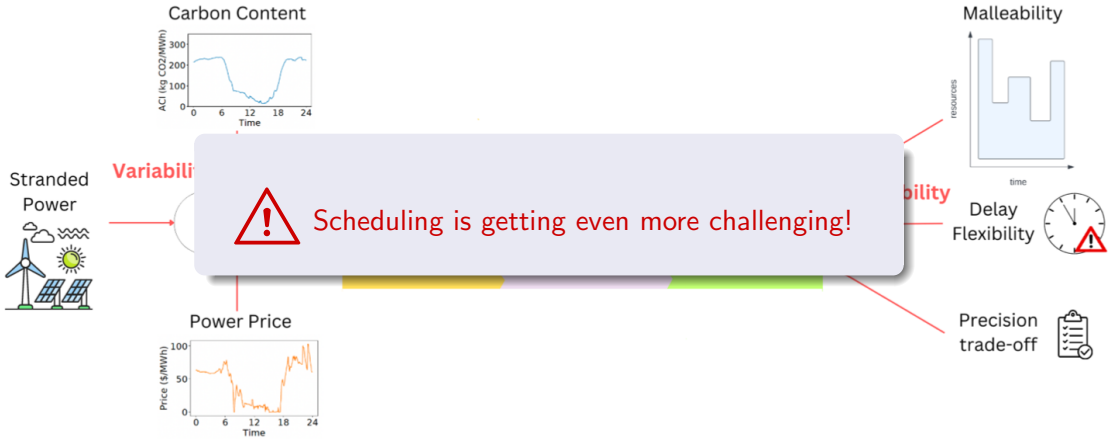
- Today's data centers assume resource capacity as a fixed quantity
- Emerging approaches:
  - Exploit grid renewable energy
  - Reduce carbon emissions

$\Rightarrow$ Variable power

Big picture


Carbon Content
ACI (kg CO2/MWh)
300
200
100
0
0
6
12
18
24
Time
Malleability
resources
time
Stranded Power
Variability
Available Power
Platforms
Variable Capacity Scheduling
Workloads
Flexibility
Delay Flexibility
Precision trade-off
Power Price
Price ($/MWh)
100
50
0
0
6
12
18
24
Time

Big picture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Scheduling is getting even more challenging!
Delay
Flexibility
Power Price
Price ($/MWh)
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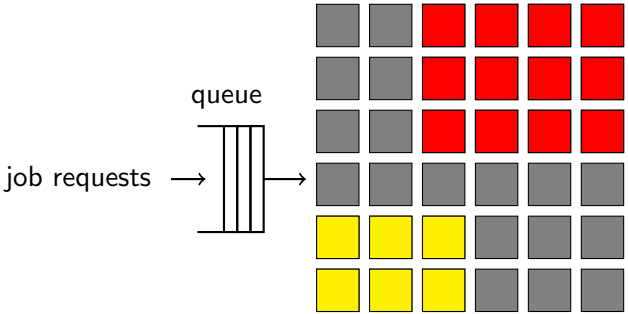
Time
Precision
trade-off

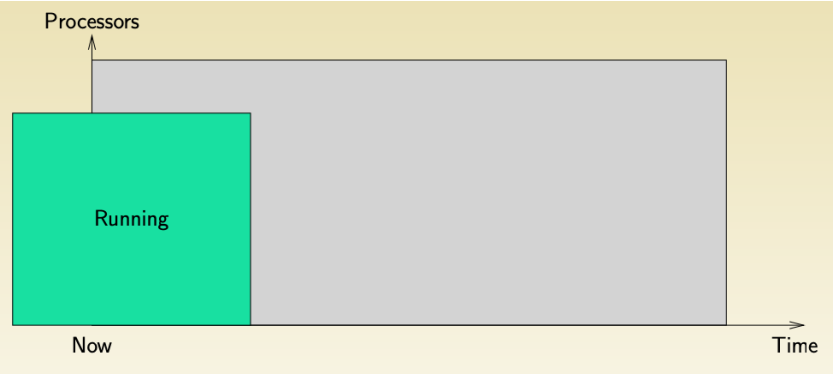
Outline

Batch scheduling

- Jobs submitted online
- Each job has a release time and a size (number of resources)
- Each job has an (estimated) execution time, a.k.a reservation length
- The Batch Scheduler is responsible for the sharing



General principle



Jobs are released one after the other and are scheduled upon arrival

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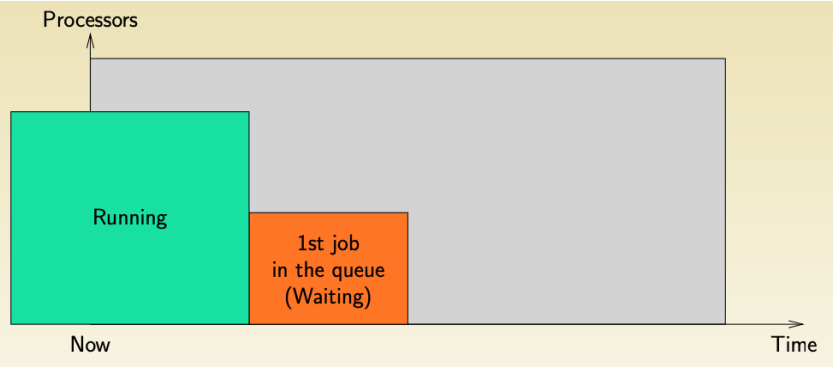

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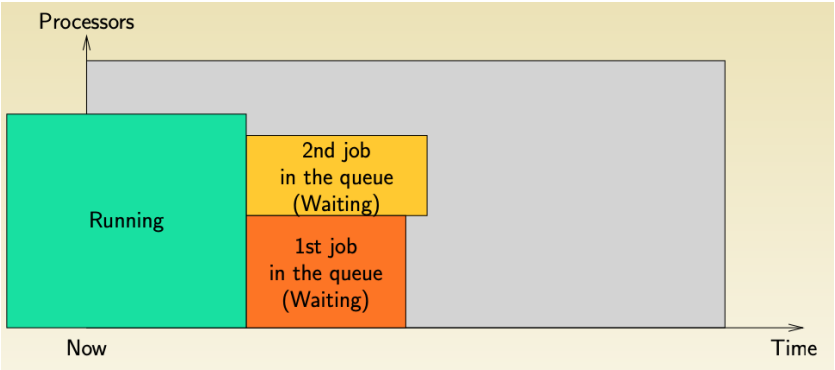

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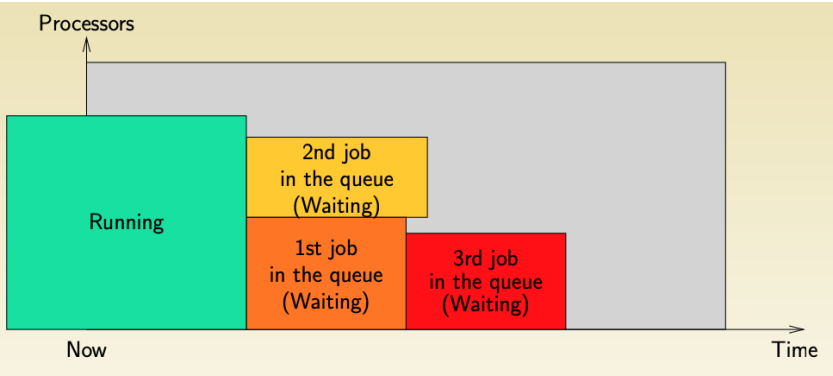

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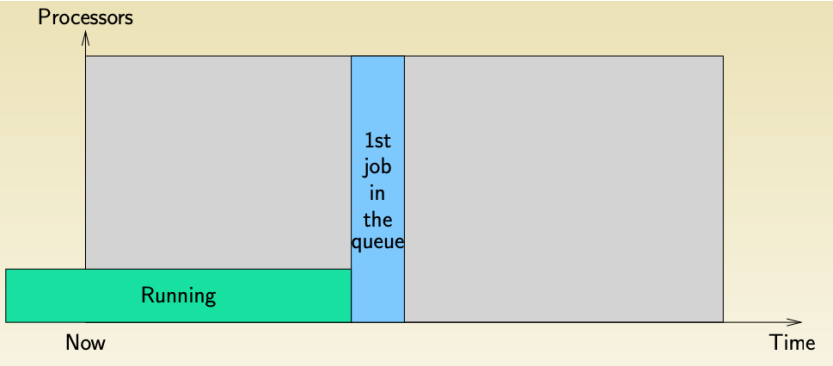
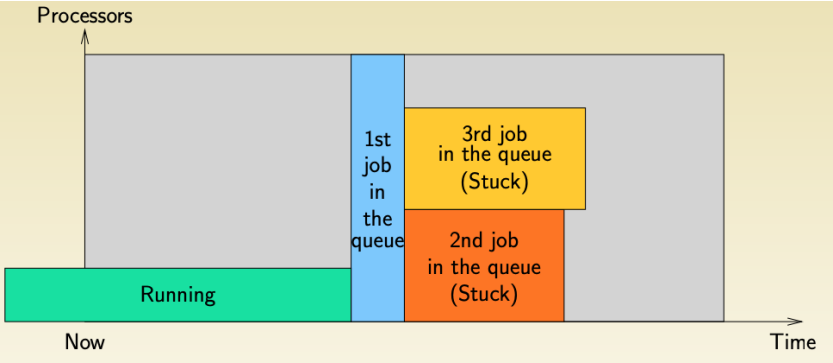
Backfilling



FCFS + FirstFit = simplest scheduling strategy

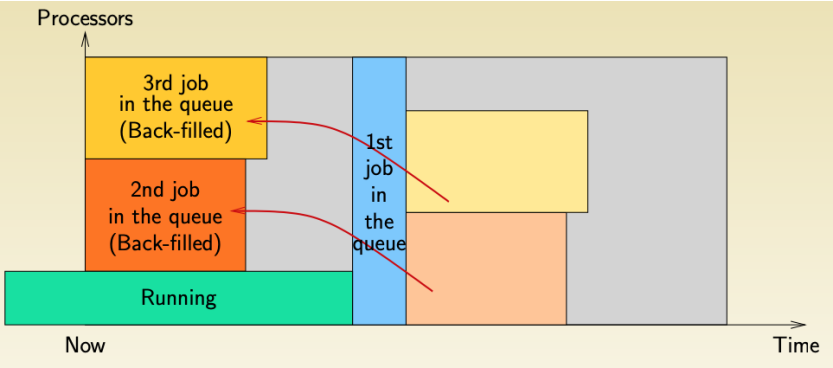
Backfilling



FCFS + FirstFit = simplest scheduling strategy

Fragmentation ☹

Backfilling



FCFS + FirstFit = simplest scheduling strategy

Fragmentation ☹ ⇒ need for backfilling

EASY Backfilling

Extensible Argonne Scheduling System

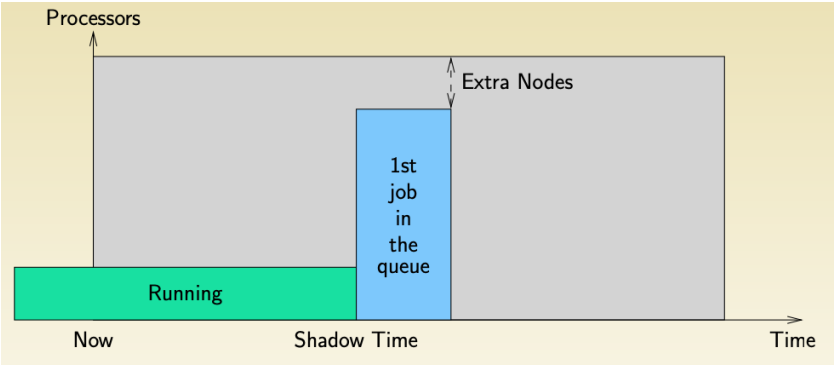
Maintain only one *reservation time*, for first job in the queue

Shadow time – Starting execution of first job in the queue

Extra nodes – Number of nodes idle at shadow time

1. Go through the queue in order, starting with second job
2. Backfill a job
   - either if it will terminate by shadow time
   - or if it needs no more nodes than the extra nodes

EASY



First job in the queue is never delayed by backfilled jobs

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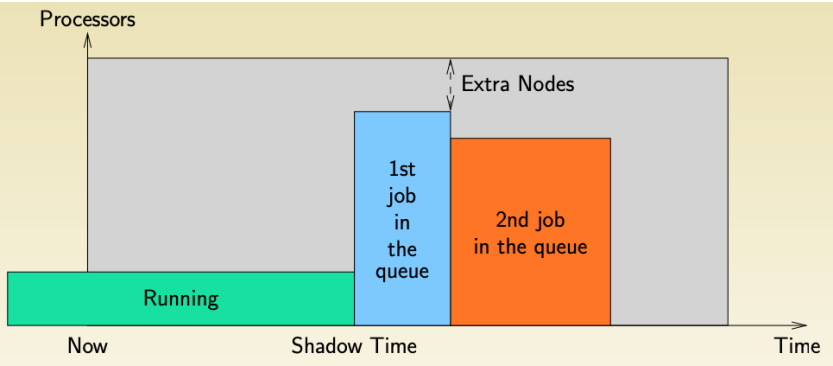

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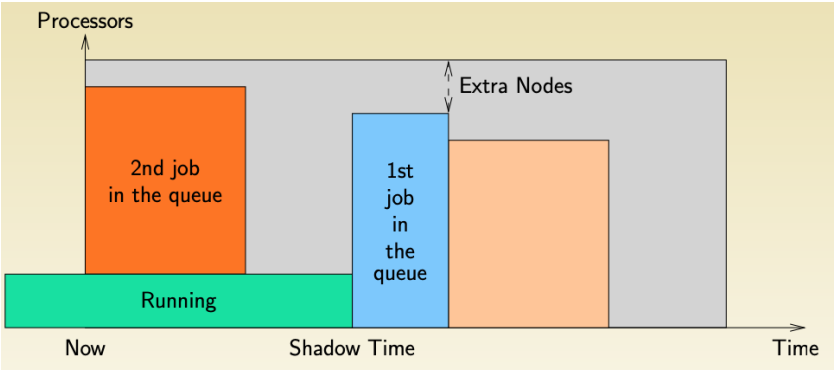

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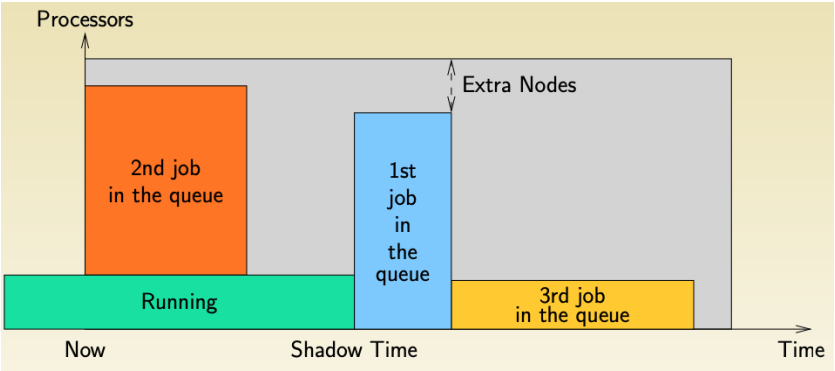

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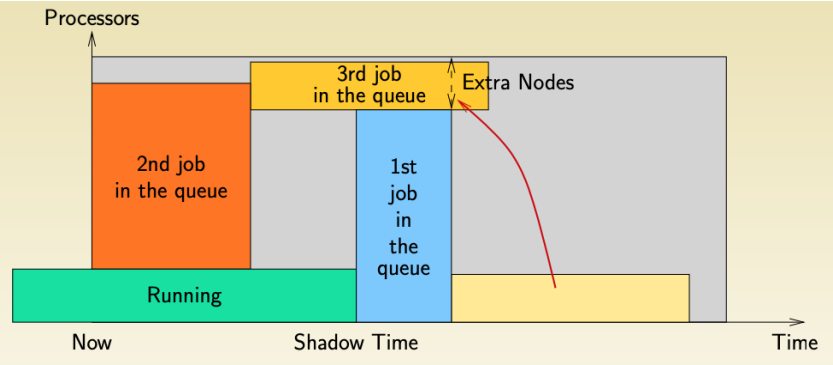

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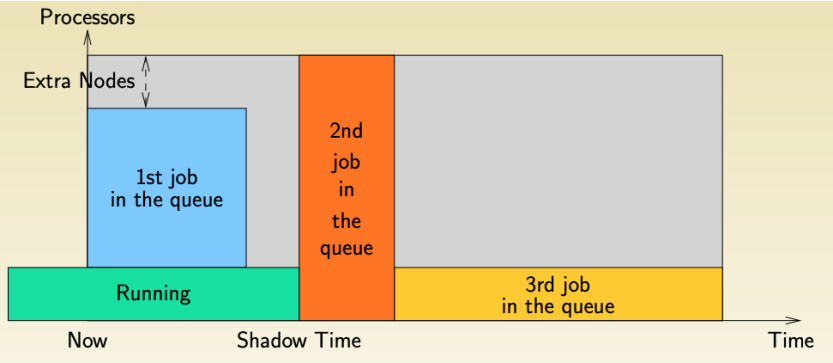

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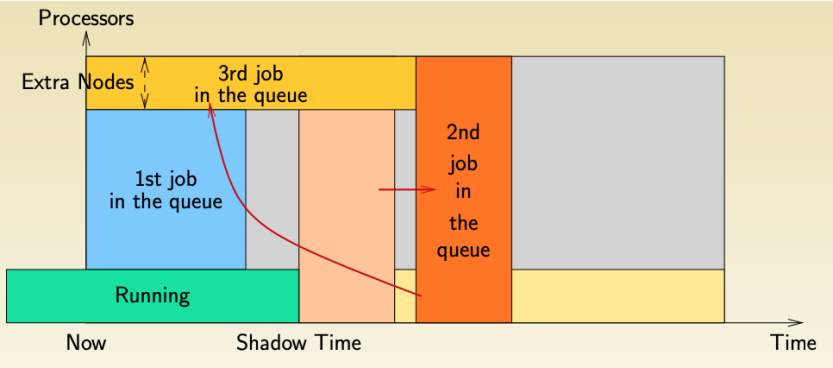
BUT other jobs may be delayed indefinitely!

EASY



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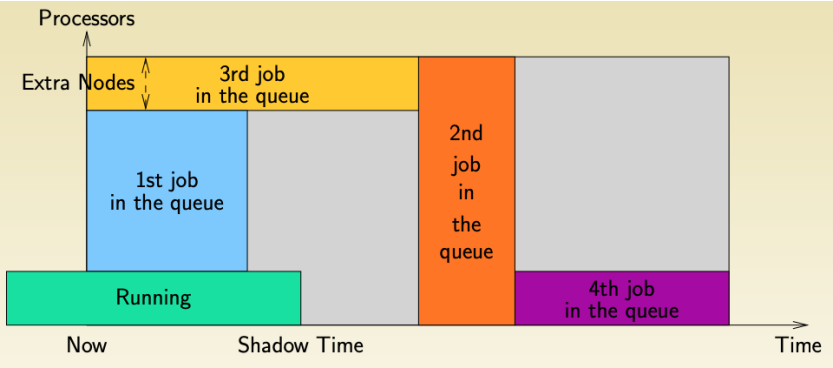

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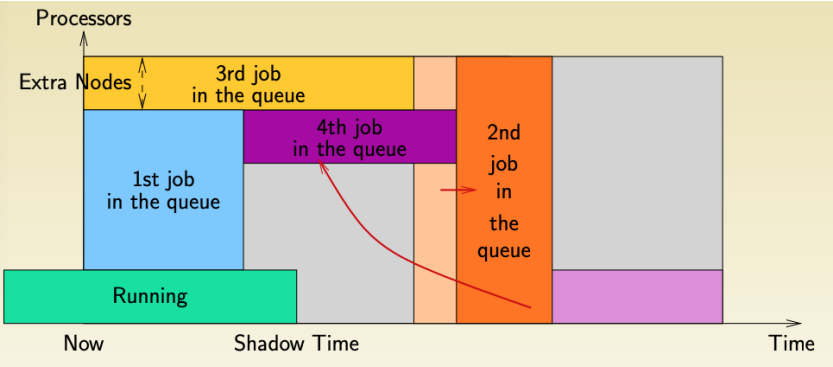

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EASY properties

Unbounded Delay

- First job in the queue is never delayed by backfilled jobs
- BUT other jobs may be delayed indefinitely!

No Starvation

- Delay of first job in the queue is bounded by runtime of current jobs
- When first job completes, second job becomes first job in the queue
- Once it is the first job, it cannot be delayed further

Behavior

- EASY favors small long jobs and delays large short jobs

Conservative backfilling

Find holes in the schedule

- *Each* job has a *reservation time*
- A job may be backfilled
  only if it does not delay any other job ahead of it in the queue
- Fixes EASY unbounded delay problem
- More complicated to implement ☹

When does backfilling happen?

Possibly when

- A new job is released
- The first job in the queue starts execution
- When a job finishes early

A job is killed if it goes over

Users provide job runtime estimates
Trade-off: provide

- a tight estimate: you go through the queue faster (may be backfilled)
- a loose estimate: your job will not be killed

When does backfilling happen?

Possibly when

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Tricks

- Pick the right "shape" so that you'll be backfilled
- Chop up your job into multiple pieces
- Aggressively submit versions of the same job (different shapes), perhaps to multiple systems, and cancel when one begins
- ...

- a loose estimate: your job will not be killed

What's a good batch schedule?

- Define a metric of goodness for this on-line scheduling problem
- **Wait time**: time spent in the queue
  - Wait time is annoying, so likely a good thing to minimize
  - Not a great idea:
    - Job #1 needs 100h on 1000 nodes and waits 1h
    - Job #2 needs 1s on 1 node and waits 1h
    - Clearly Job #1 is really happy, and Job #2 is not happy at all
- **Turn-around time**: Wait time + Execution time
  - Called *flow time* in scheduling literature
  - Not a great idea:
    - Job #1 needs 1h of compute time and waits 1s
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What's a good batch schedule?

- We want a metric that represents "happiness" for small, large, short, long jobs
- **Slowdown**: (Wait time + Execution time) / Execution time
  - Called *stretch* in scheduling literature
  - Quantifies loss of performance due to competition for the processors
  - Takes care of the short vs. long job problem
  - Doesn't really say anything about job size ...
- Two possible objectives:
  - minimize the *Sum Stretch* (make jobs happy on average)
  - minimize the *Max Stretch* (make the least happy job as happy as possible)

What's a good batch schedule?

- We want a metric that represents "happiness" for small, large, short, long jobs
- [illegible]

> Flow time measures the time that a job is in the system regardless of the service it requests; the stretch measure relies on the intuition that a job that requires a long service time must be prepared to wait longer than jobs that require small service times.
> *M. Bender et al, J. of Scheduling, 2004*

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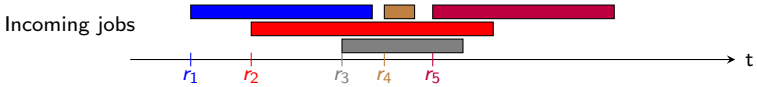
Minimizing Maximum Stretch



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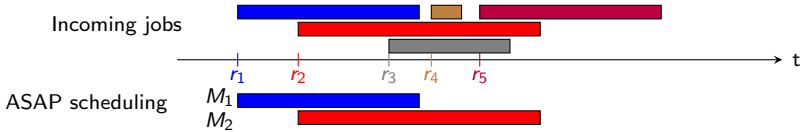

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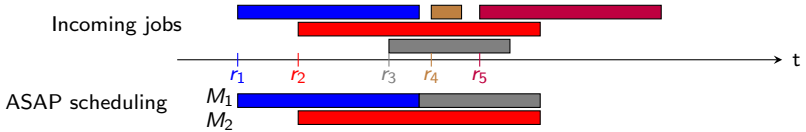

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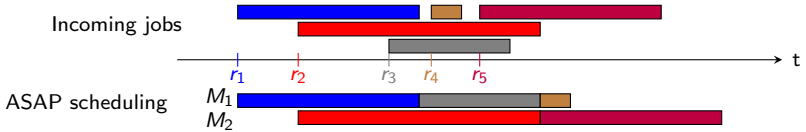

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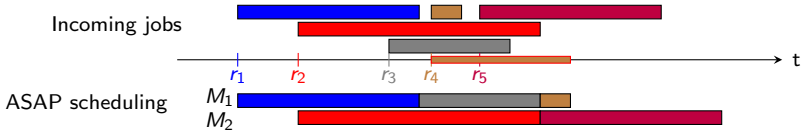

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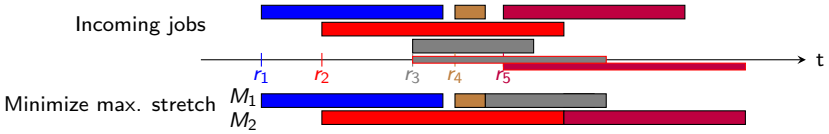


Online Max Stretch: Difficult

- The offline scheduling problem is NP-complete
- On one processor, with preemption allowed, there is a $O(\sqrt{X})$-competitive algorithm
  - X is the ratio of largest to smallest job duration
  - Competitive ratio: ratio to performance of an adversary who knows all jobs
- Without preemption, no approximation algorithm

A massive divide

Practice
- No preemption in batch scheduling
- Need for many scheduling configuration knobs

Theory
- Without preemption, we cannot do anything guaranteed anyway

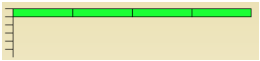
- The two remain very divorced
- Stretch used as a metric to evaluate how good scheduling is in practice
- Often, it is not the objective of the batch scheduler
- That objective is complex, sometimes mysterious, and not necessarily theoretically-motivated
- Bottom-line: Users hate the batch queue, and will use ingenuity to get ahead

Scheduling objectives

- User-oriented, performance
  - **Wait time** – Amount of time spent waiting before execution
  - **Turnaround time/Response time/Flow** – Amount of time between job release and completion
  - **Slowdown/Stretch** – Slowdown factor relative to time it would take on an unloaded system
- User-oriented, other criteria
  - **Cost** – Money paid for reservation
  - **Energy** – Energy consumed by job
- Platform-oriented
  - **Utilization** – Proportion of time spent doing computation
  - **Goodput** – Proportion of time spent doing successful computation
  - **Failure rate** – Proportion of interrupted jobs
  - **Total power** – Minimize power peak
  - **Carbon emission** – Minimize carbon emission (if green power sources available)

Outline

Flexible workloads: Parallel jobs



- **Rigid jobs**: Processor allocation is fixed
- **Moldable jobs**: Processor allocation is decided by the user or the system but cannot be changed during execution
- **Malleable jobs**: Processor allocation can be dynamically changed

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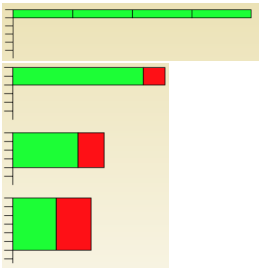

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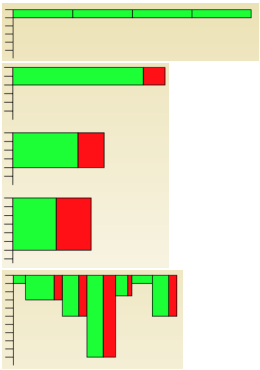

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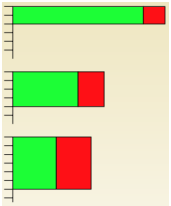

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The case for moldable jobs:

- Easily adapt to the amount of available resources (contrarily to rigid jobs)
- Easy to design/implement (contrarily to malleable jobs)
- Computational kernels in scientific libraries are provided as moldable jobs

Checkpoints

- Some jobs cannot be interrupted
- Some jobs can be checkpointed

Half the projected load for US Exascale systems include checkpointing capabilities
(from APEX worklows, Sandia/LosAlamos/NERSC report, April 2016)

Checkpoints

Scheduling opportunity

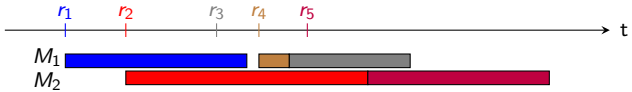
- Many checkpointable jobs are moldable
- These jobs are able to restart with a different allocation (size and shape)

Resizing impacts performance

(from APEX workflows, Sandia/LosAlamos/NERSC report, April 2016)

Risk aware?

1. **Which machine to shutdown?**



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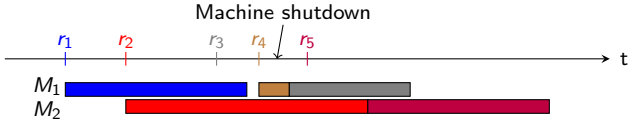

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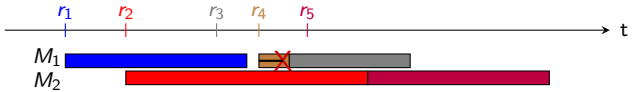

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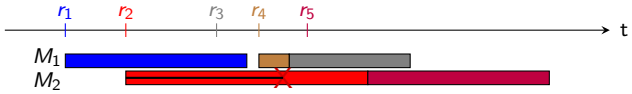

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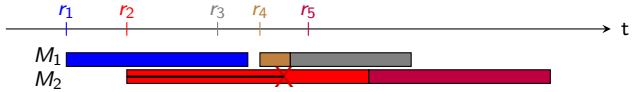

2. **How to schedule jobs to minimize impact?**

Main questions

- When power decreases, which machines to power off? Which jobs to interrupt? And to re-schedule?
- Are we notified ahead of a power change?
  - Resource variation in power obeys specific parameters whose evolution is dictated by a mix of technical availability and economic conditions
  - Accurate external predictor (precision, recall)? Maybe too optimistic ☹
- Re-scheduling interrupted jobs
  - Can we take a proactive checkpoint before the interruption?
  - Which priority should be given to each interrupted job?
  - Which geometry and which nodes for re-execution?

Outline

Framework

- **Platform**
  - Set $\mathcal{M}$ of M^+ identical parallel machines, each equipped with n_c cores, and requiring power P when switched on
  - Global available power capacity $P(t)$: function of time t (time discretized)
    $\Rightarrow M_{alive}(t)$ machines alive, with $M_{alive}(t)P \leq P(t)$

- **Rigid jobs**
  - Set $\mathcal{J}$; job $\tau_i \in \mathcal{J}$ released at date r_i, needs c_i cores, has length w_i; allocated to machine m_i at starting date s_i
  - (Predicted) completion date of job τ_i: $e_i = s_i + w_i$ if not interrupted
  - At any time, total cores used by running jobs on a machine $\leq n_c$

Resource variation

- Number of alive machines evolves over time
  (either random-length phases, or fixed-length periods)
- Number of alive machines in the next phase/period not known in advance

- Technically, $M_{alive}(t)$:
  - Always ranges in interval $[M^- = M_{avg} - M_{ra}, M^+ = M_{avg} + M_{ra}]$ centered in M_{avg}
  - Evolves according to some random walk, starting with M_{avg}
  - Stays constant, increases or decreases with same probability
    (if range bound reached, stays constant or evolves in unique possible direction, with same probability)
  - Magnitude of variation controlled by another variable

Limitations

- Rigid jobs $\Rightarrow$ no flexibility in size
- Identical multicore machines
- No checkpoints
- Power consumption at time t proportional to $M_{alive}(t)$ (actual load not accounted for)
- Resource variation not known until change

Objective function: Goodput

- $\mathcal{J}_{comp,T}$: set of jobs that are complete at time T ($e_i \leq T$)
- $\mathcal{J}_{started,T}$: set of jobs running and not finished at time T ($s_i \leq T < e_i$)
- Total number of units of work that can be executed in $[0, T]$:

$$n_c \sum_{t \in [0, T-1]} M_{alive}(t)$$

- $\textsc{Goodput}(T)$ is the fraction of useful work up to time T:

$$\textsc{Goodput}(T) = \frac{\sum_{\tau_i \in \mathcal{J}_{comp,T}} w_i c_i + \sum_{\tau_i \in \mathcal{J}_{started,T}} (T - s_i) c_i}{n_c \sum_{t \in [0, T-1]} M_{alive}(t)}$$

Keep an eye on maximum stretch

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Keep an eye on maximum stretch

Complexity

Theorem

An adversary can force any schedule to achieve no goodput at all, even with a single unicore machine

- Job τ_1 of size $c_1 = 1$ and duration $w_1 = K$ released at time $t = r_1 = 0$;
  Goodput of the machine at time $T = K$?

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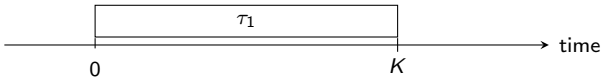

- Start τ_1 at time $s_1 > 0$: machine interrupted at time K

Complexity

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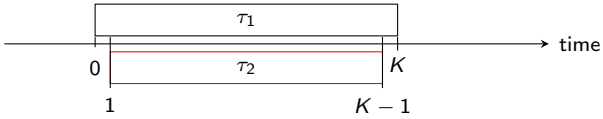
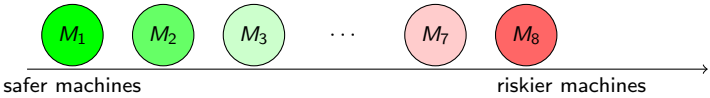


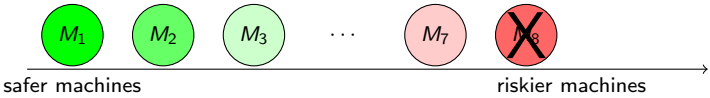
- Start τ_1 at time $s_1 = 0$: new job τ_2, machine interrupted at time $K - 1$

Risk-aware



Risk-aware job allocation strategies

Risk-aware



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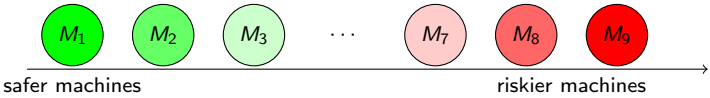

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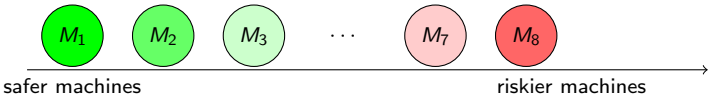

Risk-aware job allocation strategies

Events:

- **Job arrival**: When a job is released, when to schedule it and on which machine?
- **Job completion**: When a job is completed, its cores are released $\Rightarrow$ additional jobs can be scheduled
- **Machine addition**: When a new machine becomes available, how to utilize it?
- **Machine removal**: When a machine is turned off, its jobs are killed and need re-allocation

FirstFitAware

- **Job arrival**
  Assign incoming job to smallest-index machine with enough free resources
  If no machine can execute the job, it is placed in waiting queue
- **Job completion**
  Check the queue for job with smallest release date that fits in the machine m with completed job, and assigns it to m
  If a job is assigned, continues to search the queue
  If empty queue or not enough cores in m for any waiting job $\Rightarrow$ no action
- **Machine addition**
  Assign jobs to the new machine in order of increasing release date
- **Machine removal**
  Shut down machine with highest index, put all its jobs in the queue
  Assign jobs to available machines in order of increasing release date

FirstFitAware

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Risk-aware
- Ordered list of machines
- Jobs mapped to leftmost (safer) machines whenever possible
- Rightmost (riskier) machines are shutdown whenever necessary

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FirstFitUnaware: Shutdown random machines whenever necessary

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FirstFitUnaware: Shutdown random machines whenever necessary

Interrupting a long job is a big performance loss
Schedule smaller jobs on machines that are likely to be turned off
Schedule longer jobs on risk-free machines

TargetStretch

- Add one queue per machine
- Set target value for (target) maximum stretch
- **Job arrival**
  Compute job's target machine
  Consider neighboring machines if target stretch not achievable
- **Machine addition/removal**
  Set of risk-free machines recomputed
  Re-allocate pending jobs

TargetASAP & PackedTargetASAP

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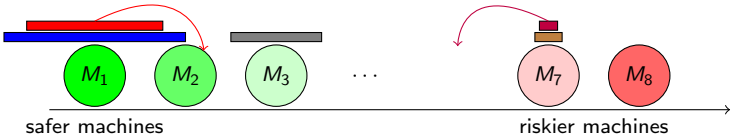
  - Otherwise, assign on machine where it can start ASAP (within acceptable distance)



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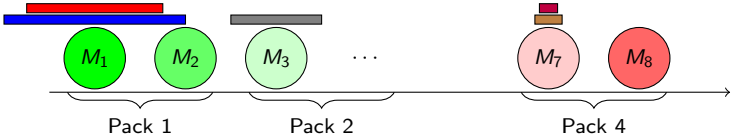
  - Otherwise, assign on machine where it can start ASAP (within acceptable distance)
- Variant PackedTargetASAP: group machines into packs, and assign jobs to first machines of the pack, to leave machines empty for future large jobs



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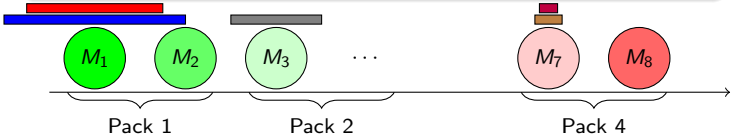
Technical and kind of painful
despite all simplifying hypotheses ☹



Simulation setting

In-house simulator, using a combination of two traces:

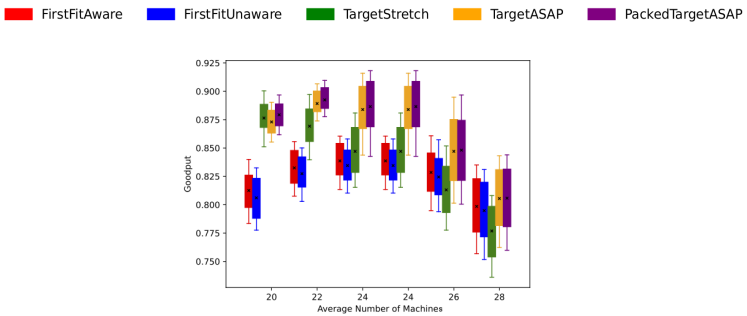
- Resource variation trace: number of machines alive at any given time
  Use of a random walk, within an interval

- Job trace:
  - Real traces coming from **Borg** (two-week traces with jobs coming from Google cluster management software: release dates, lengths, number of cores)
  - Synthetic traces to study the impact of parameters (three variants: uniform lengths, log scale, and three types of jobs) $\Rightarrow$ similar conclusions

Dimensioning

- Number of available machines always in $[M_{avg} - M_{ra}, M_{avg} + M_{ra}]$
- Total work hours $\approx$ maximum capacity of 26 machines each with 24 cores, running during 2 weeks with full peak load
- Average number of machines: $M_{avg} = 24$
- Period of machine variation: $\phi = 20$ minutes
- Range of machine variation: $M_{ra} = 8$; half the machines are safe
- Number of cores per machine: $n_c = 24$. Jobs typically use $1, 2, 4, 8$ cores
- Conservative backfilling at machine level

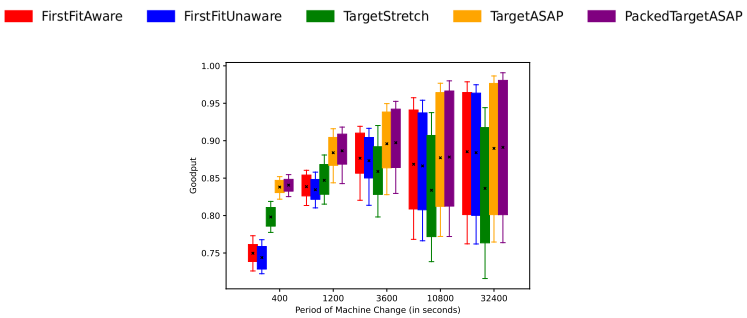
Varying the number of machines



BORG

- FIRSTFITAWARE and FIRSTFITUNAWARE never good
- TARGETSTRETCH: different behavior because of its lack of flexibility, some machines remain partially inactive even when jobs are waiting (better with fewer machines)
- TARGETASAP always good, and packed variant PACKEDTARGETASAP even better

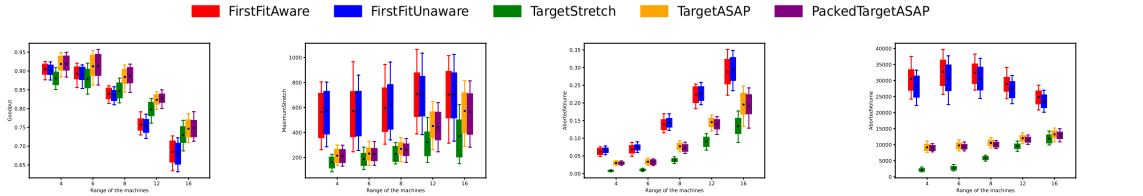
Varying the period of machine variation



BORG

- With low period (many changes), TARGETSTRETCH better by preserving long jobs
- Goodput increases with period: less changes ⇒ less job interruptions
- Better relative performance of TARGETASAP and PACKEDTARGETASAP with low periods (= high variability)

Exploring other metrics (Borg)



GOODPUT MAXIMUMSTRETCH ABORTEDVOLUME AVERAGEABORTEDTIME

- Increase in range ⇒ Degradation of the metric
- TARGETSTRETCH: lowest maximum stretch, as well as low aborted volume and time
- However, low utilization of machines for TARGETSTRETCH, with low goodput

Conclusion for this case study

- A simple case-study of scheduling with variable capacity resources
- Primary challenge: when capacity decreases, running jobs need to be terminated to meet required power load reduction
- Online risk-aware scheduling strategies to preserve performance:
  map the right job to the right machine
- Algorithmic techniques: risk index per machine, mapping longer jobs to safer machines, maintaining local queues at machines, re-executing interrupted jobs on new machines, and redistributing pending jobs as resource capacity increases
- Significant gains over first-fit algorithms with up to 10% increase in goodput, and better performance in complementary metrics (maximum and average stretch)

Outline

Model

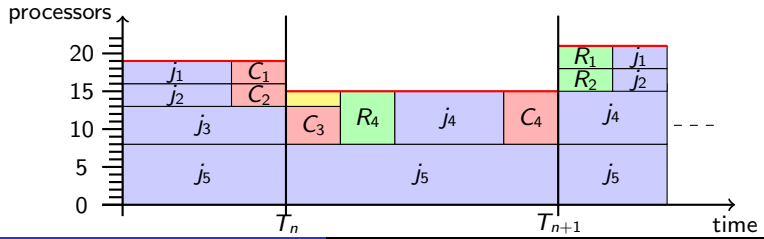
Problem: Scheduling infinite parallel rigid jobs under variable number of processors, during each *section*

Hypotheses:

- A job can be checkpointed and recovered
- Knowledge of the duration of each section, and bound on #proc difference

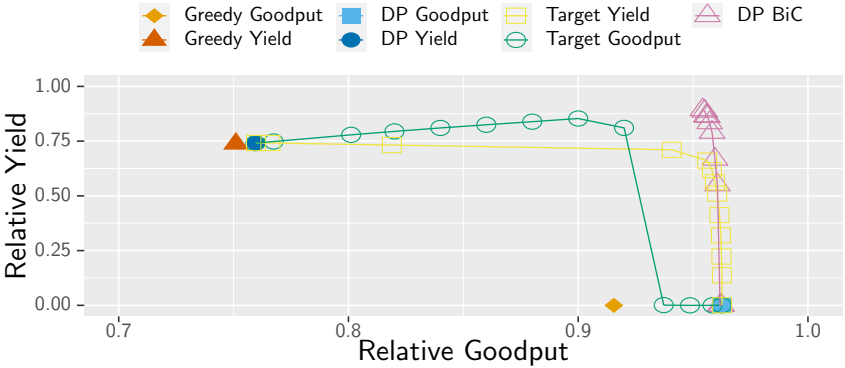
Additional constraint:

- Never lose work (i.e., checkpoint enough before section change, and never shut off a non-checkpointed job)



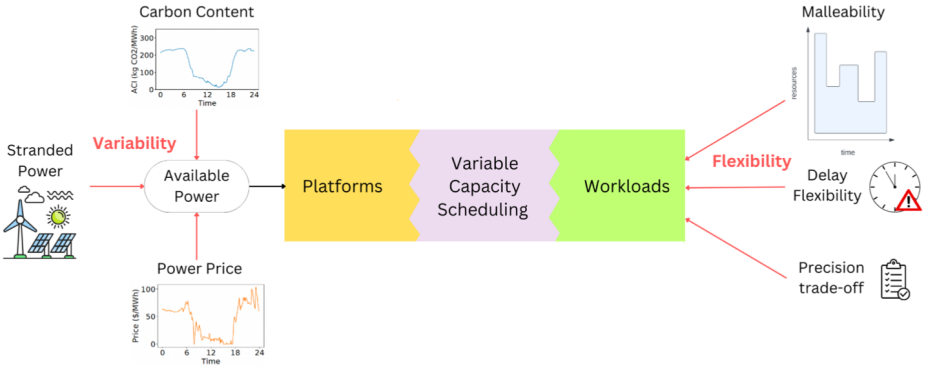
Algorithms

- Sophisticated dynamic programming algorithms to optimize goodput and/or yield at the end of a section
- Evaluation on job traces
- Improvement of novel strategies over greedy approaches



Outline

Back to the big picture



Many challenging scheduling problems ☺

Workshop report: *Scheduling Variable Capacity Resources for Sustainability*
March 29-31, 2023, U. Chicago Paris Center

Take-aways

- Today's case study: restricted instance ☹
  Risk-Aware Scheduling Algorithms for Variable Capacity Resources;
  PMBS workshop at SC'23
- With checkpoints: Many assumptions – knowledge of period changes, bound on machine variation

- In some particular settings, possible to design clever ad-hoc solutions
- Instantiate problems from real case studies, good performance

Future research directions

- Relax some hypothesis to explore further problems
- Explore other kinds of jobs: in particular moldable jobs
- Study other objective functions (carbon emissions, memory, etc.)

- Within FONDA: workflow scheduling, adaptive scheduling
  (while we have independent tasks in a static setting in what I presented)

Thanks to my colleagues Henri Casanova, Arnaud Legrand, and Yves Robert,
from whom I borrowed some slides ☺