Energy-aware checkpointing of divisible tasks with soft or hard deadlines

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Divisible load scheduling and resilience

- Divisible load scheduling: divide a computational workload into chunks
  - Arbitrary number of chunks
  - Size of chunks freely chosen by user
- Goal: minimize makespan, i.e., total execution time

- Current platforms: increasing frequency of failures
- Well-established method to deal with failures: checkpointing
- Take a checkpoint at the end of each chunk and verify result
- Re-execution in case of transient failure

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Energy: a crucial issue

- IGCC: Green Computing Conference!
- Real need to reduce energy dissipation in current processors
- Processor running at speed s: power s^3 watts
- Dynamic voltage and frequency scaling techniques (DVFS)

- Our goal: minimize energy consumption
  - including that of checkpointing and re-execution (if failure)
  - while enforcing a bound on execution time

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Outline

Framework

- Execution of a divisible task (W operations)
- Failures may occur
  - Transient faults
  - Resilience through checkpointing
- Objective: minimize expected energy consumption $\mathbb{E}(E)$, given a deadline bound D

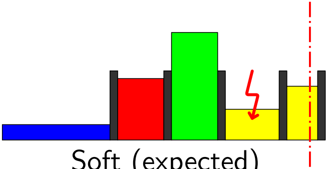
- Probabilistic nature of failure hits: expectation of energy consumption is natural (average cost over many executions)
- Deadline bound: two relevant scenarios (soft or hard deadline)

Soft vs hard deadline

- Soft deadline: met in expectation, i.e., $\mathbb{E}(T) \leq D$ (average response time)
- Hard deadline: met in the worst case, i.e., $T_{wc} \leq D$

Hard (worst-case)

VS



Soft (expected)

Execution time, one single chunk

One single chunk of size W

- Checkpoint overhead: execution time T_C
- Instantaneous failure rate: λ

- First execution at speed s: $T_{\text{exec}} = \frac{W}{s} + T_C$
- Failure probability: $P_{\text{fail}} = \lambda T_{\text{exec}} = \lambda(\frac{W}{s} + T_C)$
- In case of failure: re-execute at speed σ: $T_{\text{reexec}} = \frac{W}{\sigma} + T_C$
- And we assume success after re-execution

- $\mathbb{E}(T) = T_{\text{exec}} + P_{\text{fail}} T_{\text{reexec}} = (\frac{W}{s} + T_C) + \lambda(\frac{W}{s} + T_C)(\frac{W}{\sigma} + T_C)$
- $T_{wc} = T_{\text{exec}} + T_{\text{reexec}} = (\frac{W}{s} + T_C) + (\frac{W}{\sigma} + T_C)$

Energy consumption, one single chunk

One single chunk of size W

- Checkpoint overhead: energy consumption E_C

- First execution at speed s: $\frac{W}{s} \times s^3 + E_C = Ws^2 + E_C$
- Re-execution at speed σ: $W\sigma^2 + E_C$, with probability P_{fail} $\left(P_{\text{fail}} = \lambda T_{\text{exec}} = \lambda(\frac{W}{s} + T_C)\right)$

- $\mathbb{E}(E) = (Ws^2 + E_C) + \lambda\left(\frac{W}{s} + T_C\right)\left(W\sigma^2 + E_C\right)$

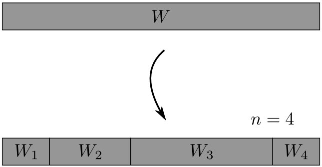
Multiple chunks

- Execution times: sum of execution times for each chunk (worst-case or expected)
- Expected energy consumption: sum of expected energy for each chunk
- Coherent failure model: consider two chunks $W_1 + W_2 = W$
- Probability of failure for first chunk: $P^1_{\text{fail}} = \lambda(\frac{W_1}{s} + T_C)$
- For second chunk: $P^2_{\text{fail}} = \lambda(\frac{W_2}{s} + T_C)$
- With a single chunk of size W: $P_{\text{fail}} = \lambda(\frac{W}{s} + T_C)$, differs from $P^1_{\text{fail}} + P^2_{\text{fail}}$ only because of extra checkpoint
- Trade-off: many small chunks (more T_C to pay, but small re-execution cost) vs few larger chunks (fewer T_C, but increased re-execution cost)

Optimization problem

- Decisions that should be taken before execution:
  - Chunks: how many (n)? which sizes (W_i for chunk i)?
  - Speeds of each chunk: first run (s_i)? re-execution (σ_i)?

- Input: W, T_C (checkpointing time), E_C (energy spent for checkpointing), λ (instantaneous failure rate), D (deadline)



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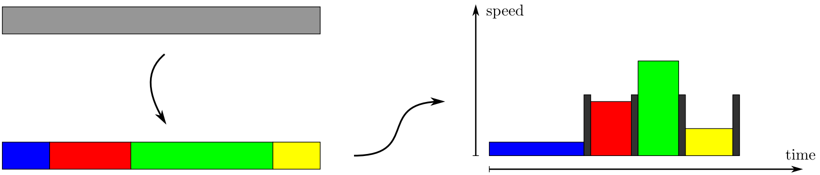

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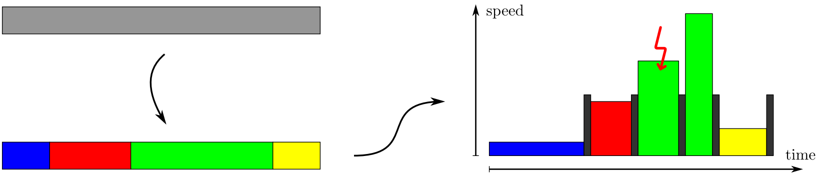


Models

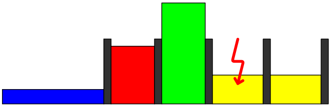
- Chunks

Single chunk of size W

VS

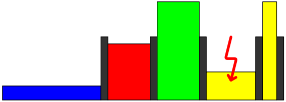
Multiple chunks (n and W_i's)

- Speed per chunk



Single speed (s)

VS

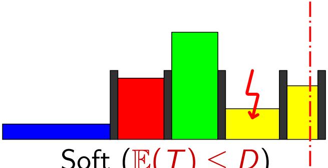


Multiple speeds (s and σ)

- Deadline bound

Hard ($T_{wc} \leq D$)

VS



Soft ($\mathbb{E}(T) \leq D$)

Outline

Single chunk and single speed

Consider first that $s = \sigma$ (single speed): need to find optimal speed

- $\mathbb{E}(E)$ is a function of s:
$$\mathbb{E}(E)(s) = (Ws^2 + E_C)(1 + \lambda(\frac{W}{s} + T_C))$$
- Lemma: this function is convex and has a unique minimum $s^\star$ (function of λ, W, E_c, T_c)
$$s^\star = \frac{\lambda W}{6(1+\lambda T_C)}\left(\frac{-(3\sqrt{3}\sqrt{27a^2-4a}-27a+2)^{1/3}}{2^{1/3}} - \frac{2^{1/3}}{(3\sqrt{3}\sqrt{27a^2-4a}-27a+2)^{1/3}} - 1\right),$$
where $a = \lambda E_C \left(\frac{2(1+\lambda T_C)}{\lambda W}\right)^2$
- $\mathbb{E}(T)$ and T_{wc}: decreasing functions of s
- Minimum speed s_{exp} and s_{wc} required to match deadline D (function of D, W, T_c, and λ for s_{exp})

$\rightarrow$ Optimal speed: maximum between $s^\star$ and s_{exp} or s_{wc}

Single chunk and multiple speeds

Consider now that $s \neq \sigma$ (multiple speeds): two unknowns

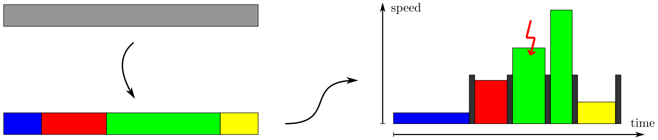
- $\mathbb{E}(E)$ is a function of s and σ:
  $$\mathbb{E}(E)(s,\sigma) = (Ws^2 + E_C) + \lambda(\frac{W}{s} + T_C)(W\sigma^2 + E_C)$$
- Lemma: energy minimized when deadline tight
  (both for wc and exp)
- $\leadsto$ σ expressed as a function of s:
  $$\sigma_{exp} = \frac{\lambda W}{\frac{D}{\frac{W}{s}+T_C} - (1+\lambda T_C)}, \quad \sigma_{wc} = \frac{W}{(D-2T_C)s - W}s$$

$\rightarrow$ Minimization of single-variable function, can be solved numerically (no expression of optimal s)

Outline

General problem with multiple chunks

- Divisible task of size W
- Split into n chunks of size W_i: $\sum_{i=1}^{n} W_i = W$
- Chunk i is executed once at speed s_i, and re-executed (if necessary) at speed σ_i
- Unknowns: n, W_i, s_i, σ_i
- $\mathbb{E}(E) = \sum_{i=1}^{n} \left(W_i s_i^2 + E_C\right) + \lambda \sum_{i=1}^{n} \left(\frac{W_i}{s_i} + T_C\right) \left(W_i \sigma_i^2 + E_C\right)$



Multiple chunks and single speed

With a single speed, $\sigma_i = s_i$ for each chunk

- Theorem: in optimal solution, n equal-sized chunks ($W_i = \frac{W}{n}$), executed at same speed $s_i = s$
  - Proof by contradiction: consider two chunks W_1 and W_2 executed at speed s_1 and s_2, with either $s_1 \neq s_2$, or $s_1 = s_2$ and $W_1 \neq W_2$
  - $\Rightarrow$ Strictly better solution with two chunks of size $w = (W_1 + W_2)/2$ and same speed s

- Only two unknowns, s and n
- Minimum speed with n chunks: $s^{\star}_{exp}(n) = W \frac{1 + 2\lambda T_C + \sqrt{4\frac{\lambda D}{n} + 1}}{2(D - nT_C(1 + \lambda T_C))}$

$\rightarrow$ Minimization of double-variable function, can be solved numerically both for expected and hard deadline

Multiple chunks and multiple speeds

Need to find n, W_i, s_i, σ_i

- With expected deadline:
  - All re-execution speeds are equal ($\sigma_i = \sigma$) and tight deadline
  - All chunks have same size and are executed at same speed
- WIth hard deadline:
  - If $s_i = s$ and $\sigma_i = \sigma$, then all W_i's are equal
  - Conjecture: equal-sized chunks, same first-execution / re-execution speeds
- σ as a function of s, bound on s given n

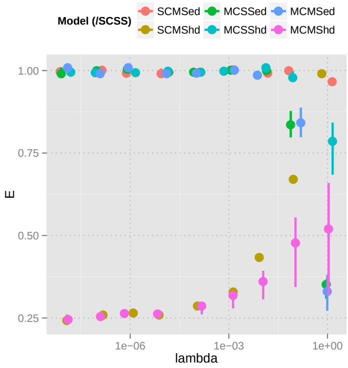
$\rightarrow$ Minimization of double-variable function, can be solved numerically

Outline

Simulation settings

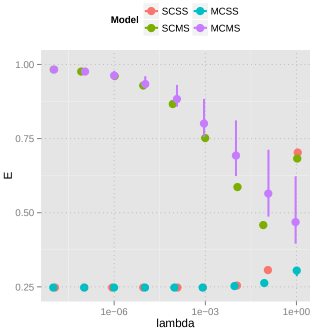
- Large set of simulations: illustrate differences between models
- Maple software to solve problems
- We plot relative energy consumption as a function of λ
  - The lower the better
  - Given a deadline constraint (hard or expected), normalize with the result of single-chunk single-speed
  - Impact of the constraint: normalize expected deadline with hard deadline
- Parameters varying within large ranges

Comparison with single-chunk single-speed



- Results identical for any value of W/D
- For expected deadline, with small λ ($< 10^{-2}$), using multiple chunks or multiple speeds do not improve energy ratio: re-execution term negligible;
  increasing λ: improvement with multiple chunks
- For hard deadline, better to run at high speed during second execution: use multiple speeds; use multiple chunks if frequent failures

Expected vs hard deadline constraint



- Important differences for single speed models, confirming previous conclusions: with hard deadline, use multiple speeds
- Multiple speeds: no difference for small λ: re-execution at maximum speed has little impact on expected energy consumption;
  increasing λ: more impact of re-execution, and expected deadline may use slower re-execution speed, hence reducing energy consumption

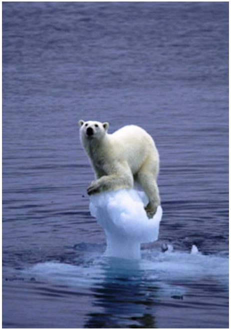
Outline

Conclusion

- Energy consumption of a divisible load workload on volatile platforms
- Soft or hard deadline constraint

- Theoretical side:
  - Formal models for the problem
  - Expression of solutions as functions to minimize
  - With multiple chunks, use same size chunks, same speed, and same re-execution speed (conjecture for multiple-speed hard-deadline)

- Simulations:
  - Single-chunk single-speed is very good for expected deadline
  - Hard deadline and small λ: use multiple speeds
  - Large values of λ: use multiple speeds and multiple chunks

What we had: 

Energy-aware checkpointing
+
frequency scaling

What we aim at: