Combing Partial Redundancy and Checkpointing for HPC

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Motivation

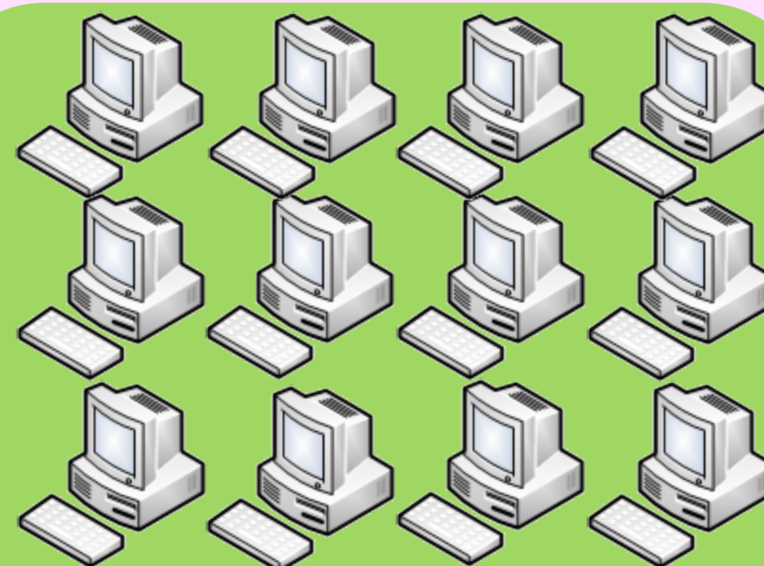
- Target:
  - High Performance Computing (HPC)
  - Assumes *capability computing* (uses entire system)
- Systems classified by floating point operations per second (FLOPS)
  - teraflop : 10^{12}; petaflop : 10^{15}; exaflop : 10^{18}
  - terascale 1990s, petascale 2008-, exascale ?
- Trends
  - Roadrunner: 1 petaflops 2008
  - K: 10 petaflops 2011
  - Sequoia: 16.32 petaflops 2012
  - Exascale by 2020
    - Top500 projection

Motivation

Assumes capability computing (using entire system)

Components have reliability

- Reliability follows a statistical distribution e.g., Exponential
- Mean Time Before Failure
  MTBF denoted as θ
- Nodes form a **system**, with **system MTBF** Θ

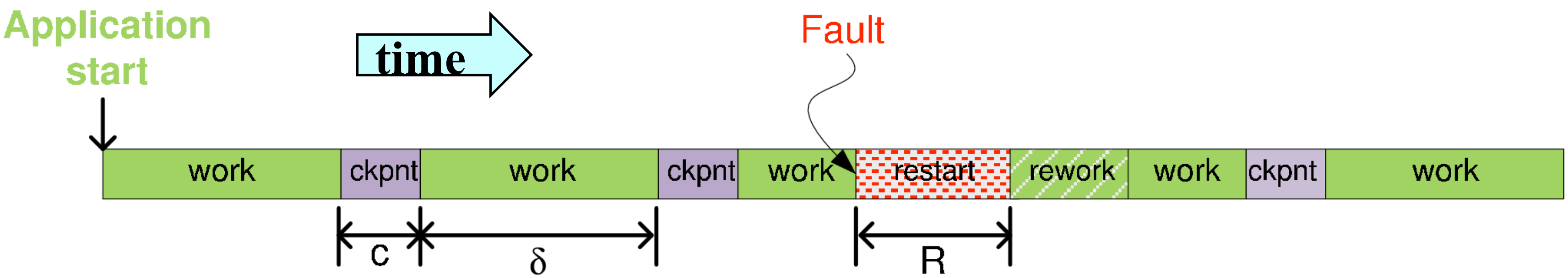


Θ = 43,800 hr.

Θ : <u>**System**</u> MTBF

Assume a node has 5yr MTBF (θ = 43,800 hours)

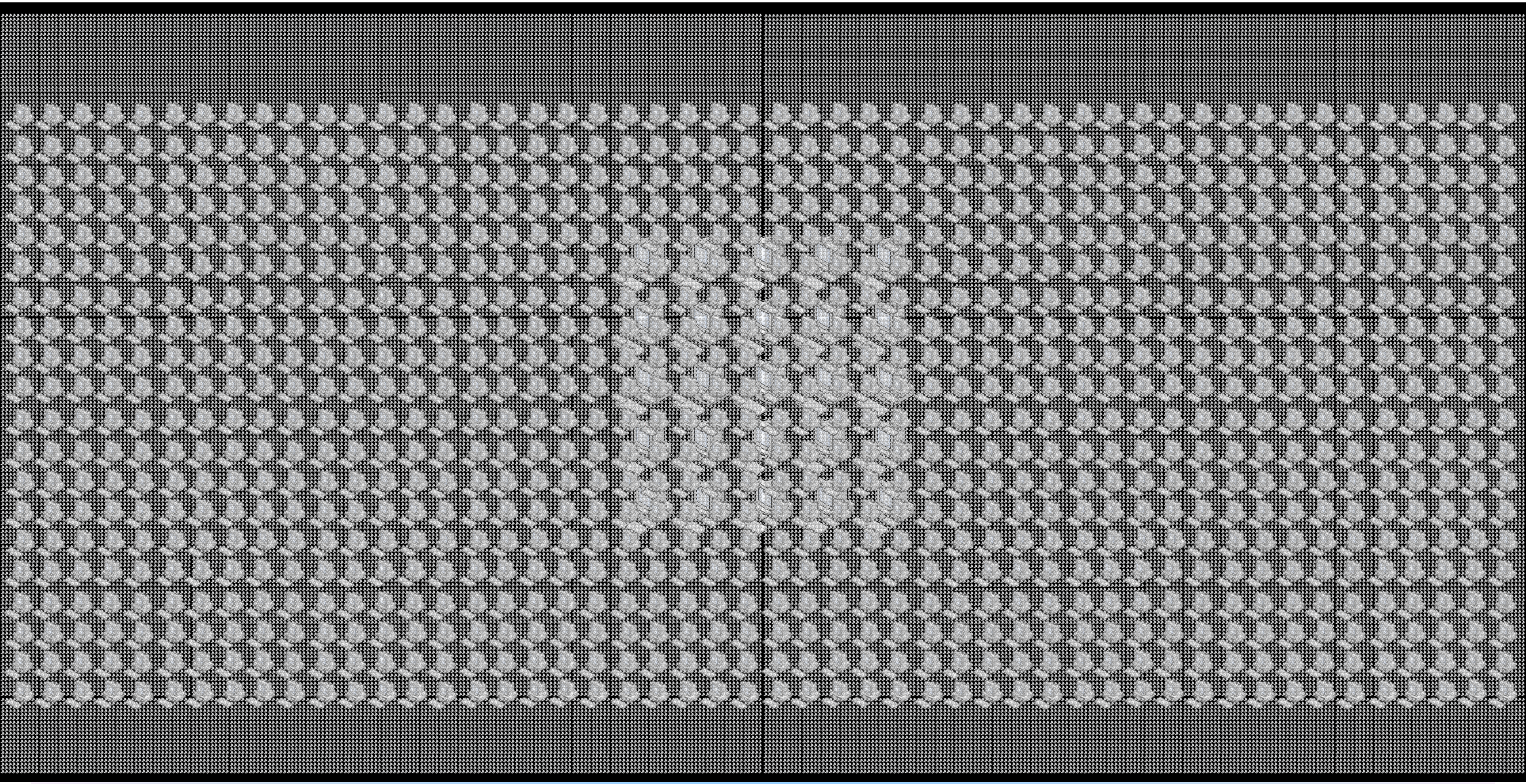
Motivation



Checkpoint Restart (C/R)

- Enable unreliable systems to complete jobs that exceed the system's reliability.
  e.g., job runtime > system MTBF
- C/R has no impact on system reliability
- ***Any component fails => application fails***
- Idea: periodically save state (**checkpoint**), if failure occurs: load prev chkpt and **restart**
- I/O from parallel file system (not local disk)

Motivation



N = 250,000 Θ = 1.75 hr. δ = 6 min.

At petascale 50yr node MTBF (438,000 hours)

Motivation

- Scalability limitations of Checkpoint/Restart

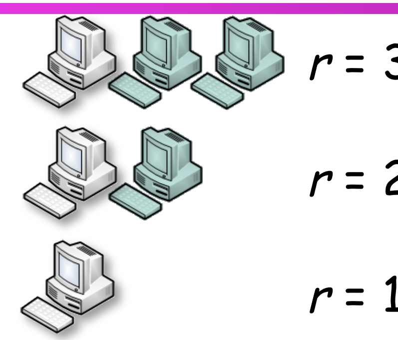
No. of Nodes	Work	Checkpoint	Re-computation	Restart
[illegible]	[illegible]	[illegible]	[illegible]	0%
1,000	92%	7%	1%	0%
10,000	75%	15%	6%	4%
100,000	35%	20%	10%	35%

Less than 50% time spent doing meaningful work

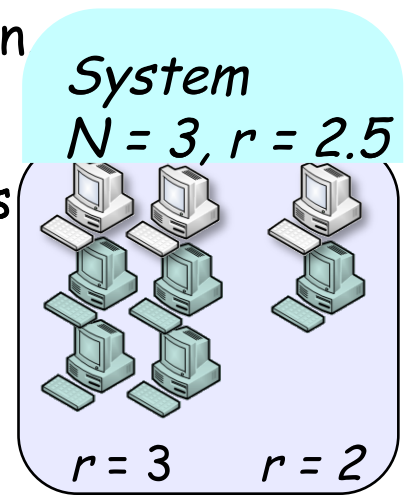
- Redundancy is expensive: **Is it advantageous to use various degrees of redundancy in conjunction with C/R to minimize job execution time?**
- **Can this relationship be modeled analytically?**
- **What are the *optimal parameters* for degree of redundancy and checkpoint interval to achieve the *lowest wallclock* time?**
- **Goal: maximize time spent in useful application work**
  - **not fault tolerance code.**

Redundancy and Partial Redundancy

- Virtual process: contains ***r*** physical processes
  - — in a parallel (redundant) configuration.



- ***r*** *:= degree of redundancy.*
  - — State machine replication.
  - — Active and redundant nodes perform same computation.
  - — Upon failure, replica process takes over execution
  - — Substantial **increase** in process MTBF.

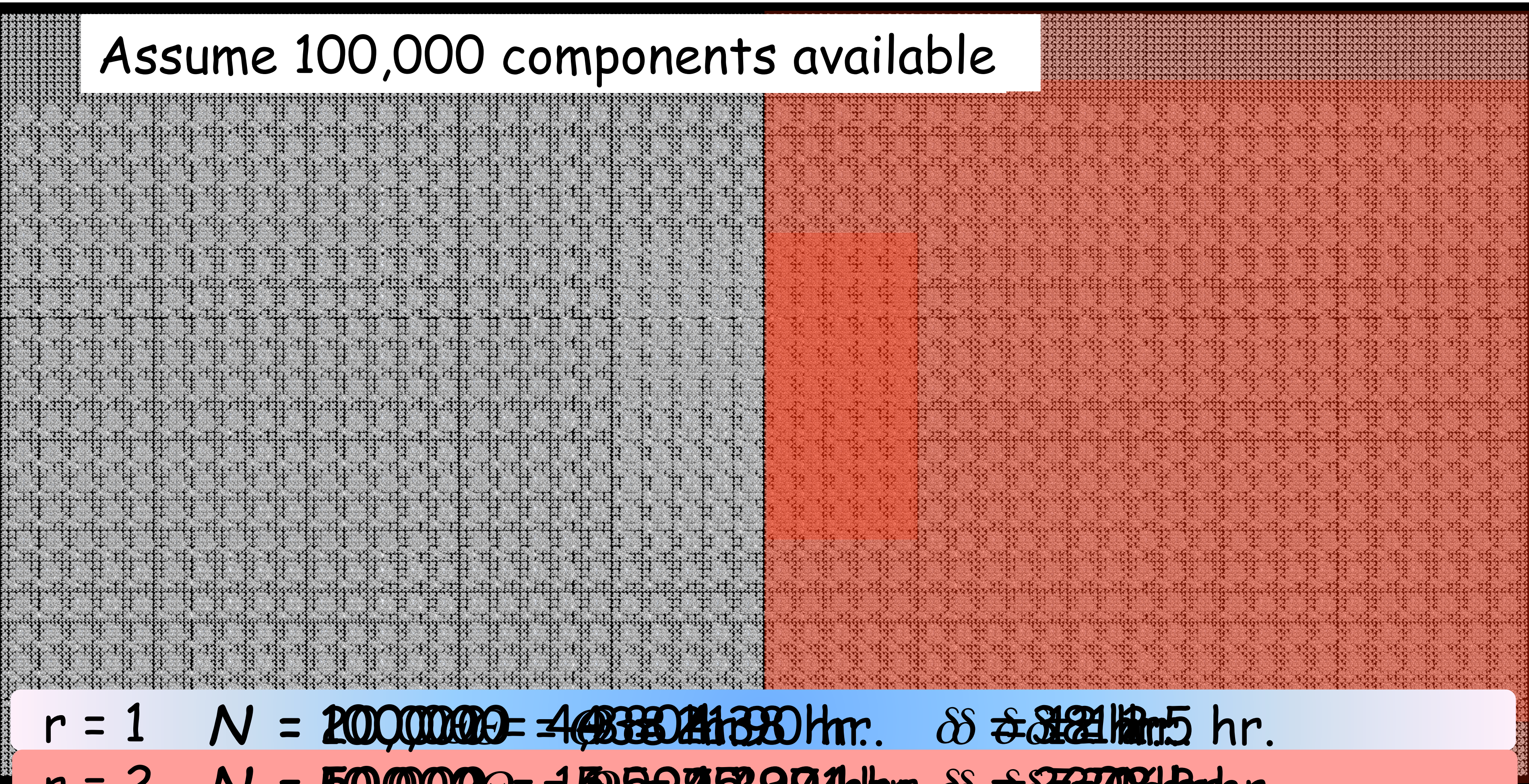


- A system of ***N*** virtual processes connected in a series configuration (**single failure = total system failure**)
- Traditional redundancy: all *N* virtual processes

  have same *r* and *r* must be a positive integer.
- **Partial redundancy**, *N* virtual processes have **ceiling(r)** or **floor(r)** level of redundancy, *r* may be a real number ≥ 1

Motivation Revisited

Assume 100,000 components available



r = 1 N = [illegible] θ = [illegible] hr. δ = [illegible] hr.

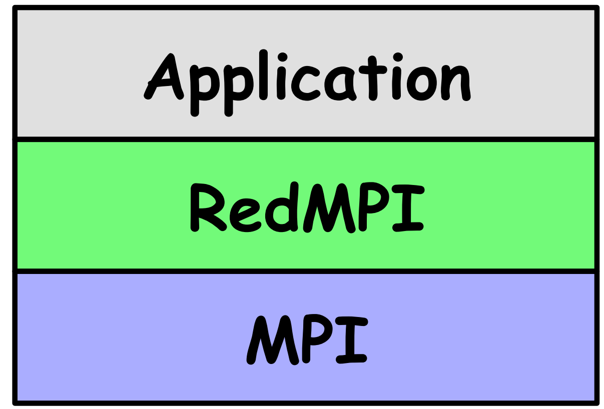
r = 2 N = [illegible] θ = [illegible] hr. δ = [illegible] hr.

(r = 1 N = [illegible] θ = [illegible] hr. δ = [illegible] hr.)

Redundancy improves system reliability

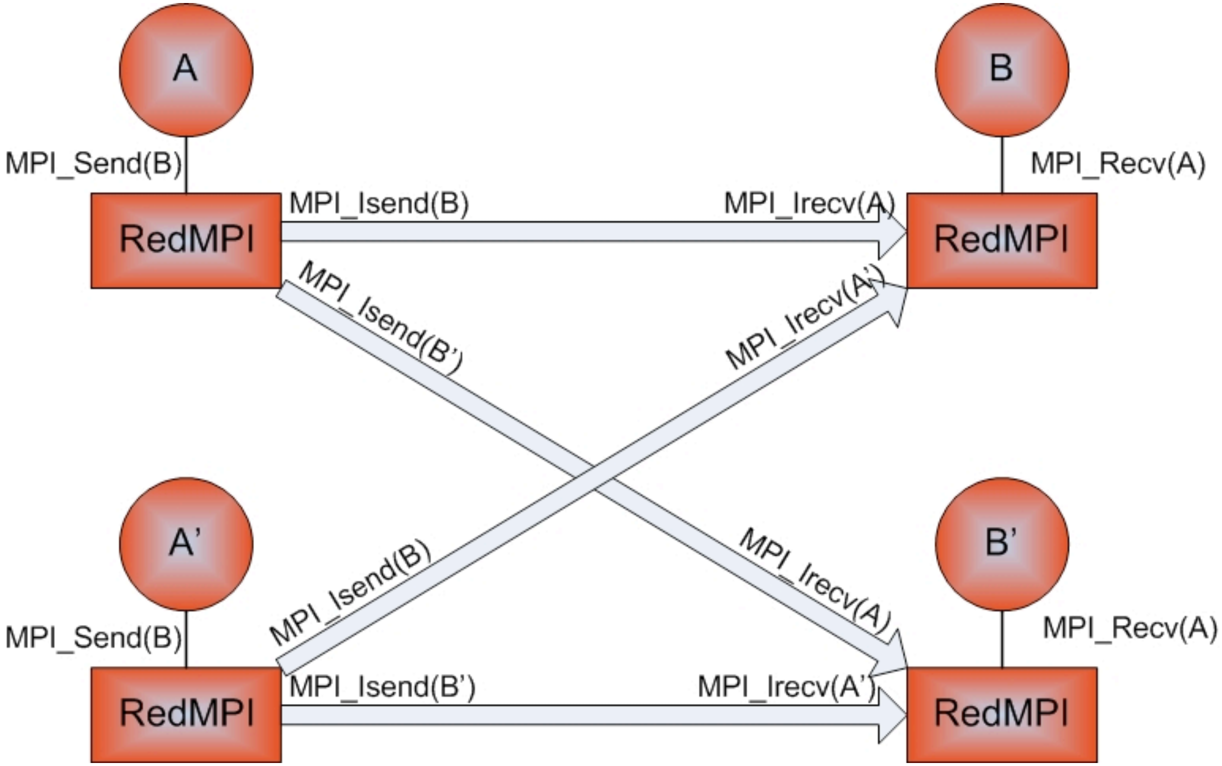
Design of Redundancy

- RedMPI library



- Works at profiling layer
- **Goal**: ensure output is correct
  - Related work already handles file IO (Böhm and Englemann '12)
  - We focus solely on MPI messages
- Intercepts MPI function calls
- MPI_Comm_rank() returns same value for replica processes
- Each redundant copy needs to receive same messages in same order
- Each message is sent/received *r* number of times.

Design of Redundancy: Blocking MPI P2P calls



- MPI_Send() -> MPI_Isend()s
  MPI_Waitall()
- Allocation of additional buffers

Design of Redundancy: Other MPI functions

- Non-blocking MPI calls
  - maintain list of MPI_Requests

- Collectives : e.g. MPI_Bcast(), MPI_Alltoall()
  - use redundant point-to-point calls

- Same info return by MPI_Probe() , MPI_Test() and MPI_Wtime() functions

Modeling Preliminaries

- A physical process (node) follows an exponential failure distribution
  - θ - Mean Time Between Failures (MTBF)
- A system of virtual processes has an exponential failure distribution
  - Θ - system MTBF
  - r - Degree of Redundancy
  - α - Communication to Computation ratio
- Failures arrive following a Poisson process
- ***Redundancy increases the system reliability.***

Modeling Preliminaries

- Effect of Redundancy on Execution Time
  - Application execution time ≥ base execution time
  - Dependent upon many factors
    - Placement of processes, communication to computation ratio, degree of redundancy, relative speed, etc.
  - Consider ideal execution environment:

$$\underbrace{t}_{Total\ time} = \underbrace{\alpha t}_{Communication} + \underbrace{(1-\alpha)t}_{Computation}$$

$$t_{Red} = (\alpha t)r + (1-\alpha)t$$

System Reliability Model

- Probability of failure of a physical node:

$$\Pr(Node\ Failure) = 1 - e^{\frac{-t}{\theta}}$$

$$\Pr(Node\ Failure) = 1 - (1 - t/\theta) = t/\theta$$

- Probability of survival of a virtual node with some integer *k* degree of redundancy

$$\Pr(Virtual\ Node\ Survival) = 1 - \prod_{i=1}^{k} t/\theta = 1 - (t/\theta)^k$$

- Partition *N* virtual processes into sets of real-world redundancy levels

$$N = N_{\lfloor r \rfloor} + N_{\lceil r \rceil}$$

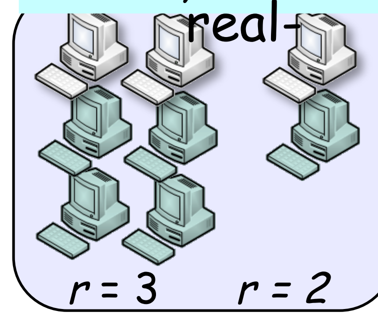
- Reliability of the system may be expressed as

$$\Pr(All\ Virtual\ Processes\ Survive)$$

$$\Pr(All\ N_{\lfloor r \rfloor}\ Processes\ Survive\ \text{and}\ All\ N_{\lceil r \rceil}\ Processes\ Survive)$$

$$R_{sys} = \left[1 - (t_{Red}/\theta)^{\lfloor r \rfloor}\right]^{N_{\lfloor r \rfloor}} \times \left[1 - (t_{Red}/\theta)^{\lceil r \rceil}\right]^{N_{\lceil r \rceil}}$$

System
N = 3, *r* = 2.5



System Reliability Model

- Assuming an Exponential distribution,

$$R_{sys} = e^{-\lambda_{sys} t_{Red}}$$

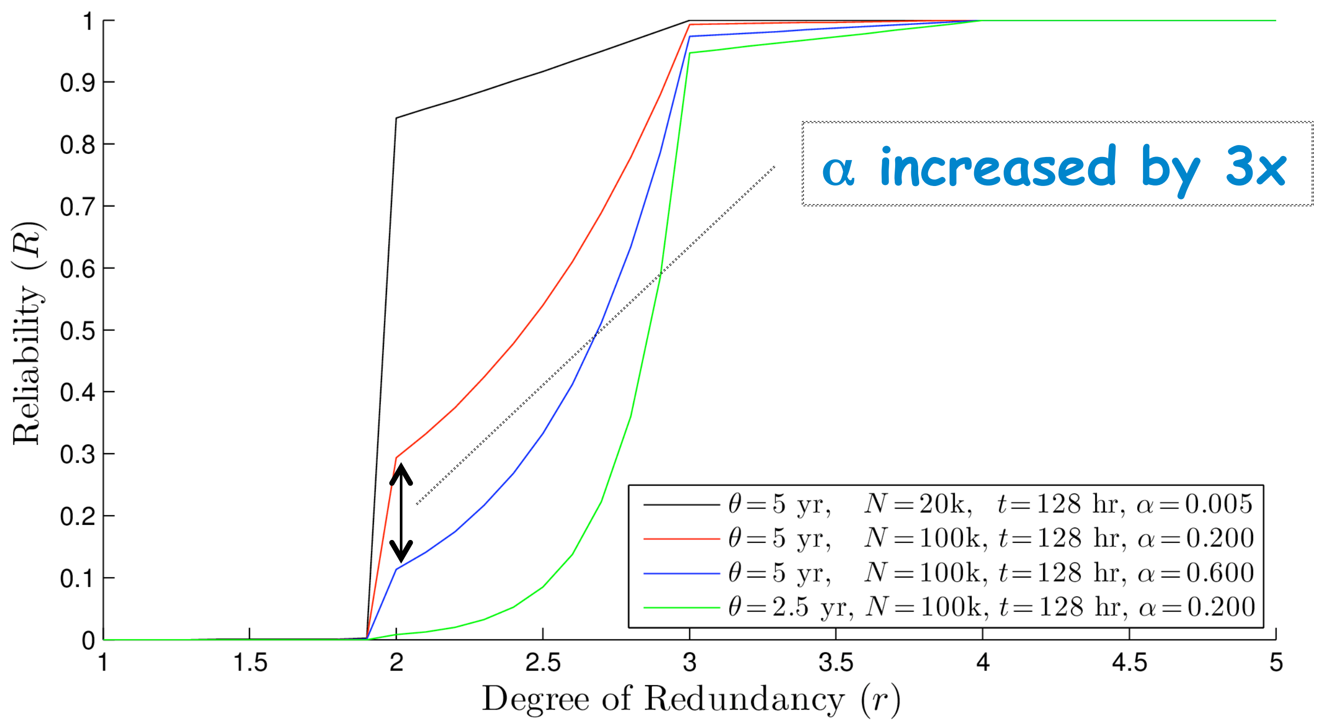
- The system failure rate is

$$\lambda_{sys} = -\ln R_{sys} / t_{Red}$$

- System MTBF is

$$\Theta_{sys} = \frac{1}{\lambda_{sys}}$$

Effect of Redundancy on Reliability



- Reliability spikes at whole number redundancy levels
  - (stepping function as component count increases)
- Reliability now depends on Communication to Computation ratio
  - **Time is a function of alpha**

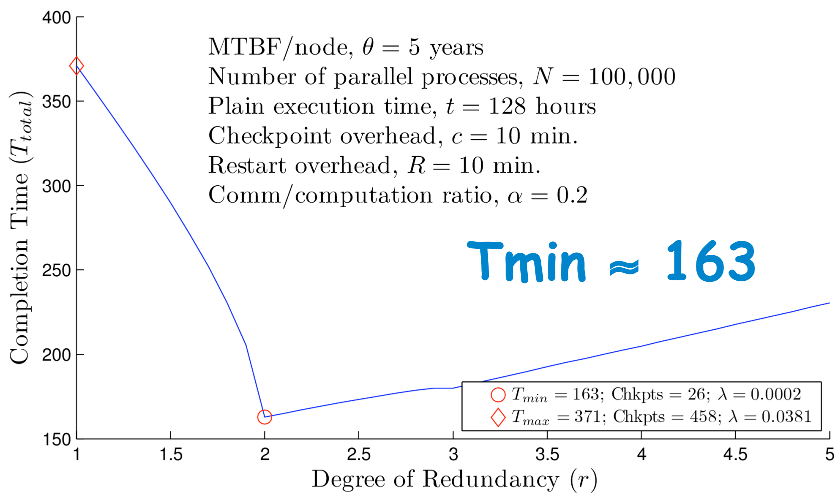
Mathematical Analysis

- Using system MTBF, optimal checkpoint interval may be calculated from Daly (Daly 2003)
- Cost function to compute total wallclock time derived by
  - Computing expected lost work
  - Computing amount of rework using lost work.
  - Total time = t + num_chkpts*chkpt_overhead + rework
- Formally,
  - ***c*** – time to write a checkpoint to storage
  - ***R*** – time to load a checkpoint from storage
  - δ - *optimal checkpoint interval*

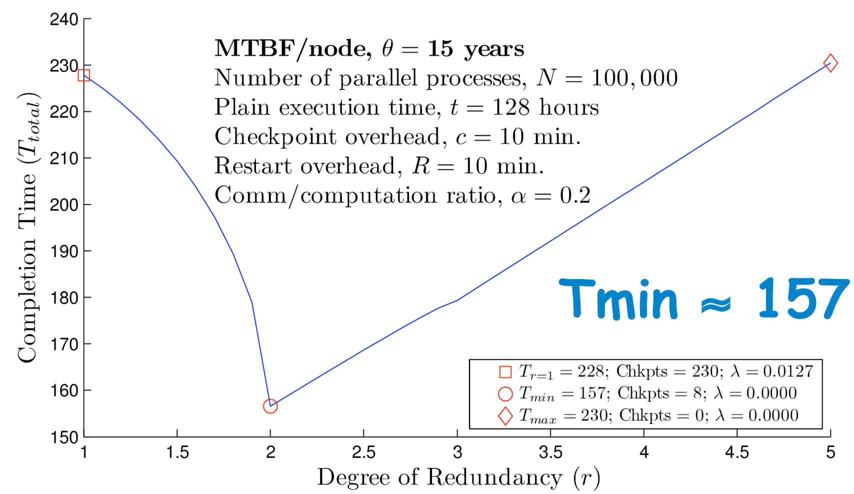
$$T_{total} = \frac{t_{Red} + \frac{t_{Red} \times c}{\delta}}{1 - \lambda_{sys} \times t_{ReWork}}$$

Model Evaluation

Base Configuration



Increased node MTBF

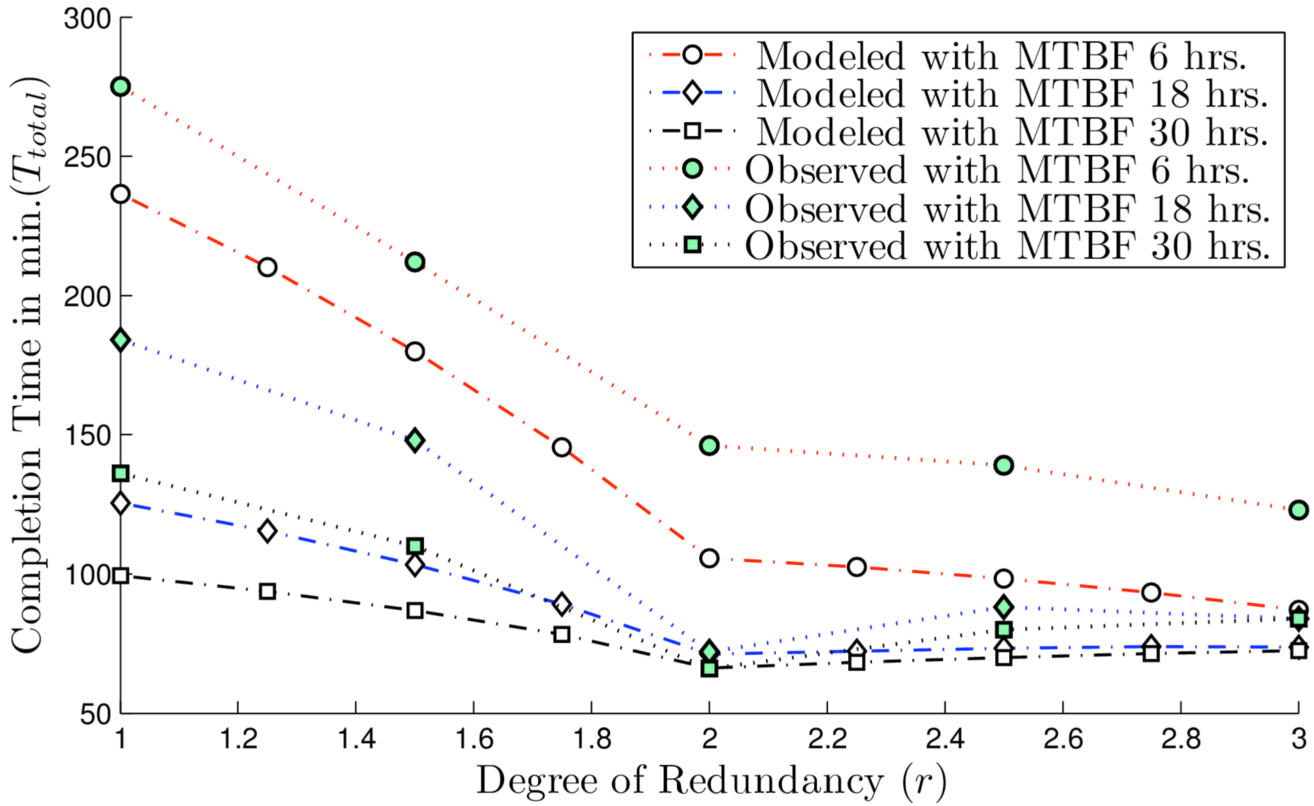


Minimum runtime similar, even though components are 3x less reliable.

Simulation Environment

- Architecture:
  - 108 node cluster (w/ 16 cores each)
  - QDR Infiniband
  - 2-socket shared-memory nodes
  - octo-core AMD Opterons per socket
- OpenMPI, BLCR, RedMPI
- NPB-CG, class D for 128 processes
- Base execution time: 46 min.
- MTBF: 6 hrs, 12 hrs, … 30 hrs
- Redundancy degree: 1x, 1.25x, 1.5x, … 3x

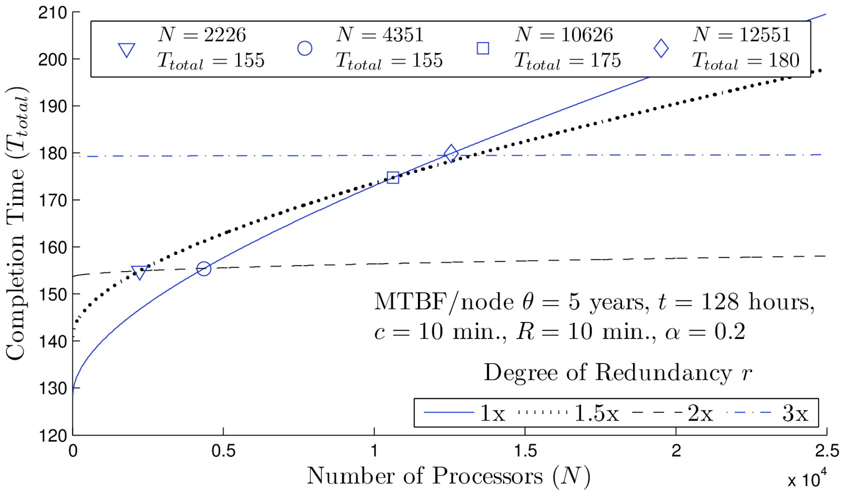
Results – Model vs. Experiment

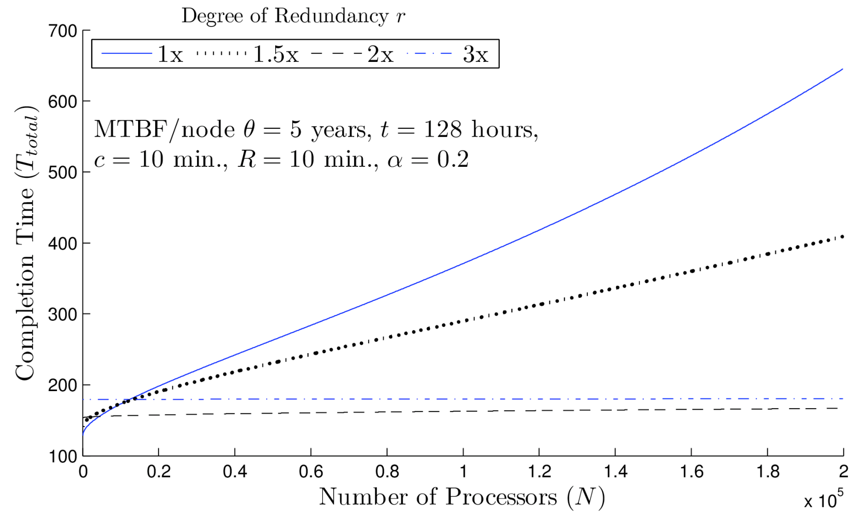


- Experiments agree with model (+ additive const)
  - **minimum runtime always achieved at 2x redundancy**

Results – Optimal Redundancy Level

- Determine when a redundancy level becomes beneficial
  - Assumes weak scaling





- Dual redundancy may be beneficial now
  - At 78,536 processes, **two dual redundant jobs** of 128 hours **can be run in the time of just one job without redundancy**.

Results – Extrapolation based on Jaguar

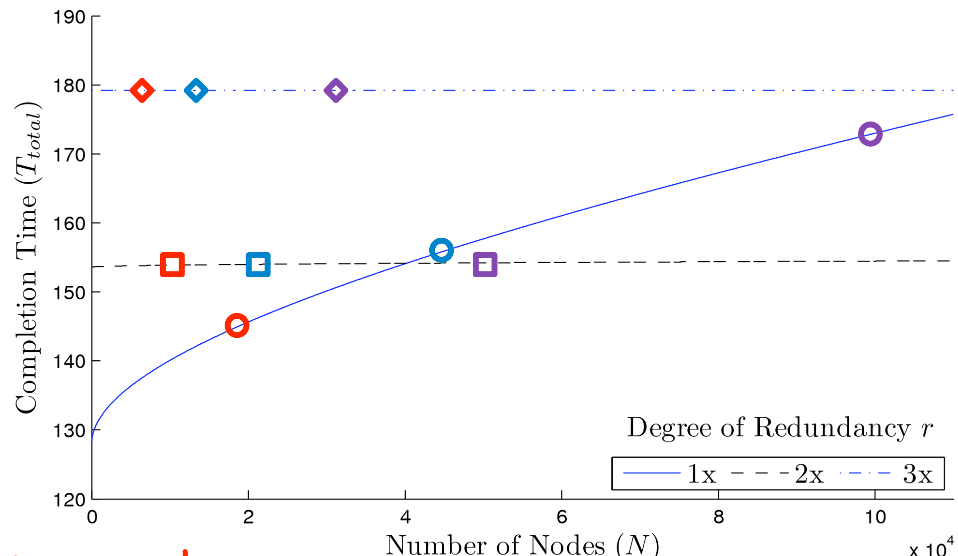
SDC – Silent Data Corruption – bit flips due to radiation, etc,…

ECC (error correcting code), correct single bit flip, detect double, triple

no protection.

- Jaguar: node MTBF ~ 50 years (on 18,688 nodes)
- K-Computer: has 2.3X more components (equiv. 44,064)
- Exascale: lane 1: ~100k nodes

	○ $r = 1$	□ $r = 2$	◇ $r = 3$
Jaguar	**145** (18,688)	154 (9,344)	179 (6,229)
K	156 (44,064)	154 (22,032)	179 (14,688)
Exascale	173 (100,000)	**154** (50,000)	179 (14,688)



- Jaguar: No redundancy necessary yet
- Titan maintains node count/component
  - **increases core count by 33%, adds GPUs→effect?**
- K-Computer: Dual redundancy possibly break-even
- Exascale: dual redundancy offers improves runtime over single,
  - triple redundancy still in the distance, unless SDC considered

Conclusions and Future Work

- Runtime of apps employing redundancy+C/R may be modeled.
  - For a large system or unreliable system
    → redundancy+C/R can achieve significantly shorter runtimes
  - @ 80,000 nodes:
    2x redundancy → 2x # resources but 2x # jobs
    @ exascale: 2x redundancy best!

- Future Work
  - Propose optimal checkpoint model that is redundancy aware
  - Work towards eliminating assumptions
    - exponential failure model of system…

Questions?

- Now is the time to ask.

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  - DOE DE-AC05-00OR22725 as well as by subcontracts from
  - Sandia and
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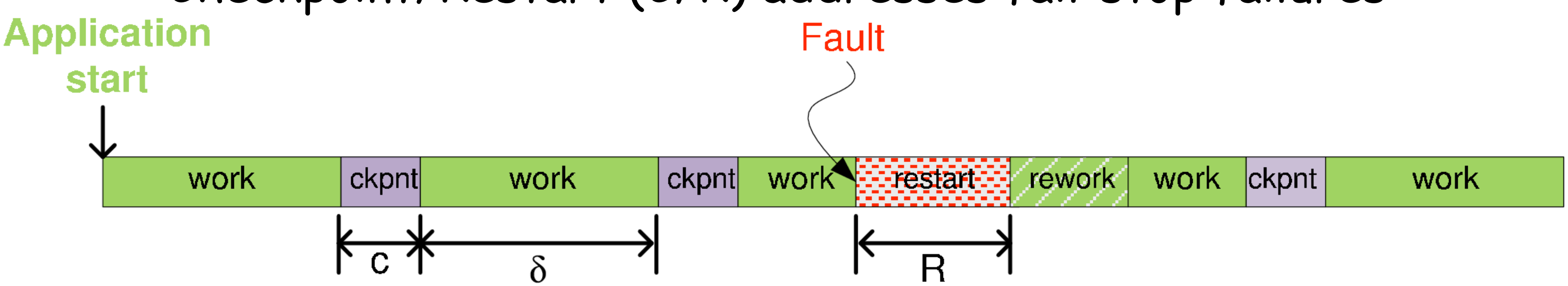
Outline

- Motivation
- Overview of Redundancy and Partial Redundancy
  - Design of Redundancy
  - Preliminaries for Redundancy model and implementation
  - System Reliability Model
  - Effect of Redundancy on Execution Time and Reliability
- Mathematical Analysis
  - Wallclock Model
  - Model Evaluation
- Simulations and Model Comparison
  - Simulations performed on ARC
  - Extrapolated model of Jaguar
- Conclusions and Future Work

Motivation

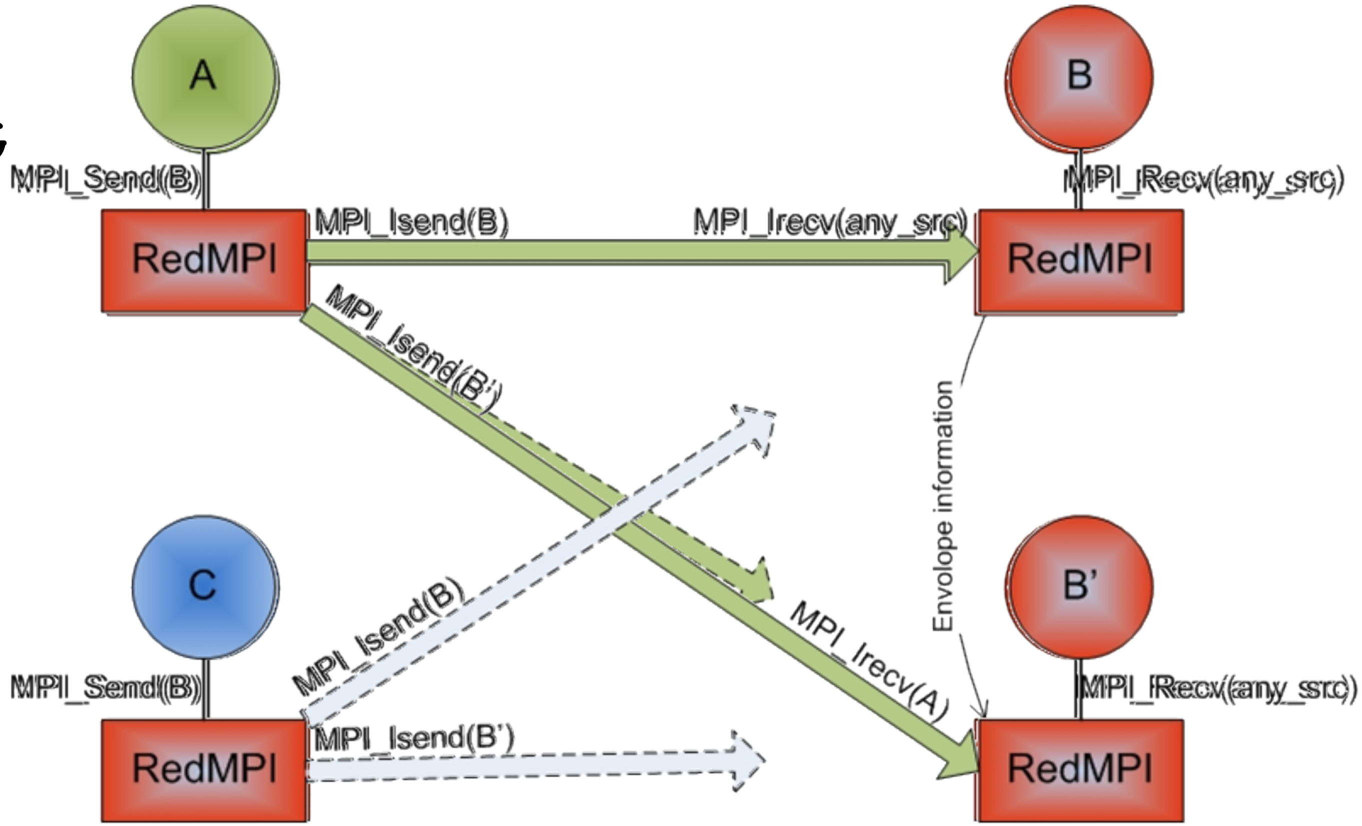
- Fault Tolerance and HPC
  - As # of components in a system increases → likelihood of failure increases
  - Fail-Stop failures
    - Node dies, switch fails,___ => running application fails
  - Checkpoint/Restart (C/R) addresses fail-stop failures



  - Periodically save application state
    - process level checkpoint on each node to shared storage, …
  - In event of failure, reload from last checkpoint

Design of Redundancy: MPI_ANY_SOURCE

- Message ordering requirement
- Primary replica posts MPI_Recv(any_src)
- Other replicas wait for primary
- Similarly for MPI_ANY_TAG

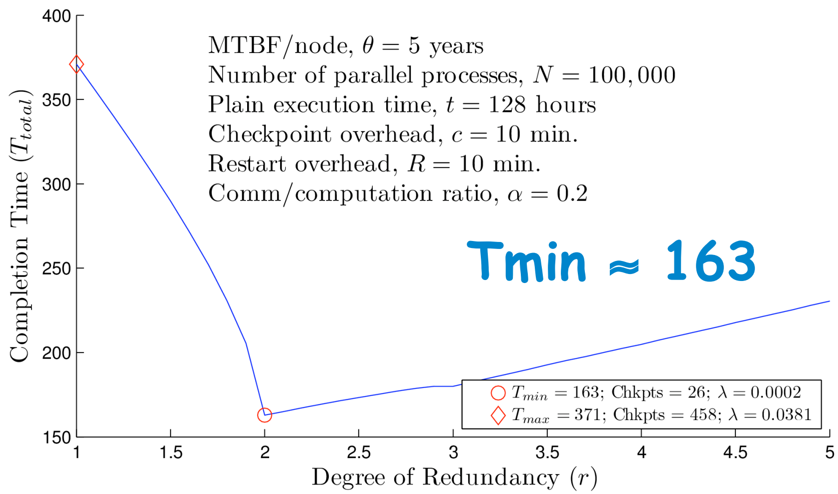


Model Evaluation

Base Configuration

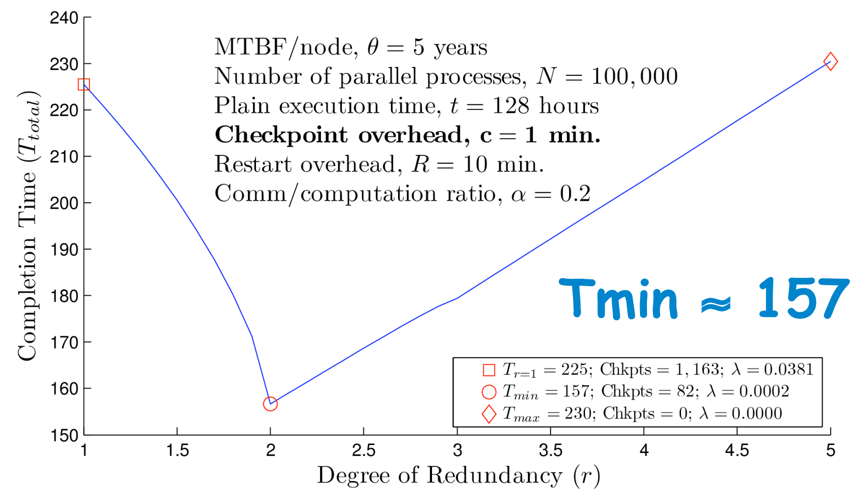
$$\delta_{opt} = 7.2$$

$$= 22.9/\sqrt{(c)} = 22.9/\sqrt{(10)}$$



Decreased Dump Time

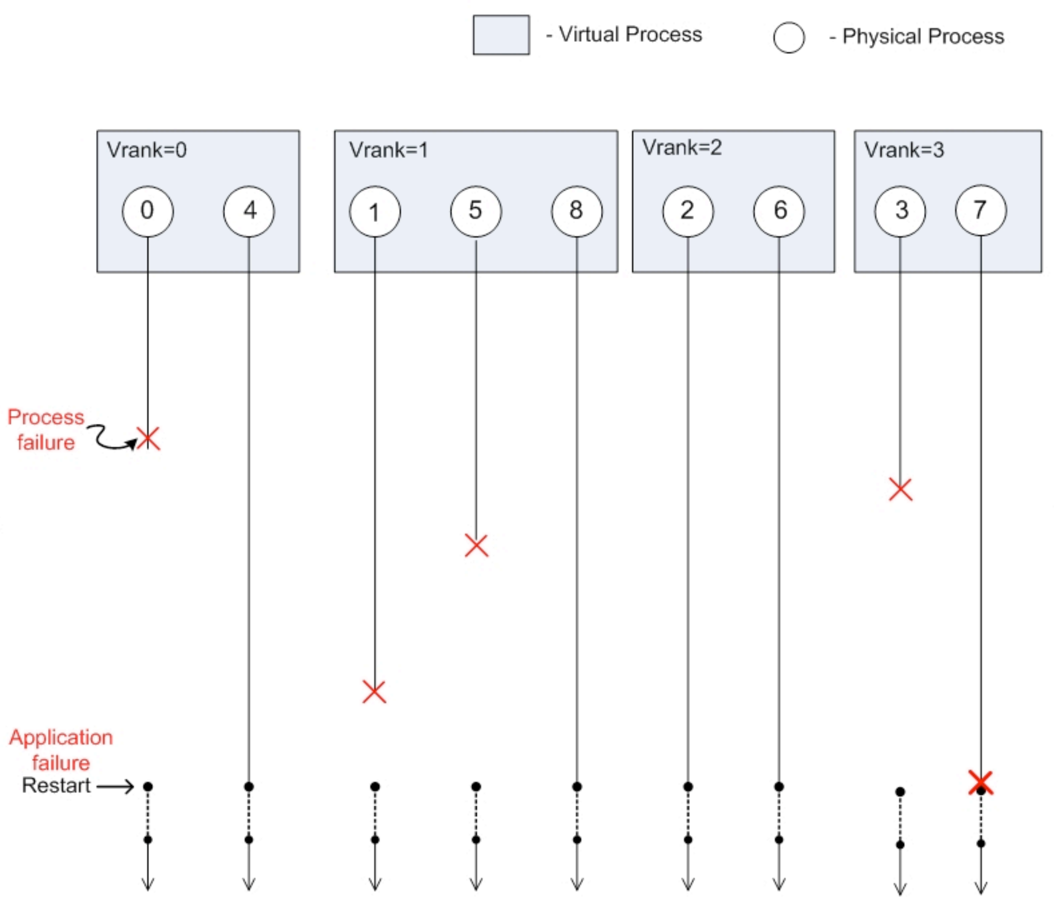
$$\delta_{opt} = 22.9$$



- Similar minimal runtime, even w/ 10X higher dump time
- Lower system MTBF = significantly fewer checkpoints
  - 458 vs 26 and 1,163 vs 82
  - minimizes impact of C/R overhead

Simulation Framework

- Background Processes
  - failure simulator
  - checkpointer
- Scaled down HPC Environment
- Goal : Validate analytical model



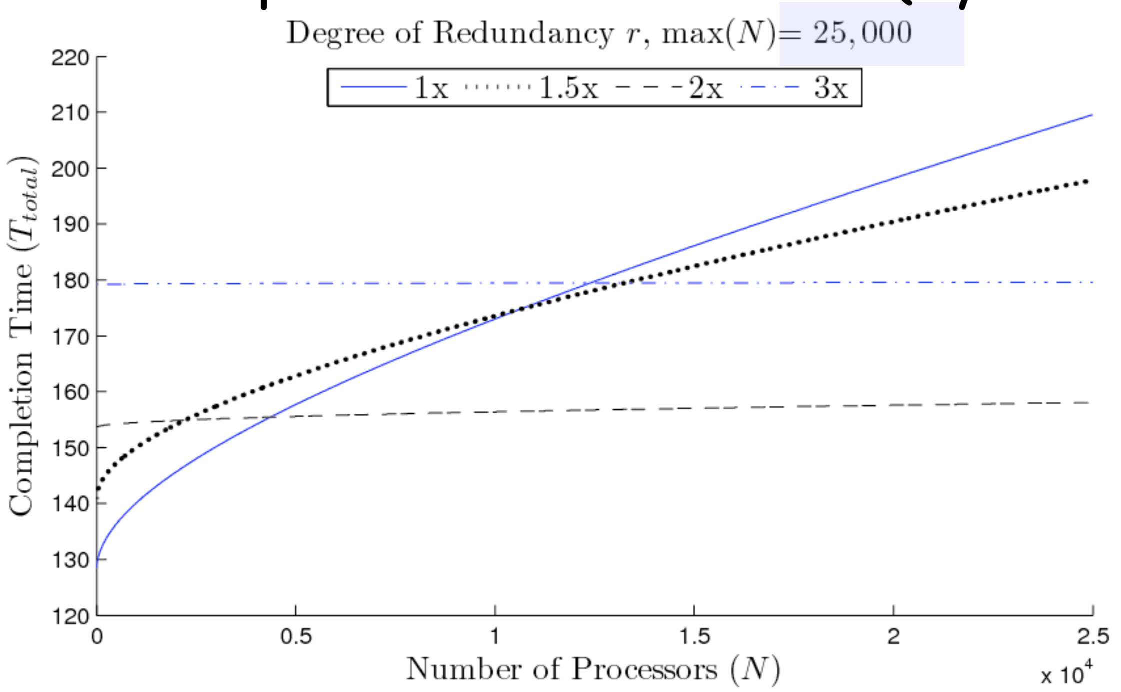
Results

- lower MTBF - 3x optimal redundancy
- Higher MTBF - 2x optimal redundancy

Redundancy degree / MTBF per node	1x	1.25x	1.5x	1.75x	2x	2.25x	2.5x	2.75x	3x
6 hrs	275	279	212	189	146	158	139	132	***123***
12 hrs	201	207	167	143	103	113	***98***	111	125
18 hrs	184	179	148	120	***72***	126	88	80	84
24 hrs	159	143	133	100	***67***	92	78	84	83
30 hrs	136	128	110	101	***66***	73	80	82	84

Results – Animated Crossover

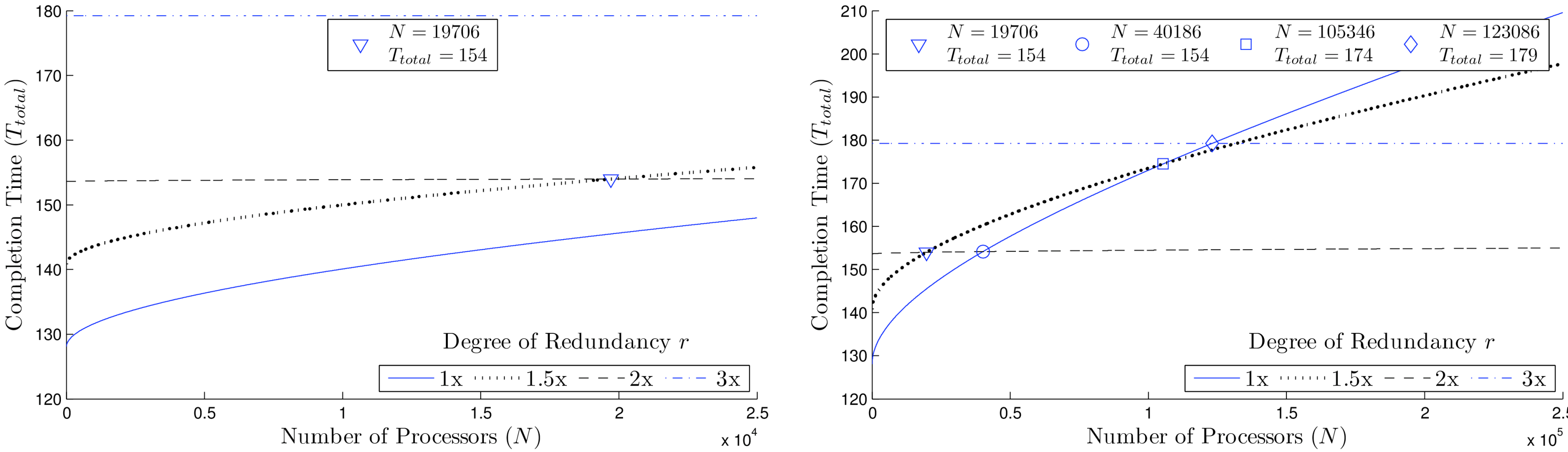
- Same params as published crossovers (5yr MTBF, etc..)



- 2x behaves like 1x, given large enough N
  - 3x should behave similarly given sufficiently large N.
- 1x fails at ~ 250k, reliability reaches floating limit for zero.

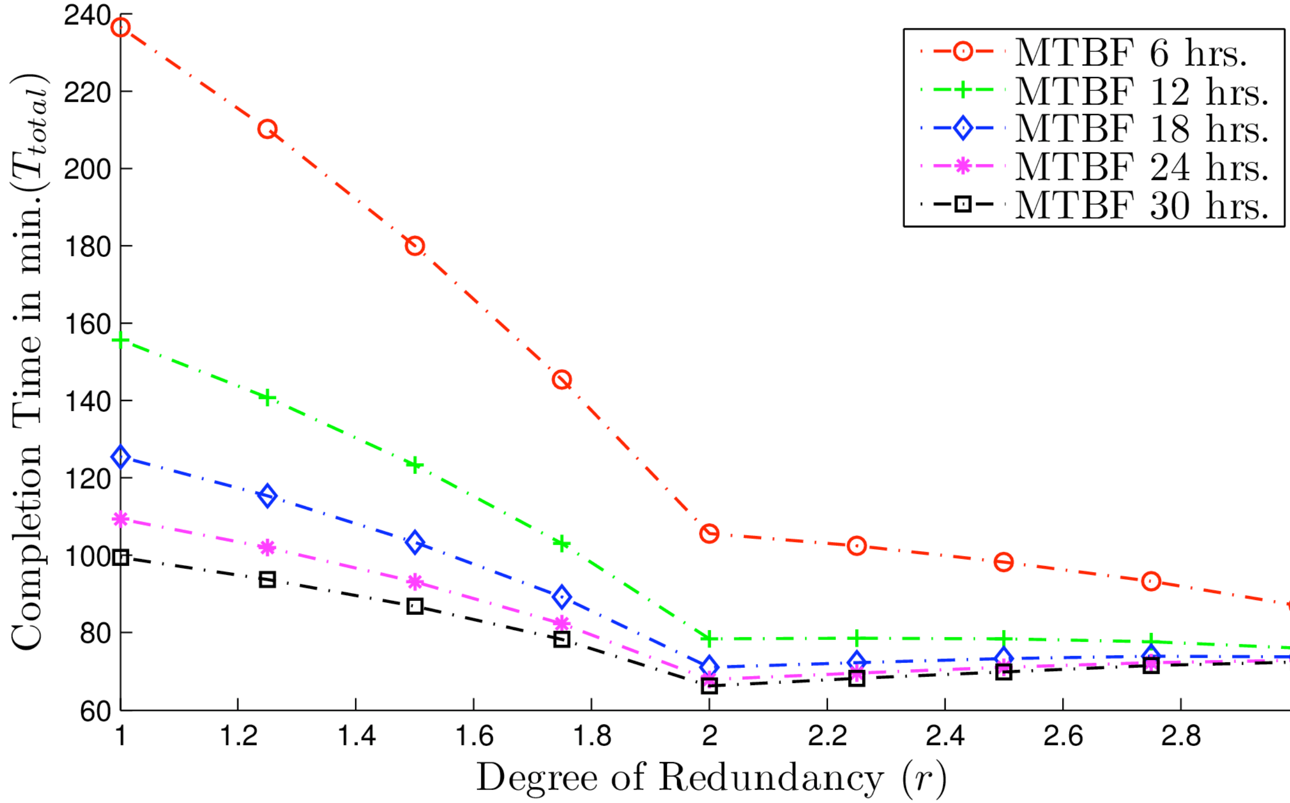
Results – Jaguar Extrapolation

- Jaguar node MTBF is estimated to be roughly 50 years
  - 18,688 nodes



- No redundancy necessary yet
- Dual redundancy in the very near future
  - Titan maintains node count
  - **increases core count by 33%, adds GPUs.**

Results – Model



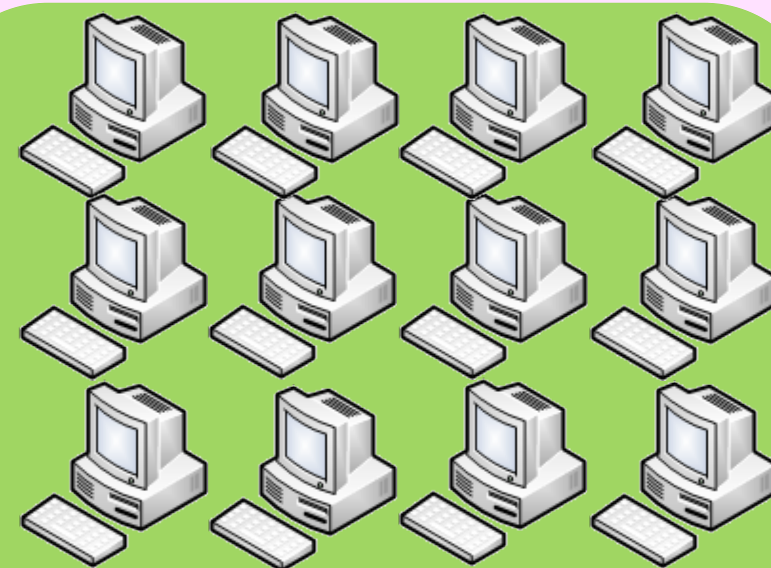
- minimum runtime always achieved at 2x redundancy

Motivation

Components have reliability

- Reliability follows a statistical distribution e.g., Exponential
- Mean Time Before Failure

MTBF denoted as θ

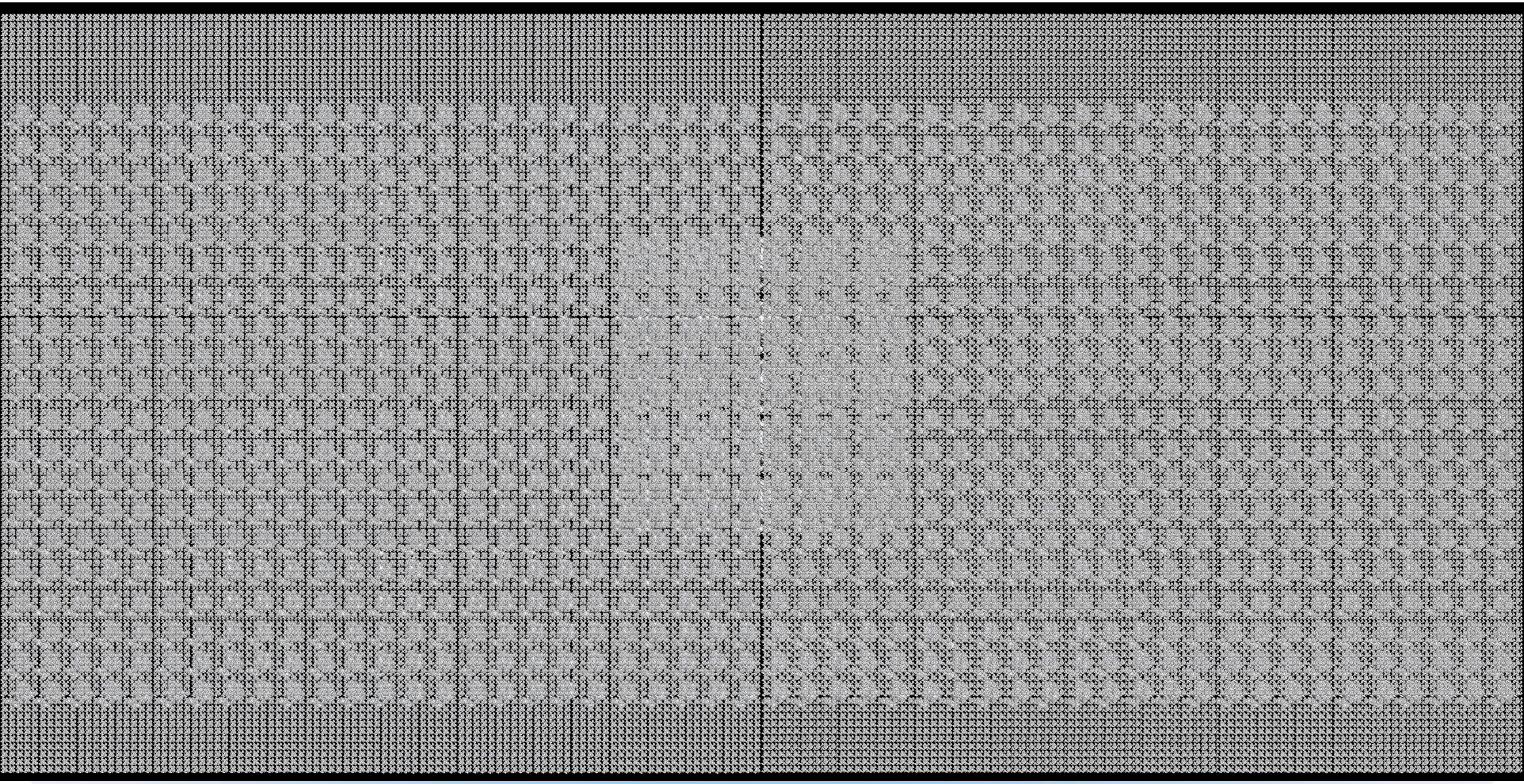


Θ = [illegible] hr.

Θ : **<u>System</u>** MTBF

Assume a node has <u>5yr MTBF (43,800 hours)</u>

Motivation



N = [illegible] Θ = [illegible] hr. δ = [illegible] min.

At petascale *50yr node MTBF (438,000 hours)*