

IMPROVING PERFORMANCE IN MULTI-CLUSTER ENVIRONMENTS THROUGH TRADING MECHANISMS

by

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A Thesis submitted to the faculty of
The University of Utah
in partial fulfillment of the requirements for the degree of

Masters of Science

in

Computer Science

School of Computing
The University of Utah

May 2024

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The University of Utah Graduate School

STATEMENT OF DISSERTATION APPROVAL

The dissertation of Hamza Fathallah Al Sheikh
has been approved by the following supervisory committee members:

<u>Robert Ricci</u> ,	Chair(s)	<u>17 Feb 2016</u> <small>Date Approved</small>
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<u>Ryan Stutsman</u> ,	Member	<u>17 Feb 2016</u> <small>Date Approved</small>
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<u>Kobus Van der Merwe</u> ,	Member	<u>17 Feb 2016</u> <small>Date Approved</small>
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by Mary Hall , Chair/Dean of
the Department/College/School of Computing
and by Darryl P. Butt , Dean of The Graduate School.

ABSTRACT

Multi-cluster topologies are becoming increasingly common due to factors like scalability, geographical considerations, multi-provider strategies, and workload partitioning. While the paradigm is promising, multi-cluster setups encounter challenges, notably resource fragmentation, increased cost, and reduced resource utilization. To mitigate these issues, we propose an intra-cluster resource trading mechanism. Controlled by user defined policies, the system facilitates peer-to-peer resource exchange among clusters by allowing foreign clusters to use local resources while retaining ownership. We evaluate the mechanism by running synthetic and production workloads on a multi-cluster simulator. [WRITE RESULTS HERE]

For my parents, Amal and Youssef.

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NOTATION AND SYMBOLS

α	fine-structure (dimensionless) constant, approximately $1/137$
α	radiation of doubly-ionized helium ions, He^{++}
β	radiation of electrons
γ	radiation of very high frequency, beyond that of X rays
γ	Euler's constant, approximately $0.577\,215 \dots$
δ	stepsize in numerical integration
$\delta(x)$	Dirac's famous function
ϵ	a tiny number, usually in the context of a limit to zero
$\zeta(x)$	the famous Riemann zeta function
\dots	\dots
$\psi(x)$	logarithmic derivative of the gamma function
ω	frequency

CHAPTER 1

INTRODUCTION

This is a chapter. Remember that there should *always* be at least of few lines of prose after each sectional heading: failure to do so is a disservice to your readers, and also produces incorrect vertical spacing.

1.1 The first section

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In **Figure 1.1** on the following page, we have a picture, and the L^AT_EX markup to include it looks like this:

```
\begin{figure}[t]
  \centerline{\includegraphics{fig1}}
  \caption{The first figure.}%
  \figlabel{fig1}
\end{figure}
```

We intentionally omitted an extension on the filename, so that this document can be processed with latex to get an output .dvi file, or with pdf_latex to get an output .pdf file. The first case uses the file fig1.eps, and the second uses fig1.pdf. The distill or ps2pdf commands can be used to convert from *Encapsulated PostScript*files to *Portable Document Format*files.

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This is Figure 1

Figure 1.1. The first figure.

1.1.1 The first subsection

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1.1.2 The second subsection

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1.1.3 The third subsection

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1.1.3.1 The first subsubsection

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1.1.3.2 The second subsubsection

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1.1.3.2.1 The first numbered paragraph Blah blah blah blah blah blah blah blah
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blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah.

1.1.3.2.2 The second numbered paragraph Blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah.

1.2 The second section

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Blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah.

In **Figure 1.2**, we have another picture.

Blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah.

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This is Figure 2

Figure 1.2. The second figure.

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In **Table 1.1**, we show the 24-character lowercase Greek alphabet.

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 blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah
 blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah.

Table 1.1. Lowercase Greek letters.

α	alpha
β	beta
γ	gamma
δ	delta
ϵ, ε	epsilon
ζ	zeta
η	eta
θ, ϑ	theta
ι	iota
κ	kappa
λ	lambda
μ	mu
ν	nu
ξ	xi
\omicron	omicron
π	pi
ρ	rho
σ, ς	sigma
τ	tau
υ	upsilon
ϕ, φ	phi
χ	chi
ψ	psi
ω	omega

Table 1.2. Uppercase Greek letters. Notice that several have the same letter shapes as Latin letters, and for those, \TeX does not define macro names. For convenience, we supply our own definitions of these macros: `\Alpha`, `\Beta`, `\Epsilon`, `\Zeta`, `\Eta`, `\Iota`, `\Kappa`, `\Mu`, `\Nu`, `\Omicron`, `\Rho`, `\Tau`, and `\Chi`.

A	Alpha
B	Beta
Γ	Gamma
Δ	Delta
E	Epsilon
Z	Zeta
H	Eta
Θ	Theta
I	Iota
K	Kappa
Λ	Lambda
M	Mu
N	Nu
Ξ	Xi
O	Omicron
Π	Pi
P	Rho
Σ	Sigma
T	Tau
Y	Upsilon
Φ	Phi
X	Chi
Ψ	Psi
Ω	Omega

Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah.
 Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah
 blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah.

1.4 Free software packages

The Free Software Foundation offers almost 300 software packages, most easily portable to many different operating systems and CPU platforms. They include at least these:

`a2ps`, `acct`, `acm`, `adns`, `alive`, `anubis`, `apl`, `archimedes`, `aris`, `aspell`, `auctex`,
`autoconf-archive`, `autoconf`, `autogen`, `automake`, `avl`, `ballandpaddle`, `barcode`, `bash`,
`bayonne`, `bc`, `binutils`, `bison`, `bool`, `bpel2owfn`, `c-graph`, `ccaudio`, `ccd2cue`, `ccrtp`,

In **Figure 1.3**, we have yet another picture.

Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah blah.

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Blah blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah.



This is Figure 3

Figure 1.3. The third figure. This one has both short and long captions. Blah blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah. Blah blah blah blah blah. Blah blah blah blah. Blah blah. Blah.

Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah.
 Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah
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Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah.
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Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah.
 Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah
 blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah.

1.5 Resizing figures

In **Figure 1.4** through **Figure 1.8** on the following page, we show how graphics files can be rescaled to convenient sizes, with input like this:

```
\begin{figure}[p]
  \centerline{\includegraphics[scale = 0.5]{fig1}}
  \caption{The fourth figure (at 50\% scale).}%
  \figlabel{fig4}
\end{figure}

\begin{figure}[p]
  \centerline{\includegraphics[scale = 0.75]{fig1}}
  \caption{The fifth figure (at 75\% scale).}%
  \figlabel{fig5}
\end{figure}
```



This is Figure 1

Figure 1.4. The fourth figure (at 50% scale).



This is Figure 1

Figure 1.5. The fifth figure (at 75% scale).



This is Figure 1

Figure 1.6. The sixth figure (at native size).



This is Figure 1

Figure 1.7. The seventh figure (at 125% scale).



This is Figure 1

Figure 1.8. The eighth figure (at 175% scale).

```

\begin{figure}[p]
  \centerline{\includegraphics{fig1}}
  \caption{The sixth figure (at native size).}%
  \figlabel{fig6}
\end{figure}

\begin{figure}[p]
  \centerline{\includegraphics[scale = 1.25]{fig1}}
  \caption{The seventh figure (at 125\% scale).}%
  \figlabel{fig7}
\end{figure}

\begin{figure}[p]
  \centerline{\includegraphics[scale = 1.75]{fig1}}
  \caption{The eighth figure (at 175\% scale).}%
  \figlabel{fig8}
\end{figure}

```

You can include multiple images, each with its own caption inside a single *unbreakable* figure environment, like this example shown in **Figure 1.9** and **Figure 1.10** on the next page, although you might want to adjust interfigure vertical space with a `\vspace{}` command:

```

\begin{figure}[t]
  \centerline{\includegraphics[scale = 0.5]{fig1}}
  \caption{The fourth figure (at 50\% scale).}%
  \figlabel{fig9}
  \vspace{3ex}
  \centerline{\includegraphics[scale = 0.75]{fig1}}
  \caption{The fifth figure (at 75\% scale).}%
  \figlabel{fig10}
\end{figure}

```

Blah blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah blah.

Blah blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah blah.

Blah blah blah blah blah blah blah blah blah blah blah blah blah blah.



This is Figure 1

Figure 1.9. The ninth figure (at 50% scale), boxed with the tenth figure.



This is Figure 1

Figure 1.10. The tenth figure (at 75% scale), boxed with the ninth figure.

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blah blah blah blah blah blah blah blah blah blah blah blah blah blah.

As a final example in this chapter, **Figure 1.11** on the following page shows how you can use L^AT_EX picture mode for annotating and positioning graphics images prepared outside L^AT_EX. The input that produced that figure looks like this:

```
\begin{figure}[t]
  %% The original image is 216bp wide by 72bp high, but we
  %% rescale it to 150 picture units divided by \unitlength:
  %% 150 / 0.75 = 112.5 mm
  \newcommand {\myfig} {\includegraphics[width = 112.5mm]{fig1}}

  \begin{center}
    %% The \unitlength is chosen to make the complete picture fit
    %% within the page margins

    \setlength{\unitlength}{0.75mm}

    %%%      insert (width,height)(lower-left-x,lower-left-y)
    \begin{picture}(170,70)(10,10)
      %% Place the included image FIRST!
      \put(10,10) {\myfig}

      %% Everything that follows OVERLAYS the original image!

      \graphpaper[10](0,0)(170,70)

      %% Mark the image center and corners by centered bullets
      \newcommand {\thedot} {\makebox (0,0) {$\bullet$}}
      \put( 85, 35) {\thedot}
      \put( 10, 10) {\thedot}
```


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CHAPTER 2

BACKGROUND AND RELATED WORK

This is a chapter.

Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah.

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blah blah blah blah blah blah blah blah blah blah blah blah blah blah.

CHAPTER 3

DESIGN

This is a chapter.

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blah blah blah blah blah blah blah blah blah blah blah blah blah blah.

blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah.

4.3 Summary and conclusions

Blah blah blah blah blah blah blah blah blah blah blah blah blah blah.
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blah blah blah blah blah blah blah blah blah blah blah blah blah blah.

CHAPTER 5

EVALUATION

APPENDIX A

THE FIRST

This is an appendix. Notice that the \LaTeX markup for an appendix is, surprisingly, `\chapter`. The `\appendix` command does not produce a heading; instead, it just changes the numbering style from numeric to alphabetic, and it changes the heading prefix from **CHAPTER** to **APPENDIX**.

Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah blah. Blah blah blah blah blah blah blah. Blah blah blah blah blah. Blah blah blah. Blah blah. Blah.

APPENDIX B

THE SECOND

This is an appendix.

[illegible]

APPENDIX C

THE THIRD

This is an appendix.

There are several books [12, 19–21, 23–25, 27–30] listed in our bibliography.

We also reference several journal articles [1, 2, 4, 8–10, 13–18, 22, 31, 32] and three famous doctoral theses of later winners [3, 6, 7] of the Nobel Prize in Physics (1922, 1933, and 1921):

Notice that, even though those citations appeared in `LATEX \cite{...}` commands with their `BIBTEX` citation labels in reverse alphabetical order, thanks to the `citesort` package, their reference-list numbers have been sorted in numerically ascending order, and then range-reduced.

Mention should also be made of a famous Dutch computer scientist’s first publication [5].

Font metrics are an important, albeit low-level, aspect of typesetting. See the *Adobe Systems* manual about that company’s procedures [26].

The bibliography at the end of this thesis contains several examples of documents with non-English titles, and their `BIBTEX` entries provide title translations following the practice recommended by the American Mathematical Society and SIAM. Here is a sample entry that shows how to do so:

```
@PhdThesis{Einstein:1905:NBM,  
  author =      "Albert Einstein",  
  title =      "{Eine Neue Bestimmung der Molek{\\"u}ldimensionen}.  
                ({German}) [{A} new determination of molecular  
                dimensions]",  
  type =      "Inaugural dissertation",  
  school =     "Bern Wyss.",  
  address =     "Bern, Switzerland",  
  year =      "1905",  
  bibdate =     "Fri Dec 17 10:46:57 2004",
```

```

bibsource =    "http://www.math.utah.edu/pub/tex/bib/einstein.bib",
note =        "Published in \cite{Einstein:1906:NBM}.",
acknowledgement = ack-nhfb,
language =    "German",
advisor =     "Alfred Kleiner (24 April 1849--3 July 1916)",
URL =        "http://en.wikipedia.org/wiki/Alfred_Kleiner",
remark =      "Received August 19, 1905 and published February 8,
               1906.",
Schilpp-number = "6",
}

```

The `note` field in that entry refers to another bibliography entry that need not have been directly cited in the document text. Such cross-references are common in BibTeX files, especially for journal articles where there may be later comments and corrigenda that should be mentioned. Embedded `\cite{}` commands ensure that those possibly-important other entries are always included in the reference list when the entry is cited. The last bibliography entry [32] in this thesis has a long `note` field that tells more about what some may view as the most important paper in mathematics in the last century.

When entries cite other entries that cite other entries that cite other entries that ..., multiple passes of L^AT_EX and BibTeX are needed to ensure consistency. That is another reason why document compilation should be guided by a Makefile or a batch script, rather than expecting the user to remember just how many passes are needed.

BibTeX entries are *extensible*, in that arbitrary key/value pairs may be present that are not necessarily recognized by any bibliography style files. The `advisor`, `acknowledgement`, `bibdate`, `bibsource`, `language`, `remark`, and `Schilpp-number` fields are examples, and may be used by other software that processes BibTeX entries, or by humans who read the entries. DOI and URL fields are currently recognized by only a few styles, but that situation will likely change as publishers demand that such important information be included in reference lists.

In BibTeX `title` fields, braces protect words, such as proper nouns and acronyms, that cannot be downcased if the selected bibliography style would otherwise do so. In German, all nouns are capitalized, and the simple way to ensure their protection is to brace the entire German text in the title, as we did in the entry above.

The world's first significant computer program may have been that written in 1842

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- [8] —, *Eine neue Bestimmung der Moleküldimensionen. (German) [A new determination of molecular dimensions]*, Annalen der Physik (1900) (series 4), 324 (1906), pp. 289–306. See corrections [9, 10]. This is a slightly revised version of Einstein's doctoral dissertation [7].
- [9] A. EINSTEIN, *Bemerkung zu meiner Arbeit: Eine Beziehung zwischen dem elastischen Verhalten. (German) [Remark on my paper: "A relationship between the elastic behavior ..."]*, Annalen der Physik (1900) (series 4), 339 (1911), pp. 590–590. See [11].
- [10] A. EINSTEIN, *Berichtigung zu meiner Arbeit: Eine neue Bestimmung der Moleküldimensionen. (German) [Corrections to my work: a new determination of molecular dimensions]*, Annalen der Physik (1900) (series 4), 339 (1911), pp. 591–592. See [8].
- [11] —, *Eine Beziehung zwischen dem elastischen Verhalten und der spezifischen Wärme bei festen Körpern mit einatomigem Molekül. (German) [A relationship between the elastic behavior and the specific heat of solid bodies with monatomic molecules]*, Annalen der Physik (1900) (series 4), 339 (1911), pp. 170–174, 590. See remarks [9, 10].

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