Aalto University
School of Science
and Technology

Methodology for Computer Science Research
Lecture 1: Introduction

Andrey Lukyanenko

Department of Computer Science and Engineering
Aalto University, School of Science
T-110.6130@aalto.fi

September 13, 2012

Course overview

Code: T-110.6130

Name: Methodology for Computer Science Research

Contact: `T-110.6130@aalto.fi`

Aim: Study of methods, tools, and development of reading and writing skills.

Structure: 6 Method lectures, 2 presentations, half lectures are removed for home study.

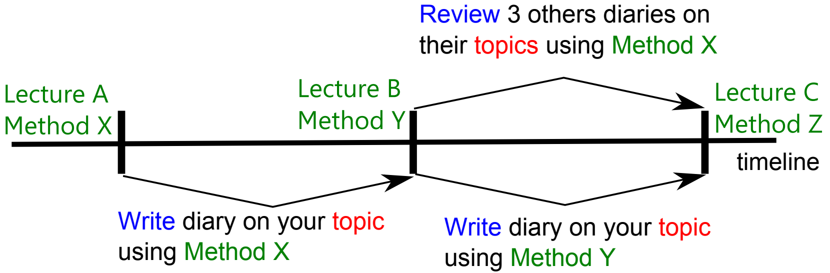
To pass the course...

... during the course:

1. Pick *one research topic* of your interest: select one of the provided by us or choose yourself (be cautious!).
2. Attend the lectures: Thu/Tue, 16:15-18:00 at T5
   13 Sep, 20 Sep, 04 Oct, 11 Oct, 18 Oct, 30 Oct, 06 Nov.
3. Write diaries after each lecture related to the methods and your topic.
4. Review diaries of others in a week after each lecture.
5. Write an assignment on the topic you chose (here the diaries could help!).
6. Short presentations on your topic 11 Dec and 12 Dec.
7. Checkout English courses in Language Center if you need help?

To pass the course...

... during the course:



Credits and grading

Credits: 5 credits

Grading:

- Diaries give 50% of the mark. (g_d)
- Presentation gives 20% of the mark. (g_p)
- Assignment gives 50% of the mark.(g_a)

The final grade g will be calculated as

$$g = \min\left\{\frac{50 \cdot g_d + 20 \cdot g_p + 50 \cdot g_a}{100}, 5\right\}.$$

Assignment topics

Each student have to pick up one topic. During the course produce analysis of the topic it with studied methods.

Topics are...

- Congestion control in TCP.
- Fairness int TCP.
- Distributed Hash Tables (DHTs).
- Unstructured Peer-to-Peer (p2p).
- Cloud computing Systems.
- Mesh Networks.
- Sensor Networks.
- Ad-hoc Networks.
- Social media.
- Delay tolerant networks.
- ...

Assignment topics (cntd)

- Security in DHT.
- Internet of things.
- Datacenter architecture.
- BitTorrent protocol (tit-for-tat).
- Routing protocols in the Internet.
- Publish/Subscribe systems.
- P2P reputation systems.
- Energy consumptions in Wireless systems.
- Denial-of-Service attack.
- Multicast protocols.

OR you can choose your own topic.
It may be what you have as Master Thesis topic, or any topic your are interested in.

Structure of the Course

Course outline:

1) 13.09 Introduction (this lecture).
2) 20.09 Computer Simulation.
3) 04.10 Data analysis.
4) 11.10 Mathematical modeling.
5) 18.10 Academic programming.
6) 30.10 Experimental research.
7) 06.11 Network business models.
8) 10.12 Presentation 1.
9) 11.12 Presentation 2.

Assignment deadline is 01.12.

Studying process (1/3)

- After this lecture pick up own topic or 3 of our topics,
- Send a topic or the list to `T-110.6130@aalto.fi` with title "T-110.6130 assignment topic" (easier to find).
- Inside e-mail write your own topic; also say few words about the reason why did you choose it,
- or list 3 topics by priority from the provided ones, e.g.

> “My priority list of topics is:
> 1. TCP.
> 2. DHT.
> 3. DoS attack”
>
> or “Own topic: <Title> (I choose it because it’s my MSc topic)”.

- Before lecture 2 you will be provided with a unique topic.

Studying process (2/3)

After each methodological lecture (lectures 2-7) you

- write a short diary note (1 page IEEE double column format, no need to write too much, no need for introduction, title or conclusion; see Diary Instructions in Noppa.)
- upload (pdf and tex) the diary to `optima.aalto.fi`

  > When logged in to optima, you will find T-110.6130 workspace with diary subsection. The diary on previously studied method should be uploaded before next lecture (or during one week)

- review 3 other's diaries from previous lectures (Diary grade is a combination of your diary quality and your review quality; Reviews are given as comments in optima.)

In this short diary you write how to use exactly given research method for your topic.

Warning: Avoid unnecessary information in diaries. Abstract, Introduction and Conclusion will be only in final assignment.

Studying process (3/3)

- Last 2 lectures are presentations. All students will have short presentations ($\approx$ 5min) on what they have studied during the course on their selected topic.
- One week before the presentations is an assignment deadline. The assignment is to cover the topic you choose with methodological view.
  Your paper should:
  - contain a short introduction to the topic,
  - clearly state all methods used to study the topic in literature,
  - compare them (pro and con),
  - present own thoughts: what in the study is missing and why?

Remember: Your diaries on the same topic will help you with the final assignment!

What is this course about?

This course is about Scientific Research in the field of Computer Science (more precisely, in the field of Data Communications).

The course tries to answer on the questions:

- How to do the Scientific Research?
- How to do the Scientific Research efficiently?
- How to do what a Scientific Community needs, in the form which the Scientific Community demands?
- How to present your Scientific Research to the Community?

Although, the above in context of Scientific Research, the same skills are useful in any kind of IT related work.

What is Computer Science Research?

It is about studying an Idea: your Idea.

Novelty of the Idea.
Research is a study of new ideas in the field where the research belongs to.

Significance for the Community.
One of the most important questions of research is to understand what kind of idea is actually needed for the community “today”.

Contribution from the Researcher.
The amount of efforts made by a researcher to study the idea.

But before...

But before...

... understanding *Novelty* and *Significance* you have to know the state-of-the-art of knowledge in Scientific Community.

How to be up-to-date?

1. Read recent journal articles, and conference papers. Almost all of them has “History”, “Introduction” and “Future work” parts. (they correspond to “Past”, “Current” and “Possible Future” of the research.)
2. Talk to colleagues and scientific advisers :) (they may suggest ideas and explain the field development, without studying).
3. Observe the business tendency and technology levels (news from industry).
4. Look through the visions of the future (Sometimes knowledgeable people publish their visions of the future).

Literature sources

The search engines (and sources) for scientific publications.

- Google Scholar: `http://scholar.google.com`
- Academic Microsoft: `http://academic.research.microsoft.com`
- ACM Portal: `http://portal.acm.org`
- IEEE xplore: `http://ieeexplore.ieee.org`

Especially, papers published in famous conferences, e.g.,

- ACM SIGCOMM: `http://www.sigcomm.org`
- INFOCOM: `http://www.ieee-infocom.org`

Additionally, many famous publications appear in less famous, but still important conferences.

AR - acceptance rates for the conferences and IF - impact factor for the journals.

Accessing the publications

1. Traditional way: Go to the library and get an article or order one (an obsoleted way).

> Unfortunately, the articles and conference books in the library are quite old. Some journals are available in the coffee room.

2. Internally: Inside Aalto University ACM, IEEE, Springer, etc websites allows to fetch articles freely.

3. Remotely: Outside Aalto University you can fetch them
   - directly from the Internet, some of them are publicly available
   - indirectly using the search site `nelliportaali.fi` or adding the proxy `libproxy.aalto.fi`, e.g. portal.acm.org.libproxy.aalto.fi

Reading as a part of Research

The reading refers to the studying of the field (remember *Significance* and *Novelty*?).

Reading:

- adds knowledge about the field.
- adds the confidence in own knowledge about the field.
- helps new Research Ideas to pop up in the mind.

Do not underestimate the Reading as a part of Research:

- Even if you have the full confidence in the new Idea, check the literature, search for it.
- If the Idea popped up after reading some paper, check who citing this paper. May be the Idea was already developed.

Remember: the previously mentioned paper search engines are able to search by criteria: "cited by".

Writing as a part of Research

The writing refers to the production of own Research (recall *Contribution*!).

Writing:

- allows you to document your work for own needs.
- allows others to see your work, to see that you are actually working.
- putting Ideas on a paper allows to polish them and even invent new or extend existing Idea.

Writing is always hard in the middle of research, but it will greatly help you later if you put on the paper even small Ideas, points, thoughts.

Reeding $\longleftrightarrow$ Writing

Question: When should I switch from reading to writing?

Answer: Never.

- Starting the research you mainly read.
- Finishing the research you mainly write.
- In between, you write, but continue to keep abreast of the development of the Community.

Conferences happen all the time, papers appears. If you produce your research based on other authors paper, always check who is citing it.

Question: When to switch from mainly reading to mainly writing?

Answer: Whenever you have confidence in the field and double checked the Idea.

What is an outcome of the Research?

Accomplished research is determined by *written* results.

Outcome of the Research may be

- a survey of the field, if it is necessary overview, timely and shows new facets of the field,
- a new algorithm/protocol, if it gives some benefits compared to already existing ones,
- a mathematical model of a protocol/algorithm, if it is better predicts different features of the protocol/algorithm,
- a performance measurement of existing protocols, with additional analysis
- many more...

All these are "Scientific Findings".
Your written results should address it clearly.

How to develop a new “clever” idea?

There is no rule for Idea generation process, but when you have *an Idea* remember:

“There is nothing new except what is forgotten” (c) Rose Bertin

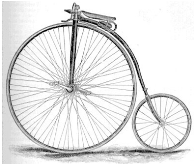


Fig. 1.—Bicycle.

- Whenever you have a new idea, double check that it was not studied previously. Even in close/related fields.
- It can be an old idea from a different field, but was forgotten and the time for it has come.

The checking allows to skip waste of time to study something that already was studied and will concentrate on application of the idea to the field.

Before the research...

There is a big difference what you see when you look inside your paper, and what others see!

Good to know from the start: Peer Review a common practice in the Scientific Community.

An Example: Peer-review process in SIGCOMM:
Papagiannaki, K. and Rizzo, L. 2009. *The ACM SIGCOMM 2009 technical program committee process.* SIGCOMM Comput. Commun. Rev. 39, 3 (Jun. 2009), 43-48

Find and read the paper yourself, you know how and also read the one which is citing it!!

TPC Review System (An Example)

Traditional points of review process:

- *** Contribution: Rate the evaluation of work and contribution.
- *** Significance: Rate the significance to theory and practice.
- *** Novelty: Rate the originality and novelty.
- *** Relevance: How relevant is the paper to the call for papers?
- *** Readability: Rate the readability and organization of the content.
- *** Overall recommendation: Would you recommend this paper for conference?
- *** Best paper award: Do you consider the paper a candidate for a best-paper award?
- *** Detailed comments

When you are finally ready!

Ready?

- You have the Idea.
- You have the confidence in the idea (novelty and significance).
- You need Contribution!!!

This is what the course is about.

The optimal process of the idea study is not unique and is fully dependent on the case, however, it has a set of known study methods:

- Mathematical Modeling.
- Computer Simulation.
- Experimental research.
- Data Analysis.
- Software Development (demo or product).

Methods: Mathematical Modeling

Mathematical modeling is a research method that performs the problem abstraction, when different properties of a system are defined using a set of parameters and interactions of these properties are defined with functions and inequalities over the parameters.

Mathematical modeling provides a set of features, it allows to

- investigate properties of the whole system, based on a subset of measured parameters.
- see the system's asymptotic behavior.
- find optimal conditions for a system.

Methods: Computer Simulation

Computer Simulation is a research methods, when a small sample program representing the studying algorithm/protocol is created for an existing toolkit (or seldom from the scratch), which simulates the network, computer or system work.

Computer Simulation allows to

- produce “cheap” evaluation research.
- do research, when the development time is crucial.
- do research, when the sources (money, number of devices) are limited.
- do research even in the black-box architecture, real development is limited.

Methods: Experimental research

Experimental research is a research method, which is mainly based on an experimentation.

Experimental research allows to

- produce a research even in case if the modeling is difficult.
- acquire result, when a simulation may be a very slow process.
- see non-trivial dependencies between parameters.

Methods: Software development

Software development is a part of the research, when a product-like software (demo) is produced. Sometimes it is even in the form of commercial product, i.e., this methods allows to show that the research idea is fully feasible.

Software development allows to:

- create a proof-of-concept.
- see design errors/pitfalls in the idea.
- produce the research with most realistic environment.

Methods: Data Analysis

Data Analysis is a research method, that in a form of a bridge, connects together other methods, allowing to compare results, make the research consistent in different aspects and produce estimations for parameters.

Data Analysis allows to

- match mathematical models and experimental research.
- give estimations on the parameters for models and algorithms.
- prove some properties with high probability rates.
- provide reader with easily readable and understandable data.

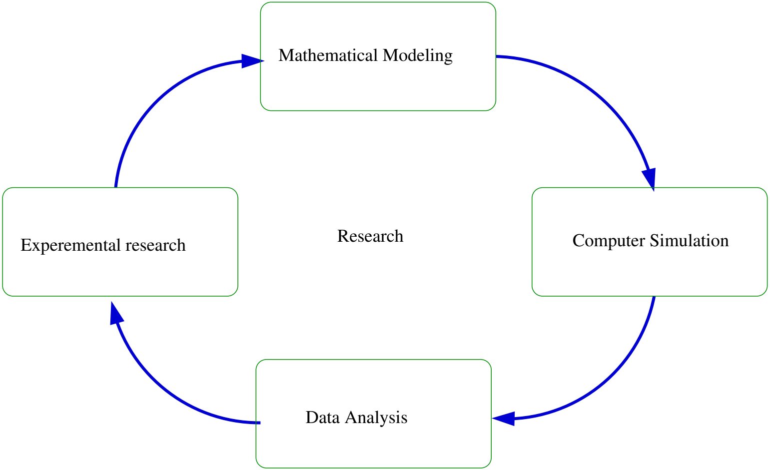
Methods: Networking business methods

Networking business research methods are the research methods examines telecommunications from the business point of view.

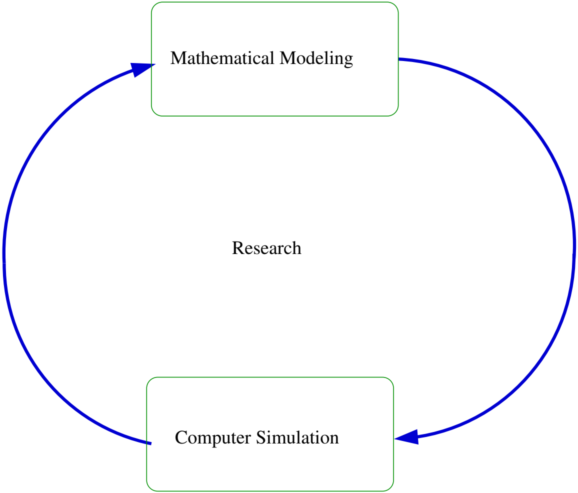
Networking business methods allows to

- study commercialization of the research.
- focus on the factors affecting the commercial success.
- predict future trends of the research and industry.

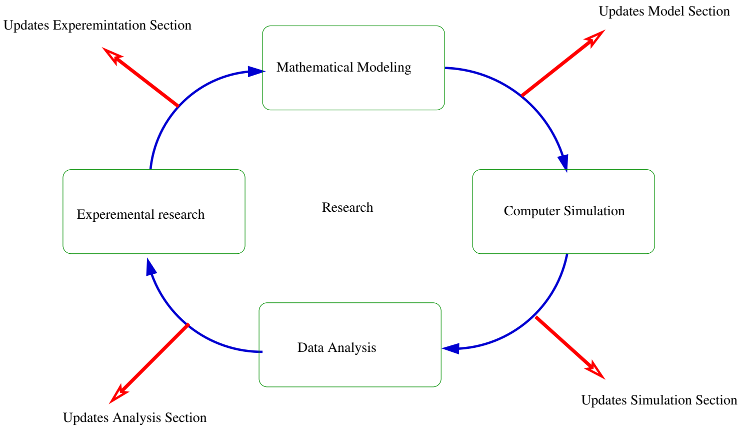
Iterative process: Big Cycles



Iterative process: Short Cycles



Iterative process: with paper outcomes



On the paper.

Section	Content
-	Title
-	Abstract
1	Introduction
2	History (Related work)
3	Idea, Algorithm
4	Model
5	Simulation, Measurements
6	Evaluation, Data Analysis
7	Implementation (Demo)
8	Discussion (Results), Future work
9	Conclusion
-	Reference

On the paper: General.

Chord: A Scalable Peer-to-peer Lookup Service for Internet Applications

Ion Stoica*, Robert Morris, David Karger, M. Frans Kaashoek, Hari Balakrishnan†
MIT Laboratory for Computer Science
chord@lcs.mit.edu
http://pdos.lcs.mit.edu/chord/

Abstract

A fundamental problem that confronts peer-to-peer applications is to efficiently locate the node that stores a particular data item. This paper presents *Chord*, a distributed lookup protocol that addresses this problem. Chord provides support for just one operation: given a key, it maps the key onto a node. Data location can be easily implemented on top of Chord by associating a key with each data item, and storing the key/data item pair at the node to which the key maps. Chord adapts efficiently as nodes join and leave the system, and can answer queries even if the system is continuously changing. Results from theoretical analysis, simulations, and experiments show that Chord is scalable, with communication cost and the state maintained by each node scaling logarithmically with the number of Chord nodes.

1. Introduction

Peer-to-peer systems and applications are distributed systems without any centralized control or hierarchical organization, where the software running at each node is equivalent in functionality. A review of the features of recent peer-to-peer applications yields a long list: redundant storage, permanence, selection of nearby servers, anonymity, search, authentication, and hierarchical naming. Despite this rich set of features, the core operation in most peer-to-peer systems is efficient location of data items. The contribution of this paper is a scalable protocol for lookup in a dynamic peer-to-peer system with frequent node arrivals and departures.

The *Chord protocol* supports just one operation: given a key, it maps the key onto a node. Depending on the application using Chord, that node might be responsible for storing a value associated with the key. Chord uses a variant of consistent hashing [11] to assign keys to Chord nodes. Consistent hashing tends to balance load, since each node receives roughly the same number of keys, and involves relatively little movement of keys when nodes join and leave the system.

Previous work on consistent hashing assumed that nodes were aware of most other nodes in the system, making it impractical to scale to large number of nodes. In contrast, each Chord node needs "routing" information about only a few other nodes. Because the routing table is distributed, a node resolves the hash function by communicating with a few other nodes. In the steady state, in an N-node system, each node maintains information only about $O(\log N)$ other nodes, and resolves all lookups via $O(\log N)$ messages to other nodes. Chord maintains its routing information as nodes join and leave the system; with high probability each such event results in no more than $O(\log^2 N)$ messages.

Three features that distinguish Chord from many other peer-to-peer lookup protocols are its simplicity, provable correctness, and provable performance. Chord is simple, routing a key through a sequence of $O(\log N)$ other nodes toward the destination. A Chord node requires information about $O(\log N)$ other nodes for *efficient* routing, but performance degrades gracefully when that information is out of date. This is important in practice because nodes will join and leave arbitrarily, and consistency of even $O(\log N)$ state may be hard to maintain. Only one piece information per node need be correct in order for Chord to guarantee correct (though slow) routing of queries; Chord has a simple algorithm for maintaining this information in a dynamic environment.

The rest of this paper is structured as follows. Section 2 compares Chord to related work. Section 3 presents the system model that motivates the Chord protocol. Section 4 presents the base Chord protocol and proves several of its properties, while Section 5 presents extensions to handle concurrent joins and failures. Section 6 demonstrates our claims about Chord's performance through simulation and experiments on a deployed prototype. Finally, we outline items for future work in Section 7 and summarize our contributions in Section 8.

2. Related Work

While Chord maps keys onto nodes, traditional name and location services provide a *direct* mapping between keys and values. A value can be an address, a document, or an arbitrary data item. Chord can easily implement this functionality by storing each key/value pair at the node to which that key maps. For this reason and to make the comparison clearer, the rest of this section assumes a Chord-based service that maps keys onto values.

DNS provides a host name to IP address mapping [15]. Chord can provide the same service with the name representing the key and the associated IP address representing the value. Chord requires no special servers, while DNS relies on a set of special root

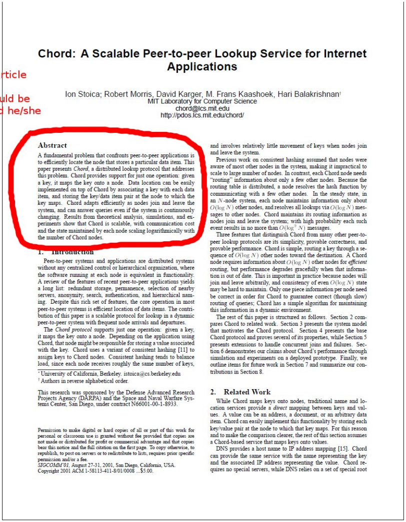
* University of California, Berkeley. istoica@cs.berkeley.edu
† Authors in reverse alphabetical order.

This research was sponsored by the Defense Advanced Research Projects Agency (DARPA) and the Space and Naval Warfare Systems Center, San Diego, under contract N66001-00-1-8933.

SIGCOMM'01, August 27-31, 2001, San Diego, California, USA.

On the paper: Abstract.

Abstract:
When somebody finds out this article
this is what is read first.
Based on abstract a person should be
able to preliminary know, should he/she
read it further or not?



Chord: A Scalable Peer-to-peer Lookup Service for Internet Applications

Ion Stoica*, Robert Morris, David Karger, M. Frans Kaashoek, Hari Balakrishnan†
MIT Laboratory for Computer Science
chord@lcs.mit.edu
http://pdos.lcs.mit.edu/chord/

Abstract

A fundamental problem that confronts peer-to-peer applications is to efficiently locate the node that stores a particular data item. This paper presents *Chord*, a distributed lookup protocol that addresses this problem. Chord provides support for just one operation: given a key, it maps the key onto a node. Data location can be easily implemented on top of Chord by associating a key with each data item, and storing the key/data item pair at the node to which the key maps. Chord adapts efficiently as nodes join and leave the system, and can answer queries even if the system is continuously changing. Results from theoretical analysis, simulations, and experiments show that Chord is scalable, with communication cost and the state maintained by each node scaling logarithmically with the number of Chord nodes.

1. Introduction

Peer-to-peer systems and applications are distributed systems without any centralized control or hierarchical organization, where the software running at each node is equivalent in functionality. A review of the features of recent peer-to-peer applications yields a long list: redundant storage, permanence, selection of nearby servers, anonymity, search, authentication, and hierarchical naming. Despite this rich set of features, the core operation in most peer-to-peer systems is efficient location of data items. The contribution of this paper is a scalable protocol for lookup in a dynamic peer-to-peer system with frequent node arrivals and departures.

The *Chord protocol* supports just one operation: given a key, it maps the key onto a node. Depending on the application using Chord, that node might be responsible for storing a value associated with the key. Chord uses a variant of consistent hashing [11] to assign keys to Chord nodes. Consistent hashing tends to balance load, since each node receives roughly the same number of keys, and involves relatively little movement of keys when nodes join and leave the system.

Previous work on consistent hashing assumed that nodes were aware of most other nodes in the system, making it impractical to scale to large number of nodes. In contrast, each Chord node needs "routing" information about only a few other nodes. Because the routing table is distributed, a node resolves the hash function by communicating with a few other nodes. In the steady state, in an N-node system, each node maintains information only about $O(\log N)$ other nodes, and resolves all lookups via $O(\log N)$ messages to other nodes. Chord maintains its routing information as nodes join and leave the system; with high probability each such event results in no more than $O(\log^2 N)$ messages.

Three features that distinguish Chord from many other peer-to-peer lookup protocols are its simplicity, provable correctness, and provable performance. Chord is simple, routing a key through a sequence of $O(\log N)$ other nodes toward the destination. A Chord node requires information about $O(\log N)$ other nodes for *efficient* routing, but performance degrades gracefully when that information is out of date. This is important in practice because nodes will join and leave arbitrarily, and consistency of even $O(\log N)$ state may be hard to maintain. Only one piece information per node need be correct in order for Chord to guarantee correct (though slow) routing of queries; Chord has a simple algorithm for maintaining this information in a dynamic environment.

The rest of this paper is structured as follows. Section 2 compares Chord to related work. Section 3 presents the system model that motivates the Chord protocol. Section 4 presents the base Chord protocol and proves several of its properties, while Section 5 presents extensions to handle concurrent joins and failures. Section 6 demonstrates our claims about Chord's performance through simulation and experiments on a deployed prototype. Finally, we outline items for future work in Section 7 and summarize our contributions in Section 8.

2. Related Work

While Chord maps keys onto nodes, traditional name and location services provide a *direct* mapping between keys and values. A value can be an address, a document, or an arbitrary data item. Chord can easily implement this functionality by storing each key/value pair at the node to which that key maps. For this reason and to make the comparison clearer, the rest of this section assumes a Chord-based service that maps keys onto values.

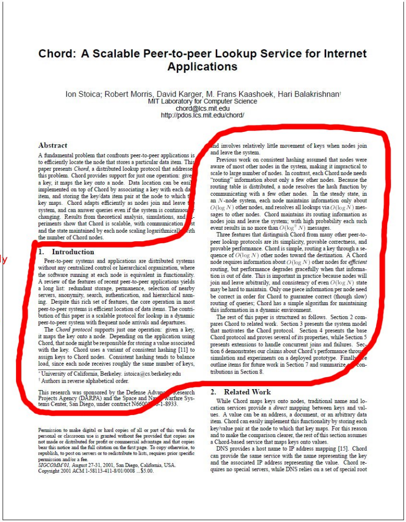
DNS provides a host name to IP address mapping [15]. Chord can provide the same service with the name representing the key and the associated IP address representing the value. Chord requires no special servers, while DNS relies on a set of special root

* University of California, Berkeley. istoica@cs.berkeley.edu
† Authors in reverse alphabetical order.

This research was sponsored by the Defense Advanced Research Projects Agency (DARPA) and the Space and Naval Warfare Systems Center, San Diego, under contract N66001-00-1-8933.

On the paper: Introduction.

Introduction describes more precisely current state of the research field, significance of the paper and relevance to it, gives some basic assumptions and limitations, as well as briefly outlines own achievements.



Chord: A Scalable Peer-to-peer Lookup Service for Internet Applications

Ion Stoica*, Robert Morris, David Karger, M. Frans Kaashoek, Hari Balakrishnan†
MIT Laboratory for Computer Science
chord@lcs.mit.edu
http://pdos.lcs.mit.edu/chord/

Abstract

A fundamental problem that confronts peer-to-peer applications is to efficiently locate the node that stores a particular data item. This paper presents *Chord*, a distributed lookup protocol that addresses this problem. Chord provides support for just one operation: given a key, it maps the key onto a node. Data location can be easily implemented on top of Chord by associating a key with each data item, and storing the key/data item pair at the node to which the key maps. Chord adapts efficiently as nodes join and leave the system, and can answer queries even if the system is continuously changing. Results from theoretical analysis, simulations, and experiments show that Chord is scalable, with communication cost and the state maintained by each node scaling logarithmically with the number of Chord nodes.

1. Introduction

Peer-to-peer systems and applications are distributed systems without any centralized control or hierarchical organization, where the software running at each node is equivalent in functionality. A review of the features of recent peer-to-peer applications yields a long list: redundant storage, permanence, selection of nearby servers, anonymity, search, authentication, and hierarchical naming. Despite this rich set of features, the core operation in most peer-to-peer systems is efficient location of data items. The contribution of this paper is a scalable protocol for lookup in a dynamic peer-to-peer system with frequent node arrivals and departures.

The *Chord protocol* supports just one operation: given a key, it maps the key onto a node. Depending on the application using Chord, that node might be responsible for storing a value associated with the key. Chord uses a variant of consistent hashing [11] to assign keys to Chord nodes. Consistent hashing tends to balance load, since each node receives roughly the same number of keys, and involves relatively little movement of keys when nodes join and leave the system.

Previous work on consistent hashing assumed that nodes were aware of most other nodes in the system, making it impractical to scale to large number of nodes. In contrast, each Chord node needs "routing" information about only a few other nodes. Because the routing table is distributed, a node resolves the hash function by communicating with a few other nodes. In the steady state, in an N-node system, each node maintains information only about $O(\log N)$ other nodes, and resolves all lookups via $O(\log N)$ messages to other nodes. Chord maintains its routing information as nodes join and leave the system; with high probability each such event results in no more than $O(\log^2 N)$ messages.

Three features that distinguish Chord from many other peer-to-peer lookup protocols are its simplicity, provable correctness, and provable performance. Chord is simple, routing a key through a sequence of $O(\log N)$ other nodes toward the destination. A Chord node requires information about $O(\log N)$ other nodes for *efficient* routing, but performance degrades gracefully when that information is out of date. This is important in practice because nodes will join and leave arbitrarily, and consistency of even $O(\log N)$ state may be hard to maintain. Only one piece information per node need be correct in order for Chord to guarantee correct (though slow) routing of queries; Chord has a simple algorithm for maintaining this information in a dynamic environment.

The rest of this paper is structured as follows. Section 2 compares Chord to related work. Section 3 presents the system model that motivates the Chord protocol. Section 4 presents the base Chord protocol and proves several of its properties, while Section 5 presents extensions to handle concurrent joins and failures. Section 6 demonstrates our claims about Chord's performance through simulation and experiments on a deployed prototype. Finally, we outline items for future work in Section 7 and summarize our contributions in Section 8.

2. Related Work

While Chord maps keys onto nodes, traditional name and location services provide a *direct* mapping between keys and values. A value can be an address, a document, or an arbitrary data item. Chord can easily implement this functionality by storing each key/value pair at the node to which that key maps. For this reason and to make the comparison clearer, the rest of this section assumes a Chord-based service that maps keys onto values.

DNS provides a host name to IP address mapping [15]. Chord can provide the same service with the name representing the key and the associated IP address representing the value. Chord requires no special servers, while DNS relies on a set of special root

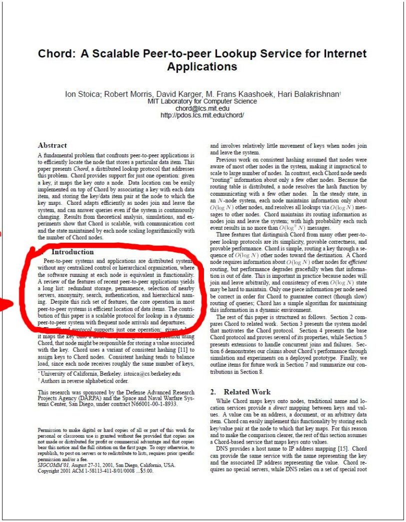
* University of California, Berkeley. istoica@cs.berkeley.edu
† Authors in reverse alphabetical order.

This research was sponsored by the Defense Advanced Research Projects Agency (DARPA) and the Space and Naval Warfare Systems Center, San Diego, under contract N6600[illegible]-1-8933.

SIGCOMM'01, August 27-31, 2001, San Diego, California, USA.

On the paper: Introduction.

The first part of Introduction
is hardest part, it always
is difficult to find what
words/sentence to use
in the beginning.



Chord: A Scalable Peer-to-peer Lookup Service for Internet Applications

Ion Stoica*, Robert Morris, David Karger, M. Frans Kaashoek, Hari Balakrishnan†
MIT Laboratory for Computer Science
chord@lcs.mit.edu
http://pdos.lcs.mit.edu/chord/

Abstract

A fundamental problem that confronts peer-to-peer applications is to efficiently locate the node that stores a particular data item. This paper presents *Chord*, a distributed lookup protocol that addresses this problem. Chord provides support for just one operation: given a key, it maps the key onto a node. Data location can be easily implemented on top of Chord by associating a key with each data item, and storing the key/data item pair at the node to which the key maps. Chord adapts efficiently as nodes join and leave the system, and can answer queries even if the system is continuously changing. Results from theoretical analysis, simulations, and experiments show that Chord is scalable, with communication cost and the state maintained by each node scaling logarithmically with the number of Chord nodes.

1. Introduction

Peer-to-peer systems and applications are distributed systems without any centralized control or hierarchical organization, where the software running at each node is equivalent in functionality. A review of the features of recent peer-to-peer applications yields a long list: redundant storage, permanence, selection of nearby servers, anonymity, search, authentication, and hierarchical naming. Despite this rich set of features, the core operation in most peer-to-peer systems is efficient location of data items. The contribution of this paper is a scalable protocol for lookup in a dynamic peer-to-peer system with frequent node arrivals and departures.

The *Chord protocol* supports just one operation: given a [illegible] it maps the key [illegible] using Chord, that node might be responsible for storing a value associated with the key. Chord uses a variant of consistent hashing [11] to assign keys to Chord nodes. Consistent hashing tends to balance load, since each node receives roughly the same number of keys, and involves relatively little movement of keys when nodes join and leave the system.

Previous work on consistent hashing assumed that nodes were aware of most other nodes in the system, making it impractical to scale to large number of nodes. In contrast, each Chord node needs "routing" information about only a few other nodes. Because the routing table is distributed, a node resolves the hash function by communicating with a few other nodes. In the steady state, in an N-node system, each node maintains information only about $O(\log N)$ other nodes, and resolves all lookups via $O(\log N)$ messages to other nodes. Chord maintains its routing information as nodes join and leave the system; with high probability each such event results in no more than $O(\log^2 N)$ messages.

Three features that distinguish Chord from many other peer-to-peer lookup protocols are its simplicity, provable correctness, and provable performance. Chord is simple, routing a key through a sequence of $O(\log N)$ other nodes toward the destination. A Chord node requires information about $O(\log N)$ other nodes for *efficient* routing, but performance degrades gracefully when that information is out of date. This is important in practice because nodes will join and leave arbitrarily, and consistency of even $O(\log N)$ state may be hard to maintain. Only one piece information per node need be correct in order for Chord to guarantee correct (though slow) routing of queries; Chord has a simple algorithm for maintaining this information in a dynamic environment.

The rest of this paper is structured as follows. Section 2 compares Chord to related work. Section 3 presents the system model that motivates the Chord protocol. Section 4 presents the base Chord protocol and proves several of its properties, while Section 5 presents extensions to handle concurrent joins and failures. Section 6 demonstrates our claims about Chord's performance through simulation and experiments on a deployed prototype. Finally, we outline items for future work in Section 7 and summarize our contributions in Section 8.

2. Related Work

While Chord maps keys onto nodes, traditional name and location services provide a *direct* mapping between keys and values. A value can be an address, a document, or an arbitrary data item. Chord can easily implement this functionality by storing each key/value pair at the node to which that key maps. For this reason and to make the comparison clearer, the rest of this section assumes a Chord-based service that maps keys onto values.

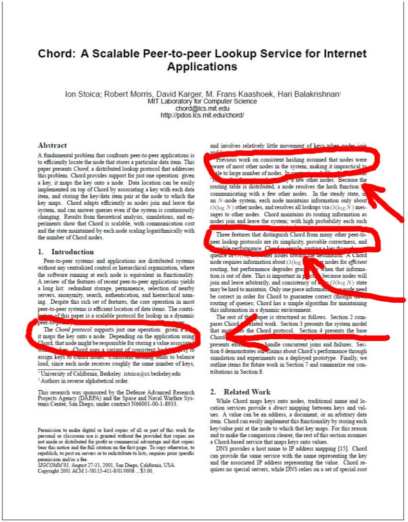
DNS provides a host name to IP address mapping [15]. Chord can provide the same service with the name representing the key and the associated IP address representing the value. Chord requires no special servers, while DNS relies on a set of special root

* University of California, Berkeley. istoica@cs.berkeley.edu
† Authors in reverse alphabetical order.

This research was sponsored by the Defense Advanced Research Projects Agency (DARPA) and the Space and Naval Warfare Systems Center, San Diego, under contract N66001-00-1-8933.

SIGCOMM'01, August 27-31, 2001, San Diego, California, USA.

On the paper: Introduction.



Chord: A Scalable Peer-to-peer Lookup Service for Internet Applications

Ion Stoica*, Robert Morris, David Karger, M. Frans Kaashoek, Hari Balakrishnan†
MIT Laboratory for Computer Science
chord@lcs.mit.edu
http://pdos.lcs.mit.edu/chord/

Abstract

A fundamental problem that confronts peer-to-peer applications is to efficiently locate the node that stores a particular data item. This paper presents *Chord*, a distributed lookup protocol that addresses this problem. Chord provides support for just one operation: given a key, it maps the key onto a node. Data location can be easily implemented on top of Chord by associating a key with each data item, and storing the key/data item pair at the node to which the key maps. Chord adapts efficiently as nodes join and leave the system, and can answer queries even if the system is continuously changing. Results from theoretical analysis, simulations, and experiments show that Chord is scalable, with communication cost and the state maintained by each node scaling logarithmically with the number of Chord nodes.

1. Introduction

Peer-to-peer systems and applications are distributed systems without any centralized control or hierarchical organization, where the software running at each node is equivalent in functionality. A review of the features of recent peer-to-peer applications yields a long list: redundant storage, permanence, selection of nearby servers, anonymity, search, authentication, and hierarchical naming. Despite this rich set of features, the core operation in most peer-to-peer systems is efficient location of data items. The contribution of this paper is a scalable protocol for lookup in a dynamic peer-to-pe[illegible]

The *Chord protocol* supports just one operation: given a k[illegible] it maps the key onto a node. Depending on the application using Chord, that node might be responsible for storing a value associated wi[illegible] key. Chord uses a variant of consistent ha[illegible] to assign keys to Chord nodes. Consistent [illegible] tends to balance load, since each node receives roughly the same number of keys, and involves relatively little movement of keys when nodes join and l[illegible]

Previous work on consistent hashing assumed that nodes were aware of most other nodes in the system, making it impractical to [illegible]le to large number of nodes. In co[illegible] [illegible] a few other nodes. Because the routing table is distributed, a node resolves the hash function [illegible] communicating with a few other nodes. In the steady state, in an N-node system, each node maintains information only about $O(\log N)$ other nodes, and resolves all lookups via $O(\log N)$ messages to other nodes. Chord maintains its routing information as nodes join and leave the system; with high probability each such [illegible]

Three features that distinguish Chord from many other peer-to-peer lookup protocols are its simplicity, provable correctness, and [illegible] performance. Chord is simple, routing a key throu[illegible] quence of [illegible] other nodes toward the destination. A Chord node requires information about $O(\log$ [illegible] nodes for *efficient* routing, but performance degrades grac[illegible] when that information is out of date. This is important in p[illegible] because nodes will join and leave arbitrarily, and consistency of [illegible] $O(\log N)$ state may be hard to maintain. Only one piece informati[illegible] node need be correct in order for Chord to guarantee correct (thoug[illegible]) routing of queries; Chord has a simple algorithm for maintaining this information in a dynamic environment.

The rest of thi[illegible] paper is structured as follows. Section 2 compares Chord [illegible]elated work. Section 3 presents the system model that moti[illegible]es the Chord protocol. Section 4 presents the base Chord [illegible] presents exte[illegible] handle concurrent joins and failures. Section 6 demonstrates ou[illegible]laims about Chord's performance through simulation and experiments on a deployed prototype. Finally, we outline items for future work in Section 7 and summarize our contributions in Section 8.

2. Related Work

While Chord maps keys onto nodes, traditional name and location services provide a *direct* mapping between keys and values. A value can be an address, a document, or an arbitrary data item. Chord can easily implement this functionality by storing each key/value pair at the node to which that key maps. For this reason and to make the comparison clearer, the rest of this section assumes a Chord-based service that maps keys onto values.

DNS provides a host name to IP address mapping [15]. Chord can provide the same service with the name representing the key and the associated IP address representing the value. Chord requires no special servers, while DNS relies on a set of special root

* University of California, Berkeley. istoica@cs.berkeley.edu
† Authors in reverse alphabetical order.

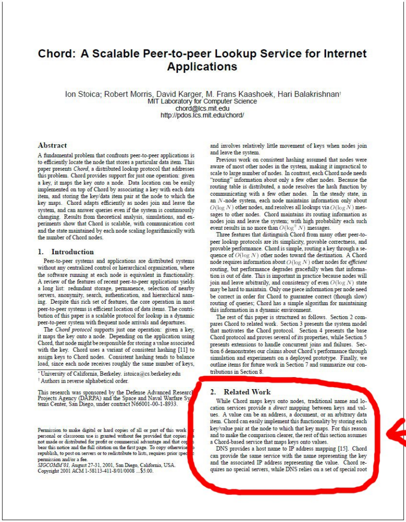
This research was sponsored by the Defense Advanced Research Projects Agency (DARPA) and the Space and Naval Warfare Systems Center, San Diego, under contract N66001-00-1-8933.

SIGCOMM'01, August 27-31, 2001, San Diego, California, USA.

Normally, the first sentence of each paragraph is general sentence, which includes all the knowledge, while the remaining parts are details, which provides the ground for the first sentence.

When you start writing an article, you can write down a set of general sentences and organize the article structure based on them, and later provide specific details about those.

On the paper: Related work.



Chord: A Scalable Peer-to-peer Lookup Service for Internet Applications

Ion Stoica*, Robert Morris, David Karger, M. Frans Kaashoek, Hari Balakrishnan†
MIT Laboratory for Computer Science
chord@lcs.mit.edu
http://pdos.lcs.mit.edu/chord/

Abstract

A fundamental problem that confronts peer-to-peer applications is to efficiently locate the node that stores a particular data item. This paper presents *Chord*, a distributed lookup protocol that addresses this problem. Chord provides support for just one operation: given a key, it maps the key onto a node. Data location can be easily implemented on top of Chord by associating a key with each data item, and storing the key/data item pair at the node to which the key maps. Chord adapts efficiently as nodes join and leave the system, and can answer queries even if the system is continuously changing. Results from theoretical analysis, simulations, and experiments show that Chord is scalable, with communication cost and the state maintained by each node scaling logarithmically with the number of Chord nodes.

1. Introduction

Peer-to-peer systems and applications are distributed systems without any centralized control or hierarchical organization, where the software running at each node is equivalent in functionality. A review of the features of recent peer-to-peer applications yields a long list: redundant storage, permanence, selection of nearby servers, anonymity, search, authentication, and hierarchical naming. Despite this rich set of features, the core operation in most peer-to-peer systems is efficient location of data items. The contribution of this paper is a scalable protocol for lookup in a dynamic peer-to-peer system with frequent node arrivals and departures.

The *Chord protocol* supports just one operation: given a key, it maps the key onto a node. Depending on the application using Chord, that node might be responsible for storing a value associated with the key. Chord uses a variant of consistent hashing [11] to assign keys to Chord nodes. Consistent hashing tends to balance load, since each node receives roughly the same number of keys, and involves relatively little movement of keys when nodes join and leave the system.

Previous work on consistent hashing assumed that nodes were aware of most other nodes in the system, making it impractical to scale to large number of nodes. In contrast, each Chord node needs "routing" information about only a few other nodes. Because the routing table is distributed, a node resolves the hash function by communicating with a few other nodes. In the steady state, in an N-node system, each node maintains information only about $O(\log N)$ other nodes, and resolves all lookups via $O(\log N)$ messages to other nodes. Chord maintains its routing information as nodes join and leave the system; with high probability each such event results in no more than $O(\log^2 N)$ messages.

Three features that distinguish Chord from many other peer-to-peer lookup protocols are its simplicity, provable correctness, and provable performance. Chord is simple, routing a key through a sequence of $O(\log N)$ other nodes toward the destination. A Chord node requires information about $O(\log N)$ other nodes for *efficient* routing, but performance degrades gracefully when that information is out of date. This is important in practice because nodes will join and leave arbitrarily, and consistency of even $O(\log N)$ state may be hard to maintain. Only one piece information per node need be correct in order for Chord to guarantee correct (though slow) routing of queries; Chord has a simple algorithm for maintaining this information in a dynamic environment.

The rest of this paper is structured as follows. Section 2 compares Chord to related work. Section 3 presents the system model that motivates the Chord protocol. Section 4 presents the base Chord protocol and proves several of its properties, while Section 5 presents extensions to handle concurrent joins and failures. Section 6 demonstrates our claims about Chord's performance through simulation and experiments on a deployed prototype. Finally, we outline items for future work in Section 7 and summarize our contributions in Section 8.

2. Related Work

While Chord maps keys onto nodes, traditional name and location services provide a *direct* mapping between keys and values. A value can be an address, a document, or an arbitrary data item. Chord can easily implement this functionality by storing each key/value pair at the node to which that key maps. For this reason and to make the comparison clearer, the rest of this section assumes a Chord-based service that maps keys onto values.

DNS provides a host name to IP address mapping [15]. Chord can provide the same service with the name representing the key and the associated IP address representing the value. Chord requires no special servers, while DNS relies on a set of special root

* University of California, Berkeley. istoica@cs.berkeley.edu
† Authors in reverse alphabetical order.

This research was sponsored by the Defense Advanced Researc Projects Agency (DARPA) and the Space and Naval Warfare Sy tems Center, San Diego, under contract N66001-00-1-8933.

Related work section contains the most significant knowledge a researcher have discovered concerning the topic.

It is the starting point of any article or any scientific work. You can start this section even during when you still study your field. It shows that you well aware of the topic.

On the paper: Finalizing the paper.

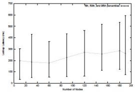


Figure 13: Lookup latency on the Internet prototype, as a function of the total number of nodes. Each of the ten physical sites runs multiple independent copies of the Chord node software.

copies of the Chord software at each site. This is different from running $O(\log N)$ virtual nodes at each site to provide good load balance; rather, the intention is to measure how well our implementation scales even though we do not have more than a small number of deployed nodes.

For each number of nodes shown in Figure 13, each physical site issues 16 Chord lookups for randomly chosen keys one-by-one. The graph plots the median, the 5th, and the 95th percentile of lookup latency. The median latency ranges from 180 to 285 ms, depending on number of nodes. For the case of 180 nodes, a typical lookup involves five two-way message exchanges: four for the Chord lookup, and a final message to the successor node. Typical round-trip delays between sites are 60 milliseconds (as measured by `ping`). Thus the expected lookup time for 180 nodes is about 300 milliseconds, which is close to the measured median of 285. The low 5th percentile latencies are caused by lookups for keys close (in ID space) to the querying node and by query hops that remain local to the physical site. The high 95th percentiles are caused by lookups whose hops follow high delay paths.

The lesson from Figure 13 is that lookup latency grows slowly with the total number of nodes, confirming the simulation results that demonstrate Chord's scalability.

7. Future Work

Based on our experience with the prototype mentioned in Section 6.6, we would like to improve the Chord design in the following areas.

Chord currently has no specific mechanism to heal partitioned rings; such rings could appear locally consistent to the stabilization procedure. One way to check global consistency is for each node n to periodically ask other nodes to do a Chord lookup for n; if the lookup does not yield node n, there may be a partition. This will only detect partitions whose nodes know of each other. One way to obtain this knowledge is for every node to know of the same small set of initial nodes. Another approach might be for nodes to maintain long-term memory of a random set of nodes they have encountered in the past; if a partition forms, the random sets in one partition are likely to include nodes from the other partition.

A malicious or buggy set of Chord participants could present an incorrect view of the Chord ring. Assuming that the data Chord is being used to locate is cryptographically authenticated, this is a threat to availability of data rather than to authenticity. The same approach used above to detect partitions could help victims realize that they are not seeing a globally consistent view of the Chord ring.

An attacker could target a particular data item by inserting a node into the Chord ring with an ID immediately following the item's key, and having the node return errors when asked to retrieve the data. Requiring (and checking) that nodes use IDs derived from the SHA-1 hash of their IP addresses makes this attack harder.

Even $\log N$ messages per lookup may be too many for some applications of Chord, especially if each message must be sent to a random Internet host. Instead of placing its fingers at distances that are all powers of 2, Chord could easily be changed to place its fingers at distances that are all integer powers of $1 + 1/d$. Under such a scheme, a single routing hop could decrease the distance to a query to $1/(1+d)$ of the original distance, meaning that $\log_{1+d} N$ hops would suffice. However, the number of fingers needed would increase to $\log N/(\log(1 + 1/d) \approx O(d \log N)$.

A different approach to improving lookup latency might be to use server selection. Each finger table entry could point to the first k nodes in that entry's interval on the ID ring, and a node could measure the network delay to each of the k nodes. The k nodes are generally equivalent for purposes of lookup, so a node could forward lookups to the one with lowest delay. This approach would be most effective with recursive Chord lookups, in which the node measuring the delays is also the node forwarding the lookup.

8. Conclusion

Many distributed peer-to-peer applications need to determine the node that stores a data item. The Chord protocol solves this challenging problem in decentralized manner. It offers a powerful primitive: given a key, it determines the node responsible for storing the key's value, and does so efficiently. In the steady state, in an N-node network, each node maintains routing information for only about $O(\log N)$ other nodes, and resolves all lookups via $O(\log N)$ messages to other nodes. Updates to the routing information for nodes leaving and joining require only $O(\log^2 N)$ messages.

Attractive features of Chord include its simplicity, provable correctness, and provable performance even in the face of concurrent node arrivals and departures. It continues to function correctly, albeit at degraded performance, when a node's information is only partially correct. Our theoretical analysis, simulations, and experimental results confirm that Chord scales well with the number of nodes, recovers from large numbers of simultaneous node failures and joins, and answers most lookups correctly even during recovery.

We believe that Chord will be a valuable component for peer-to-peer, large-scale distributed applications such as cooperative file sharing, time-shared available storage systems, distributed indices for document and service discovery, and large-scale distributed computing platforms.

Acknowledgments

We thank Frank Dabek for the measurements of the Chord prototype described in Section 6.6, and David Andersen for setting up the testbed used in those measurements.

9. References

[1] ANDERSEN, D. Resilient overlay networks. Master's thesis, Department of EECS, MIT, May 2001. `http://nms.lcs.mit.edu/projects/ron/`.

[2] BAKKER, A., AMADE, E., BALLINTIJN, G., KUZ, I., VERKAIK, P., VAN DER WIJK, I., VAN STEEN, M., AND TANENBAUM., A.

On the paper: Discussion.

In Discussion or Future Work section you touch the important questions related to the work, which though stayed out of the scope of the paper are still important to mention explicitly.

Additionally, here You can discuss extensions, limitations and problems of the paper, and how to improve or solve them in the future.

You can strengthen own paper, if you add in this section solutions for possible flaws of your work. This will show to the reviewers that you aware of these limitations, and at least know how to extend the work to overcome them, or why those scenarios are insignificant.

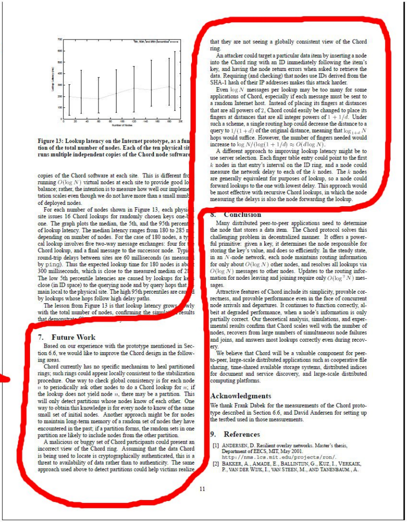


Figure 13: Lookup latency on the Internet prototype, as a fun tion of the total number of nodes. Each of the ten physical sit runs multiple independent copies of the Chord node software

copies of the Chord software at each site. This is different fro running $O(\log N)$ virtual nodes at each site to provide good lo balance; rather, the intention is to measure how well our impleme tation scales even though we do not have more than a small numb of deployed nodes.

For each number of nodes shown in Figure 13, each physic site issues 16 Chord lookups for randomly chosen keys one-b one. The graph plots the median, the 5th, and the 95th percent of lookup latency. The median latency ranges from 180 to 285 m depending on number of nodes. For the case of 180 nodes, a ty cal lookup involves five two-way message exchanges: four for t Chord lookup, and a final message to the successor node. Typic round-trip delays between sites are 60 milliseconds (as measur by ping). Thus the expected lookup time for 180 nodes is abo 300 milliseconds, which is close to the measured median of 28 The low 5th percentile latencies are caused by lookups for ke close (in ID space) to the querying node and by query hops that main local to the physical site. The high 95th percentiles are cau d by lookups whose hops follow high delay paths.

The lesson from Figure 13 is that lookup latency grows wly with the total number of nodes, confirming the simula results that demonstrate C

7. Future Work

Based on our experience with the prototype mentioned in Section 6.6, we would like to improve the Chord design in the following areas.

Chord currently has no specific mechanism to heal partitioned rings; such rings could appear locally consistent to the stabilization procedure. One way to check global consistency is for each node n to periodically ask other nodes to do a Chord lookup for n; if the lookup does not yield node n, there may be a partition. This will only detect partitions whose nodes know of each other. One way to obtain this knowledge is for every node to know of the same small set of initial nodes. Another approach might be for nodes to maintain long-term memory of a random set of nodes they have encountered in the past; if a partition forms, the random sets in one partition are likely to include nodes from the other partition.

A malicious or buggy set of Chord participants could present an incorrect view of the Chord ring. Assuming that the data Chord is being used to locate is cryptographically authenticated, this is a threat to availability of data rather than to authenticity. The same approach used above to detect partitions could help victims realize that they are not seeing a globally consistent view of the Chord ring.

An attacker could target a particular data item by inserting a node into the Chord ring with an ID immediately following the item's key, and having the node return errors when asked to retrieve the data. Requiring (and checking) that nodes use IDs derived from the SHA-1 hash of their IP addresses makes this attack harder.

Even $\log N$ messages per lookup may be too many for some applications of Chord, especially if each message must be sent to a random Internet host. Instead of placing its fingers at distances that are all powers of 2, Chord could easily be changed to place its fingers at distances that are all integer powers of $1 + 1/d$. Under such a scheme, a single routing hop could decrease the distance to a query to $1/(1+d)$ of the original distance, meaning that $\log_{1+d} N$ hops would suffice. However, the number of fingers needed would increase to $\log N/(\log(1 + 1/d) \approx O(d \log N)$.

A different approach to improving lookup latency might be to use server selection. Each finger table entry could point to the first k nodes in that entry's interval on the ID ring, and a node could measure the network delay to each of the k nodes. The k nodes are generally equivalent for purposes of lookup, so a node could forward lookups to the one with lowest delay. This approach would be most effective with recursive Chord lookups, in which the node measuring the delays is also the node forwarding the lookup.

8. Conclusion

Many distributed peer-to-peer applications need to determine the node that stores a data item. The Chord protocol solves this challenging problem in decentralized manner. It offers a powerful primitive: given a key, it determines the node responsible for storing the key's value, and does so efficiently. In the steady state, in an N-node network, each node maintains routing information for only about $O(\log N)$ other nodes, and resolves all lookups via $O(\log N)$ messages to other nodes. Updates to the routing information for nodes leaving and joining require only $O(\log^2 N)$ messages.

Attractive features of Chord include its simplicity, provable correctness, and provable performance even in the face of concurrent node arrivals and departures. It continues to function correctly, albeit at degraded performance, when a node's information is only partially correct. Our theoretical analysis, simulations, and experimental results confirm that Chord scales well with the number of nodes, recovers from large numbers of simultaneous node failures and joins, and answers most lookups correctly even during recovery.

We believe that Chord will be a valuable component for peer-to-peer, large-scale distributed applications such as cooperative file sharing, time-shared available storage systems, distributed indices for document and service discovery, and large-scale distributed computing platforms.

Acknowledgments

We thank Frank Dabek for the measurements of the Chord prototype described in Section 6.6, and David Andersen for setting up the testbed used in those measurements.

9. References

[1] ANDERSEN, D. Resilient overlay networks. Master's thesis, Department of EECS, MIT, May 2001. http://nms.lcs.mit.edu/projects/ron/.

[2] BAKKER, A., AMADE, E., BALLINTIJN, G., KUZ, I., VERKAIK, P., VAN DER WIJK, I., VAN STEEN, M., AND TANENBAUM., A.

On the paper: Conclusion.

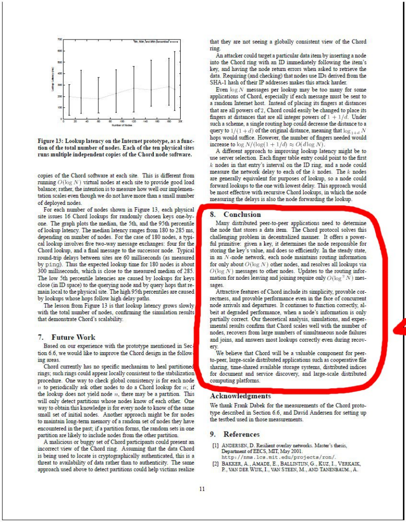


Figure 13: Lookup latency on the Internet prototype, as a function of the total number of nodes. Each of the ten physical sites runs multiple independent copies of the Chord node software.

copies of the Chord software at each site. This is different from running $O(\log N)$ virtual nodes at each site to provide good load balance; rather, the intention is to measure how well our implementation scales even though we do not have more than a small number of deployed nodes.

For each number of nodes shown in Figure 13, each physical site issues 16 Chord lookups for randomly chosen keys one-by-one. The graph plots the median, the 5th, and the 95th percentile of lookup latency. The median latency ranges from 180 to 285 ms, depending on number of nodes. For the case of 180 nodes, a typical lookup involves five two-way message exchanges: four for the Chord lookup, and a final message to the successor node. Typical round-trip delays between sites are 60 milliseconds (as measured by ping). Thus the expected lookup time for 180 nodes is about 300 milliseconds, which is close to the measured median of 285. The low 5th percentile latencies are caused by lookups for keys close (in ID space) to the querying node and by query hops that remain local to the physical site. The high 95th percentiles are caused by lookups whose hops follow high delay paths.

The lesson from Figure 13 is that lookup latency grows slowly with the total number of nodes, confirming the simulation results that demonstrate Chord's scalability.

7. Future Work

Based on our experience with the prototype mentioned in Section 6.6, we would like to improve the Chord design in the following areas.

Chord currently has no specific mechanism to heal partitioned rings; such rings could appear locally consistent to the stabilization procedure. One way to check global consistency is for each node n to periodically ask other nodes to do a Chord lookup for n; if the lookup does not yield node n, there may be a partition. This will only detect partitions whose nodes know of each other. One way to obtain this knowledge is for every node to know of the same small set of initial nodes. Another approach might be for nodes to maintain long-term memory of a random set of nodes they have encountered in the past; if a partition forms, the random sets in one partition are likely to include nodes from the other partition.

A malicious or buggy set of Chord participants could present an incorrect view of the Chord ring. Assuming that the data Chord is being used to locate is cryptographically authenticated, this is a threat to availability of data rather than to authenticity. The same approach used above to detect partitions could help victims realize that they are not seeing a globally consistent view of the Chord ring.

An attacker could target a particular data item by inserting a node into the Chord ring with an ID immediately following the item's key, and having the node return errors when asked to retrieve the data. Requiring (and checking) that nodes use IDs derived from the SHA-1 hash of their IP addresses makes this attack harder.

Even $\log N$ messages per lookup may be too many for some applications of Chord, especially if each message must be sent to a random Internet host. Instead of placing its fingers at distances that are all powers of 2, Chord could easily be changed to place its fingers at distances that are all integer powers of $1 + 1/d$. Under such a scheme, a single routing hop could decrease the distance to a query to $1/(1+d)$ of the original distance, meaning that $\log_{1+d} N$ hops would suffice. However, the number of fingers needed would increase to $\log N/(\log(1+1/d)) \approx O(d \log N)$.

A different approach to improving lookup latency might be to use server selection. Each finger table entry could point to the first k nodes in that entry's interval on the ID ring, and a node could measure the network delay to each of the k nodes. The k nodes are generally equivalent for purposes of lookup, so a node could forward lookups to the one with lowest delay. This approach would be most effective with recursive Chord lookups, in which the node measuring the delays is also the node forwarding the lookup.

8. Conclusion

Many distributed peer-to-peer applications need to determine the node that stores a data item. The Chord protocol solves this challenging problem in decentralized manner. It offers a powerful primitive: given a key, it determines the node responsible for storing the key's value, and does so efficiently. In the steady state, in an N-node network, each node maintains routing information for only about $O(\log N)$ other nodes, and resolves all lookups via $O(\log N)$ messages to other nodes. Updates to the routing information for nodes leaving and joining require only $O(\log^2 N)$ messages.

Attractive features of Chord include its simplicity, provable correctness, and provable performance even in the face of concurrent node arrivals and departures. It continues to function correctly, albeit at degraded performance, when a node's information is only partially correct. Our theoretical analysis, simulations, and experimental results confirm that Chord scales well with the number of nodes, recovers from large numbers of simultaneous node failures and joins, and answers most lookups correctly even during recovery.

We believe that Chord will be a valuable component for peer-to-peer, large-scale distributed applications such as cooperative file sharing, time-shared available storage systems, distributed indices for document and service discovery, and large-scale distributed computing platforms.

Acknowledgments

We thank Frank Dabek for the measurements of the Chord prototype described in Section 6.6, and David Andersen for setting up the testbed used in those measurements.

9. References

[1] ANDERSEN, D. Resilient overlay networks. Master's thesis, Department of EECS, MIT, May 2001. http://nms.lcs.mit.edu/projects/ron/.

[2] BAKKER, A., AMADE, E., BALLINTIJN, G., KUZ, I., VERKAIK, P., VAN DER WIJK, I., VAN STEEN, M., AND TANENBAUM., A.

Conclusion is the section for the final words about the work done. Here you almost repeat what was mentioned in Abstract and Introduction.

Naturally, if your paper reveals something new and important, You will try to put it as close as possible to the beginning of the paper: into Abstract and Introduction.

Here, however, you just list all those main findings of your paper and probably the impact of it onto the corresponding field.

On the paper: Acknowledgement.

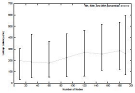


Figure 13: Lookup latency on the Internet prototype, as a function of the total number of nodes. Each of the ten physical sites runs multiple independent copies of the Chord node software.

copies of the Chord software at each site. This is different from running $O(\log N)$ virtual nodes at each site to provide good load balance; rather, the intention is to measure how well our implementation scales even though we do not have more than a small number of deployed nodes.

For each number of nodes shown in Figure 13, each physical site issues 16 Chord lookups for randomly chosen keys one-by-one. The graph plots the median, the 5th, and the 95th percentile of lookup latency. The median latency ranges from 180 to 285 ms, depending on number of nodes. For the case of 180 nodes, a typical lookup involves five two-way message exchanges: four for the Chord lookup, and a final message to the successor node. Typical round-trip delays between sites are 60 milliseconds (as measured by `ping`). Thus the expected lookup time for 180 nodes is about 300 milliseconds, which is close to the measured median of 285. The low 5th percentile latencies are caused by lookups for keys close (in ID space) to the querying node and by query hops that remain local to the physical site. The high 95th percentiles are caused by lookups whose hops follow high delay paths.

The lesson from Figure 13 is that lookup latency grows slowly with the total number of nodes, confirming the simulation results that demonstrate Chord's scalability.

7. Future Work

Based on our experience with the prototype mentioned in Section 6.6, we would like to improve the Chord design in the following areas.

Chord currently has no specific mechanism to heal partitioned rings; such rings could appear locally consistent to the stabilization procedure. One way to check global consistency is for each node n to periodically ask other nodes to do a Chord lookup for n; if the lookup does not yield node n, there may be a partition. This will only detect partitions whose nodes know of each other. One way to obtain this knowledge is for every node to know of the same small set of initial nodes. Another approach might be for nodes to maintain long-term memory of a random set of nodes they have encountered in the past; if a partition forms, the random sets in one partition are likely to include nodes from the other partition.

A malicious or buggy set of Chord participants could present an incorrect view of the Chord ring. Assuming that the data Chord is being used to locate is cryptographically authenticated, this is a threat to availability of data rather than to authenticity. The same approach used above to detect partitions could help victims realize that they are not seeing a globally consistent view of the Chord ring.

An attacker could target a particular data item by inserting a node into the Chord ring with an ID immediately following the item's key, and having the node return errors when asked to retrieve the data. Requiring (and checking) that nodes use IDs derived from the SHA-1 hash of their IP addresses makes this attack harder.

Even $\log N$ messages per lookup may be too many for some applications of Chord, especially if each message must be sent to a random Internet host. Instead of placing its fingers at distances that are all powers of 2, Chord could easily be changed to place its fingers at distances that are all integer powers of $1 + 1/d$. Under such a scheme, a single routing hop could decrease the distance to a query to $1/(1+d)$ of the original distance, meaning that $\log_{1+d} N$ hops would suffice. However, the number of fingers needed would increase to $\log N/(\log(1 + 1/d) \approx O(d \log N)$.

A different approach to improving lookup latency might be to use server selection. Each finger table entry could point to the first k nodes in that entry's interval on the ID ring, and a node could measure the network delay to each of the k nodes. The k nodes are generally equivalent for purposes of lookup, so a node could forward lookups to the one with lowest delay. This approach would be most effective with recursive Chord lookups, in which the node measuring the delays is also the node forwarding the lookup.

8. Conclusion

Many distributed peer-to-peer applications need to determine the node that stores a data item. The Chord protocol solves this challenging problem in decentralized manner. It offers a powerful primitive: given a key, it determines the node responsible for storing the key's value, and does so efficiently. In the steady state, in an N-node network, each node maintains routing information for only about $O(\log N)$ other nodes, and resolves all lookups via $O(\log N)$ messages to other nodes. Updates to the routing information for nodes leaving and joining require only $O(\log^2 N)$ messages.

Attractive features of Chord include its simplicity, provable correctness, and provable performance even in the face of concurrent node arrivals and departures. It continues to function correctly, albeit at degraded performance, when a node's information is only partially correct. Our theoretical analysis, simulations, and experimental results confirm that Chord scales well with the number of nodes, recovers from large numbers of simultaneous node failures and joins, and answers most lookups correctly even during recovery.

We believe that Chord will be a valuable component for peer-to-peer, large-scale distributed applications such as cooperative file sharing, time-shared available storage systems, distributed indices for document and service discovery, and large-scale distributed computing platforms.

Acknowledgments

We thank Frank Dabek for the measurements of the Chord prototype described in Section 6.6, and David Andersen for setting up the testbed used in those measurements.

9. References

[1] ANDERSEN, D. Resilient overlay networks. Master's thesis, Department of EECS, MIT, May 2001. http://nms.lcs.mit.edu/projects/ron/.

[2] BAKKER, A., AMADE, E., BALLINTIJN, G., KUZ, I., VERKAIK, P., VAN DER WIJK, I., VAN STEEN, M., AND TANENBAUM., A.

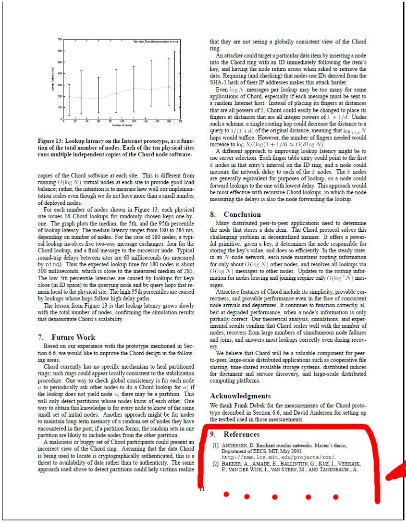
11

Acknowledgements section is for the mentioning people and grants, which helped you with preporation of the paper.

You can mention here proof readers, people who helped you and sometimes guide.

You don't need (and have no obligation to put all those people into author list, though sometimes people mistakenly put them there) to put everyone as your co-author. This is the right place.

On the paper: References.



that they are not seeing a globally consistent view of the Chord ring.

Figure 13: Lookup latency on the Internet prototype, as a function of the total number of nodes. Each of the ten physical sites runs multiple independent copies of the Chord node software.

copies of the Chord software at each site. This is different from running $O(\log N)$ virtual nodes at each site to provide good load balance; rather, the intention is to measure how well our implementation scales even though we do not have more than a small number of deployed nodes.

For each number of nodes shown in Figure 13, each physical site issues 16 Chord lookups for randomly chosen keys one-by-one. The graph plots the median, the 5th, and the 95th percentile of lookup latency. The median latency ranges from 180 to 285 ms, depending on number of nodes. For the case of 180 nodes, a typical lookup involves five two-way message exchanges: four for the Chord lookup, and a final message to the successor node. Typical round-trip delays between sites are 60 milliseconds (as measured by `ping`). Thus the expected lookup time for 180 nodes is about 300 milliseconds, which is close to the measured median of 285. The low 5th percentile latencies are caused by lookups for keys close (in ID space) to the querying node and by query hops that remain local to the physical site. The high 95th percentiles are caused by lookups whose hops follow high delay paths.

The lesson from Figure 13 is that lookup latency grows slowly with the total number of nodes, confirming the simulation results that demonstrate Chord's scalability.

7. Future Work

Based on our experience with the prototype mentioned in Section 6.6, we would like to improve the Chord design in the following areas.

Chord currently has no specific mechanism to heal partitioned rings; such rings could appear locally consistent to the stabilization procedure. One way to check global consistency is for each node n to periodically ask other nodes to do a Chord lookup for n; if the lookup does not yield node n, there may be a partition. This will only detect partitions whose nodes know of each other. One way to obtain this knowledge is for every node to know of the same small set of initial nodes. Another approach might be for nodes to maintain long-term memory of a random set of nodes they have encountered in the past; if a partition forms, the random sets in one partition are likely to include nodes from the other partition.

A malicious or buggy set of Chord participants could present an incorrect view of the Chord ring. Assuming that the data Chord is being used to locate is cryptographically authenticated, this is a threat to availability of data rather than to authenticity. The same approach used above to detect partitions could help victims realize that they are not seeing a globally consistent view of the Chord ring.

An attacker could target a particular data item by inserting a node into the Chord ring with an ID immediately following the item's key, and having the node return errors when asked to retrieve the data. Requiring (and checking) that nodes use IDs derived from the SHA-1 hash of their IP addresses makes this attack harder.

Even $\log N$ messages per lookup may be too many for some applications of Chord, especially if each message must be sent to a random Internet host. Instead of placing its fingers at distances that are all powers of 2, Chord could easily be changed to place its fingers at distances that are all integer powers of $1 + 1/d$. Under such a scheme, a single routing hop could decrease the distance to a query to $1/(1+d)$ of the original distance, meaning that $\log_{1+d} N$ hops would suffice. However, the number of fingers needed would increase to $\log N/(\log(1+1/d) \approx O(d \log N)$.

A different approach to improving lookup latency might be to use server selection. Each finger table entry could point to the first k nodes in that entry's interval on the ID ring, and a node could measure the network delay to each of the k nodes. The k nodes are generally equivalent for purposes of lookup, so a node could forward lookups to the one with lowest delay. This approach would be most effective with recursive Chord lookups, in which the node measuring the delays is also the node forwarding the lookup.

8. Conclusion

Many distributed peer-to-peer applications need to determine the node that stores a data item. The Chord protocol solves this challenging problem in decentralized manner. It offers a powerful primitive: given a key, it determines the node responsible for storing the key's value, and does so efficiently. In the steady state, in an N-node network, each node maintains routing information for only about $O(\log N)$ other nodes, and resolves all lookups via $O(\log N)$ messages to other nodes. Updates to the routing information for nodes leaving and joining require only $O(\log^2 N)$ messages.

Attractive features of Chord include its simplicity, provable correctness, and provable performance even in the face of concurrent node arrivals and departures. It continues to function correctly, albeit at degraded performance, when a node's information is only partially correct. Our theoretical analysis, simulations, and experimental results confirm that Chord scales well with the number of nodes, recovers from large numbers of simultaneous node failures and joins, and answers most lookups correctly even during recovery.

We believe that Chord will be a valuable component for peer-to-peer, large-scale distributed applications such as cooperative file sharing, time-shared available storage systems, distributed indices for document and service discovery, and large-scale distributed computing platforms.

Acknowledgments

We thank Frank Dabek for the measurements of the Chord prototype described in Section 6.6, and David Andersen for setting up the testbed used in those measurements.

9. References

[1] ANDERSEN, D. Resilient overlay networks. Master's thesis, Department of EECS, MIT, May 2001. http://nms.lcs.mit.edu/projects/ron/.

[2] BAKKER, A., AMADE, E., BALLINTIJN, G., KUZ, I., VERKAIK, P., VAN DER WIJK, I., VAN STEEN, M., AND TANENBAUM., A.

11

Reference section is for all relevant work you mention in the text. Most of the references goes from the Related work and Introduction section.

Never, include as references papers which you do not mention at all, or mention "not-enough". Some reviewers use reference list to understand how good you studied your own field. Try to be up-to-date here also.

Time usage

Try to optimize your time. You paper should be multi-sided, address different aspects, different methods. Find time for every side, even for self-criticism.

Remember:

- Conferences happens all the time, but try to aim at some conference with fixed date.
- Put as much deadlines for yourself as possible. This help you to organize your time.
- All documented small outcomes that are collected in one work produce big work.
- Having all pieces on the paper put your ideas in order and allow not to lose results.
- Find time for reading (and studying), find time for writing.

Tools to use

Researcher has a various set of tools to use for all the Research methods. They are not emerging as often as new papers, but still remember to keep track of the current tools. They are created to help you.

There are a lot of tools for Data communication researcher:

- Simulators (NS-2, NS-3, OverSim, OMNeT++).
- Development tools (Eclipse, Visual Studio, EMacs).
- Document preparation systems (WYSIWYG) ($\TeX$, MS Word, OpenOffice).
- Networking tools (BRITE, Wirshark).
- Data Analysis tools (R, GnuPlot).
- Mathematical labs (MatLab, Mathematica).
- Networking labs (PlanetLab, OneLab).

Other methods to increase own understanding

There is a set of other methods to increase the quality of a research:

- attend Computer Science courses and border Science courses.
- attend public presentations, especially with presenters from other groups and Universities.
- take part in the review process.

What else?

Non-formal collaboration!!!

Questions and Comments?

Thank you.