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Computer Networking : Principles, Protocols and Practice

Part 2 : Applications

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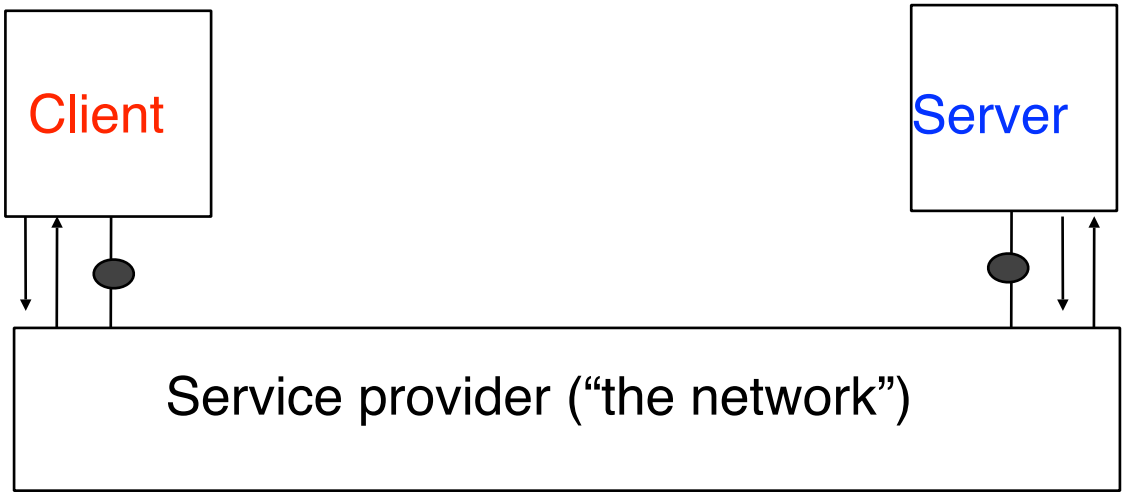
The Application Layer

- Contents
  - The client-server model
  - Name to address resolution
  - email
  - world wide web
  - peer-to-peer applications

The client server model



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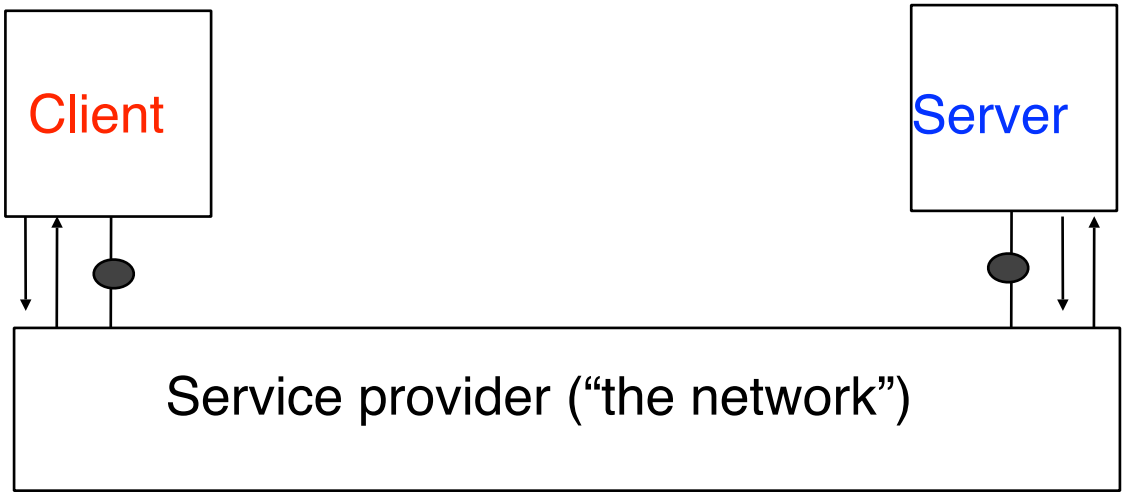
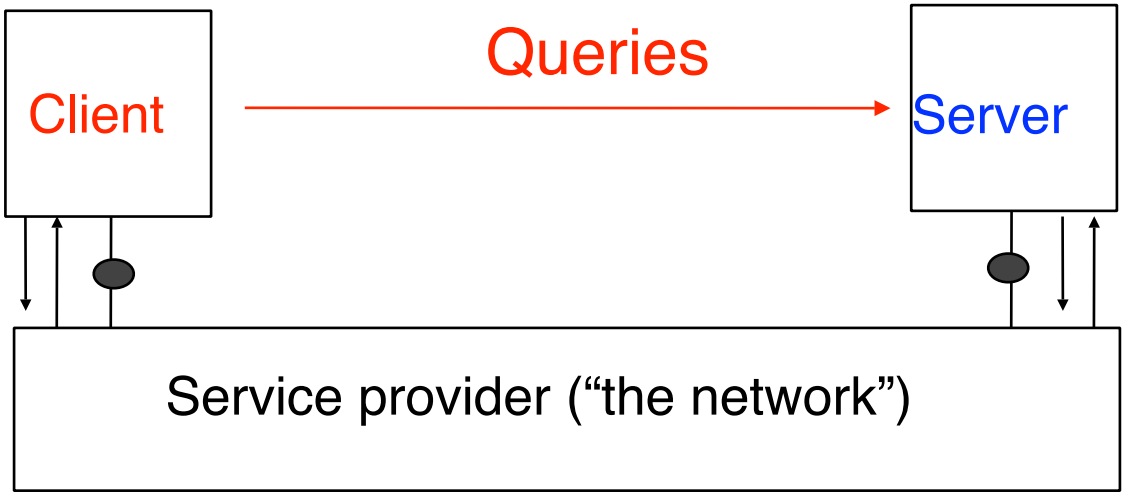


- Client
  - interacts with server through transport layer
  - sends queries or commands

The client server model



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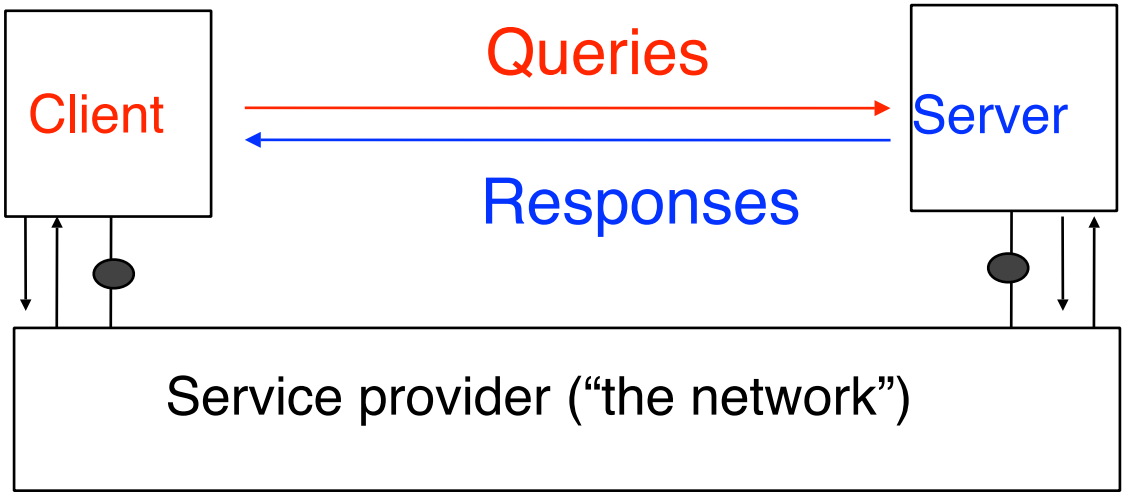
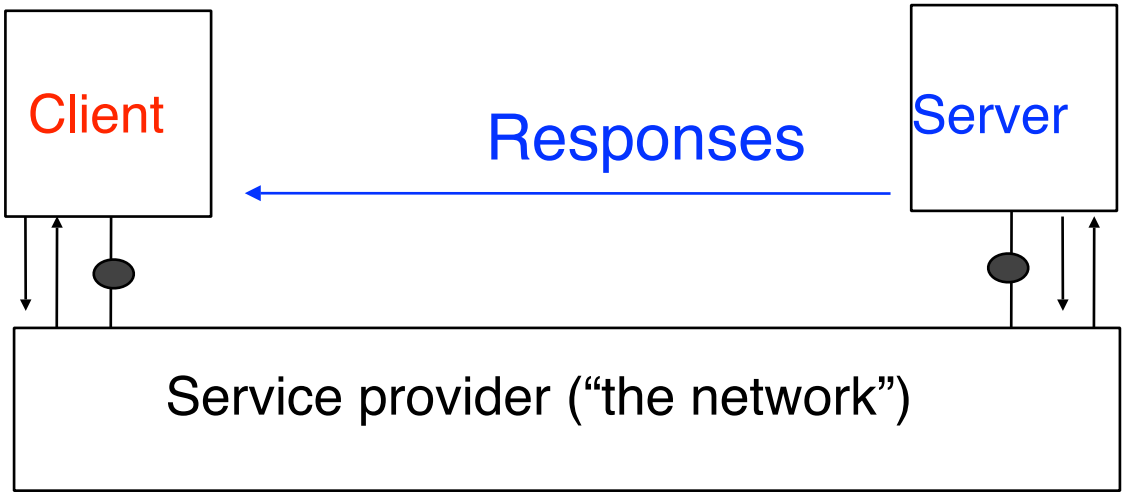


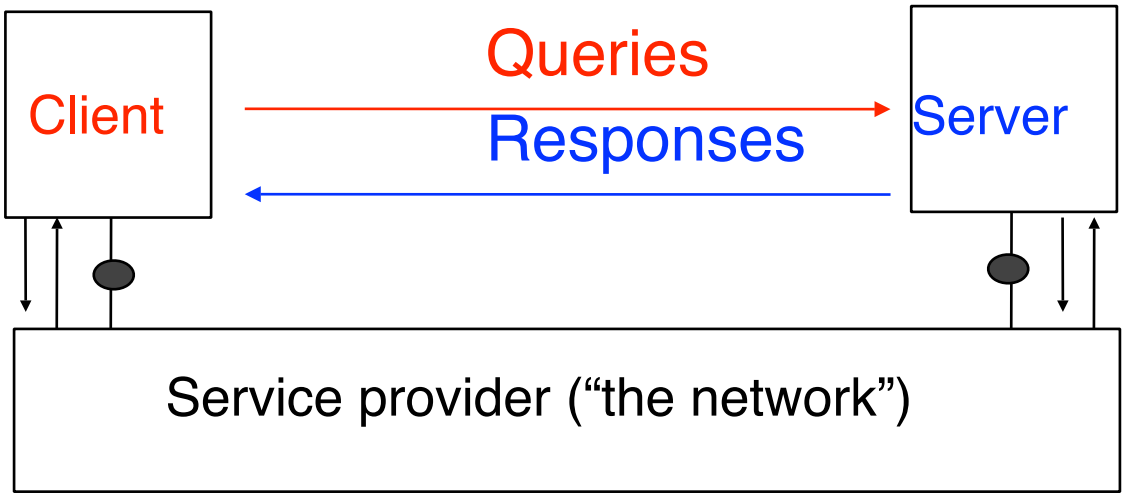
- Client
  - interacts with server through transport layer
  - sends queries or commands
- Server
  - Answers the queries received from clients
  - Executes the commands from clients
  - Many clients can use the same server
- Example : email, www, ...

The client server model (2)



- Client and servers interact with service provider
- Both the client and the server must speak the same language
  - Application-level protocol : set of syntactical and semantical rules that define the messages exchanged between the client and the server and their ordering

The client server model (2)



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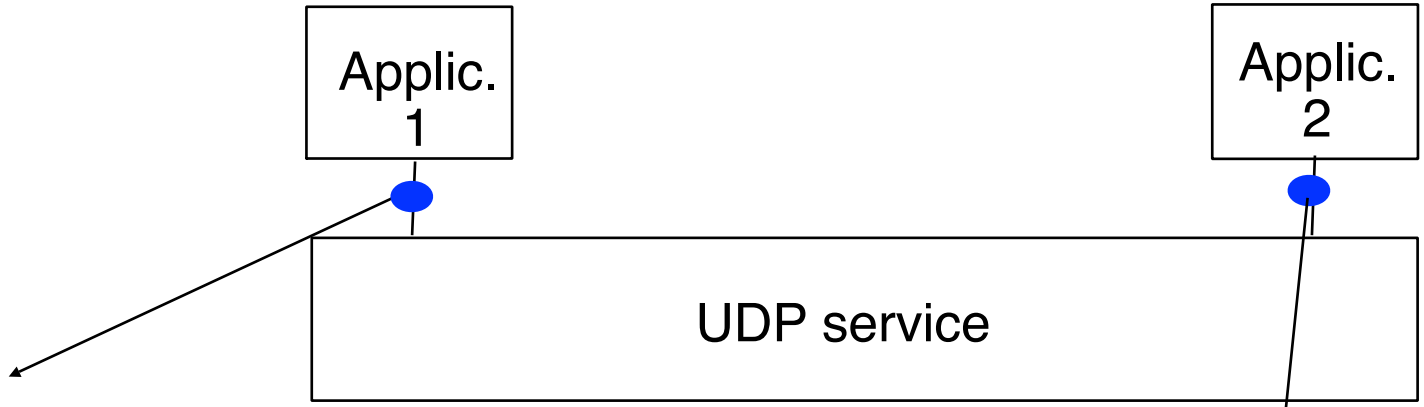
Transport service on the Internet

- On the Internet, applications can use two different transport services
  - The service provided by the User Datagram Protocol (UDP)
    - unreliable connectionless service with error detection
  - The service provided by the Transmission Control Protocol (TCP)
    - reliable bytestream connection-oriented service

UDP service

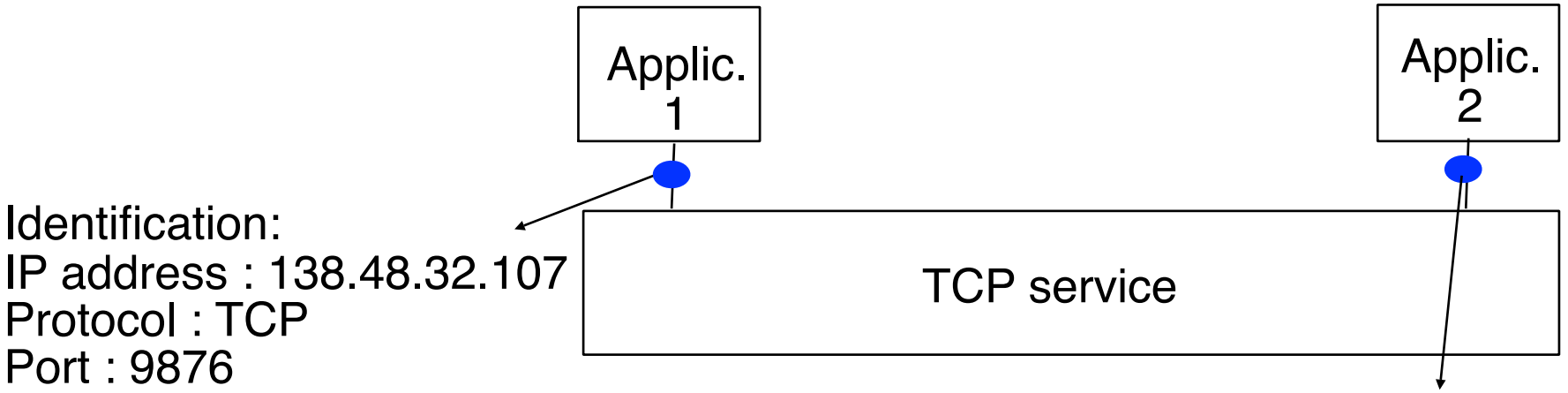


Identification:
IP address : 2001:6a8:3080:2:217:f2ff:fed6:65c0
Protocol : UDP
Port : 1234

Identification
IP address : 2001:4860:a005::68
Protocol : UDP
Port : 53

- Identification of an application
  - IP address + UDP + port number
- Characteristics of UDP service
  - connectionless
  - unreliable
    - messages can be lost
    - transmission errors can be detected but not recovered
    - sequence is not preserved
  - Maximum size of messages : almost 64 Kbytes

TCP service



- Identification of an application
  - IP address + UDP + port number
- Characteristics of TCP service
  - connection-oriented
  - bidirectional
  - reliable
  - byte stream
  - connection release
    - abrupt if initiated by service provider
    - graceful or abrupt if initiated by user

Internet applications

- Contents
  - The client-server model
  - Name to address resolution
  - email
  - world wide web
  - peer-to-peer applications

Names and addresses

Names and addresses

- Address of a server
  - IP Address of the host on which the server is running port number (TCP or UDP)
    - usually well known port number

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  - Difficult to remember an IP address for a human

Names and addresses

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- Drawback
  - Difficult to remember an IP address for a human
- Idea
  - Replace IP address by a hostname
  - Easier for humans
    - but IP address is necessary to contact server
  - How to translate a hostname in an IP address ?

Names and addresses (2)

- `hosts.txt` file
  - contains the name-address table
  - must be updated regularly

```
#
# Internet host table
#
127.0.0.1         localhost
138.48.32.99      babbage
138.48.32.100     leibniz
138.48.32.1       routeur
138.48.32.92      corneille
138.48.32.107     backus
138.48.20.152     arzach
138.48.32.137     almin01
138.48.32.170     duke
```

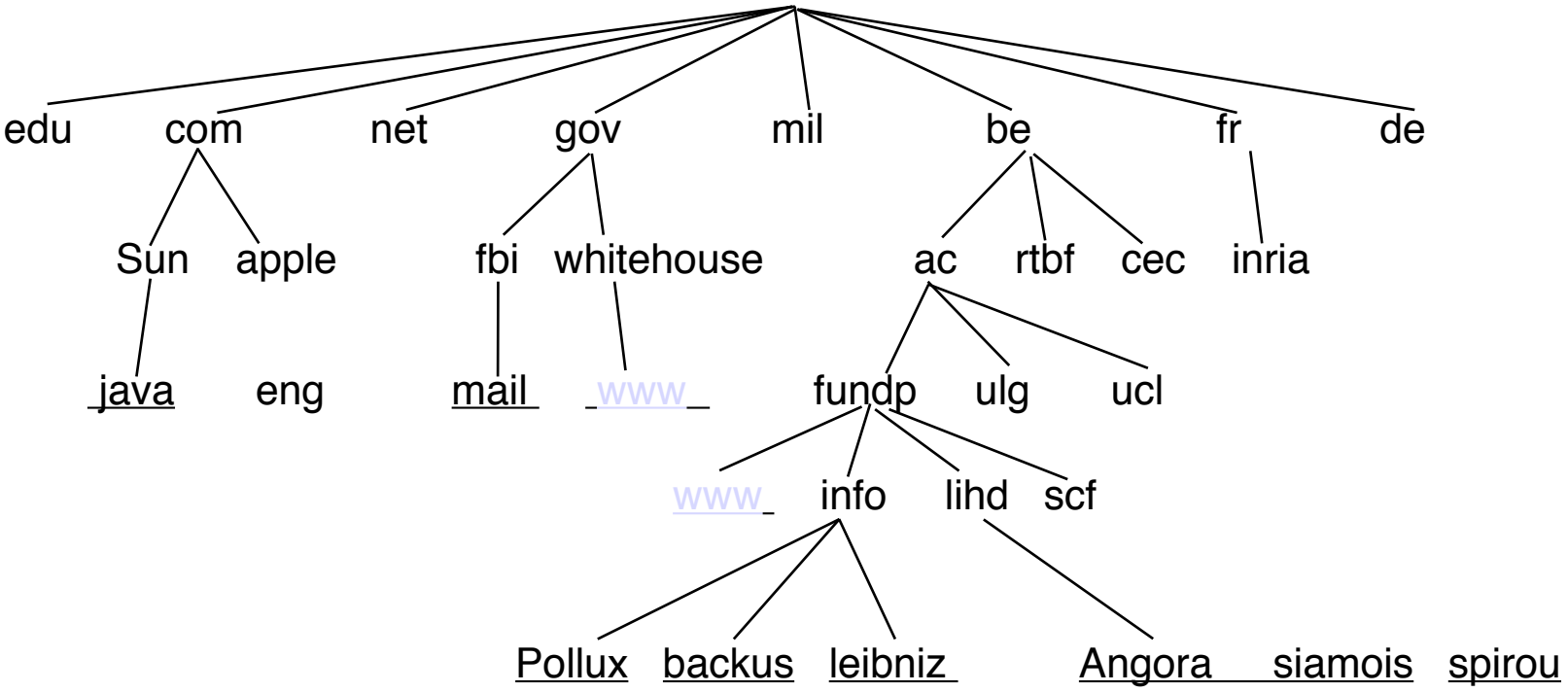
  - cannot be used in a large network

Hostnames

- Requirement
  - Host names should be unique
- How to achieve this in a scalable manner ?
  - Introduce hierarchy
  - Each hostname is composed of two parts
    - domain name (globally unique)
    - hostname (unique within a given domain)
  - How to uniquely distribute domain names ?
    - Introduce hierarchy
    - A small number of top-level domain names
    - Inside each top-level domain, allocate uniquely second level domain names
    - Inside each seconde-level domain, allocate uniquely either third-level domain names or host names,
    - ...

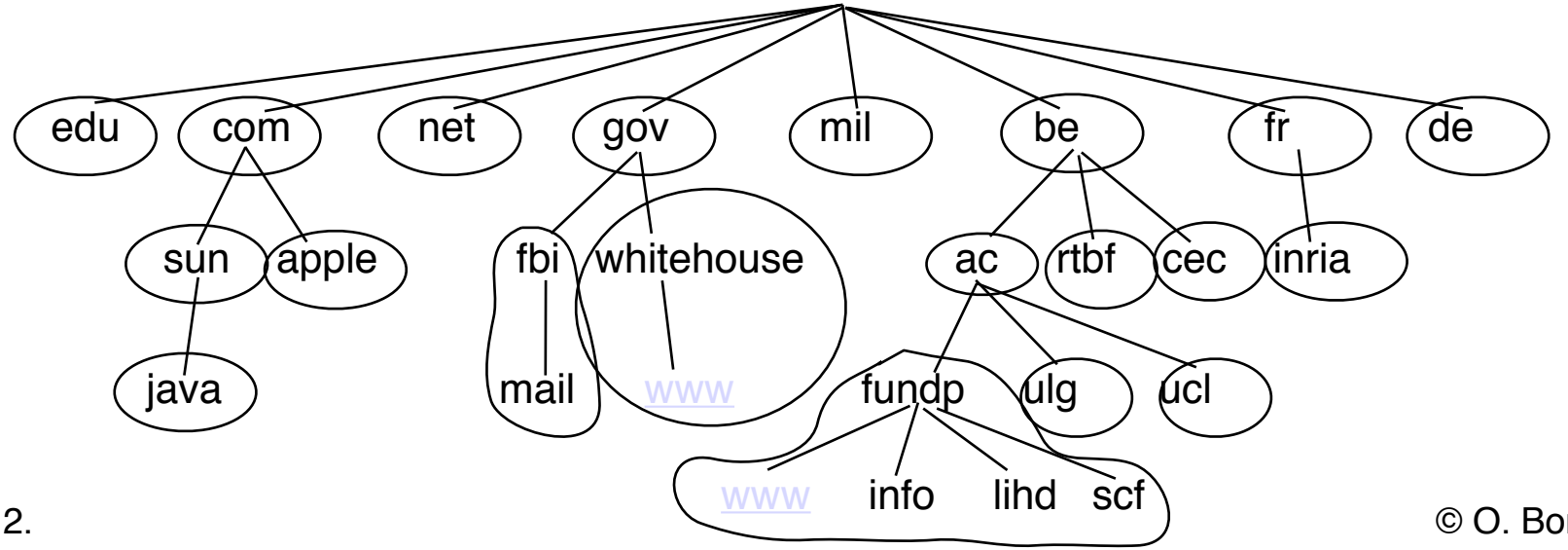
Host names and domain names

- Tree of all host names



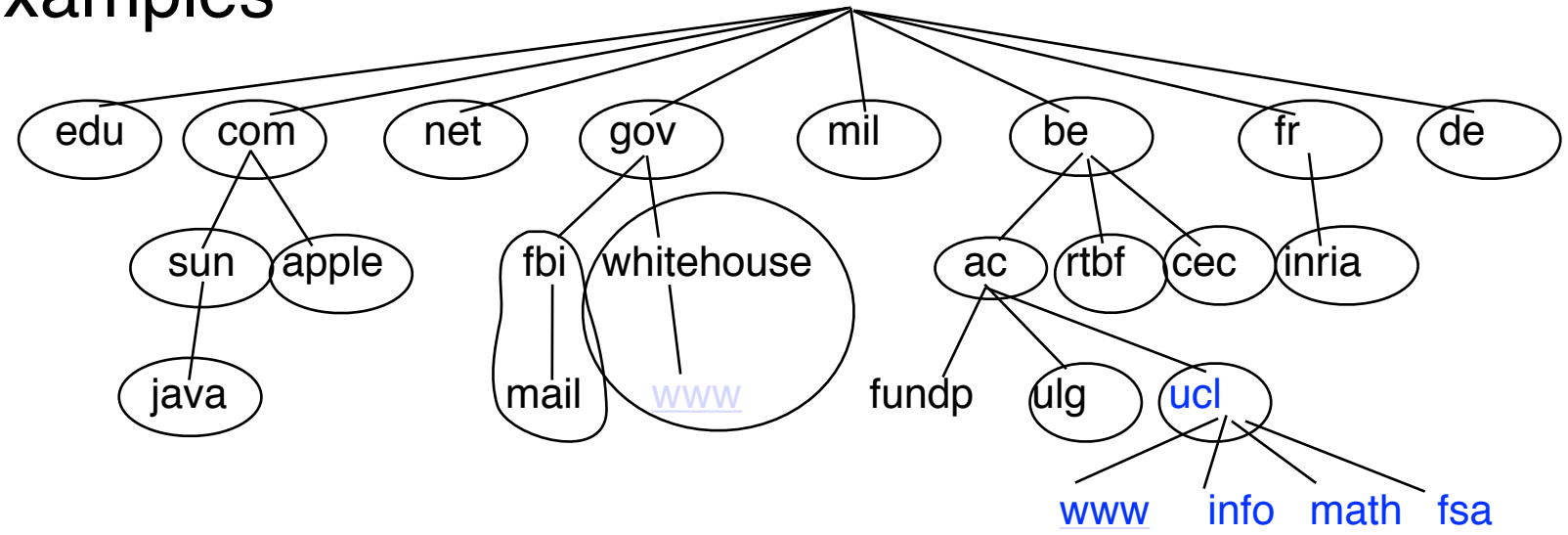
How to translate names into addresses ?

- How to efficiently translate a host name ?
  - By using a centralised database
    - there are more than 1 billion host names today
  - By using a distributed database
    - DNS : Domain Name System
    - relies on the hierarchy of domain names
    - there is one server responsible for each domain and this server must be queried to translate host names inside this domain



How to translate names into addresses ?

- Domain Name Service (DNS)
  - Each DNS server is responsible for a domain and knows
    - The IP addresses of all host names in this domain
    - The IP addresses of the DNS servers responsible for subdomains
  - Examples



    - java.sun.com
    - www.ucl.ac.be

DNS resolver

- To be able to translate name to addresses, a DNS implementation needs
  - to know actual list of IP addresses of root servers
  - to implement the DNS protocol and traverse the domain names hierarchy
  - Difficult to do this on all endhosts

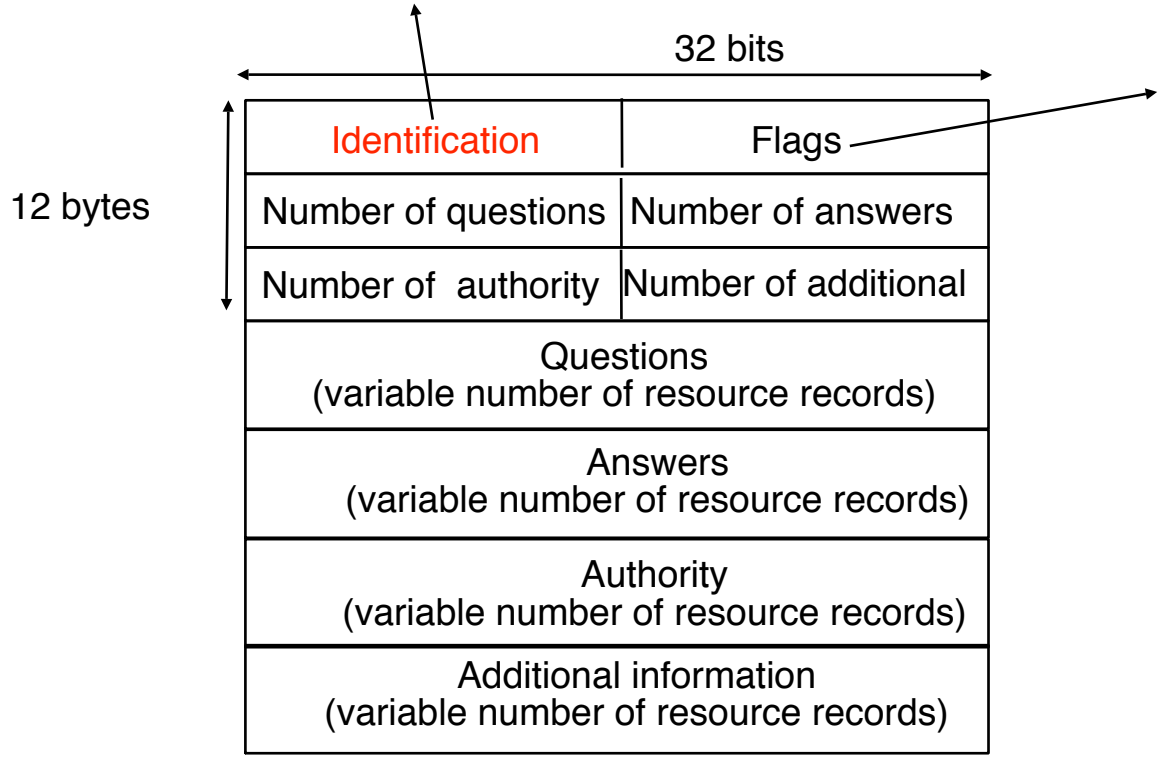
- Solution
  - DNS resolver
    - one resolver for a set of endhosts
    - maintains up-to-date list of IP addresses of root servers
    - implements DNS protocol
  - endhosts
    - only need to be able to send DNS requests to resolver
    - must know IP address of closest DNS resolvers

DNS : optimisations

- Reduce risk of failures
  - several root-servers
  - server DNS servers authoritative for each domain
  - each endhost can send queries to multiple resolvers
- Improved performance
  - avoid sending several times the same query
  - cache memory on DNS resolvers containing
    - recent name-addresses translations
    - addresses of DNS servers recently contacted
- DNS protocol
  - usually runs over UDP
  - sometimes is also used over TCP

DNS : message format

Each DNS request contains a number that will be returned in the response by the server to allow the client to match the request.



- Question/Response
- Recursive question or not
- Authoritative answer or not
- Possible error

DNS : resource records

- Each DNS messages is composed of resource records (RR) encoded as TLV
  - < Name, Value, Type, TTL>
  - Types de RR
    - A (Address)
      - Name is a hostname and Value an **IPv4 address**
    - AAAA (Address)
      - Name is a hostname and Value an **IPv6 address**
    - NS (NameServer)
      - Name is a domain name and Value is the hostname of the DNS server responsible for this domain
    - MX (Mail Exchange)
      - Name is a domain name and Value is the name of the SMTP server that must be contacted to send emails to this domain
    - Type CNAME
      - Alias

Lifetime of the RR in server's cache

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Email

- Simplified model
  - Alice sends an email to Bob

Alice@a.net

Alice's
email server

b.net 's
email server

Bob@b.net

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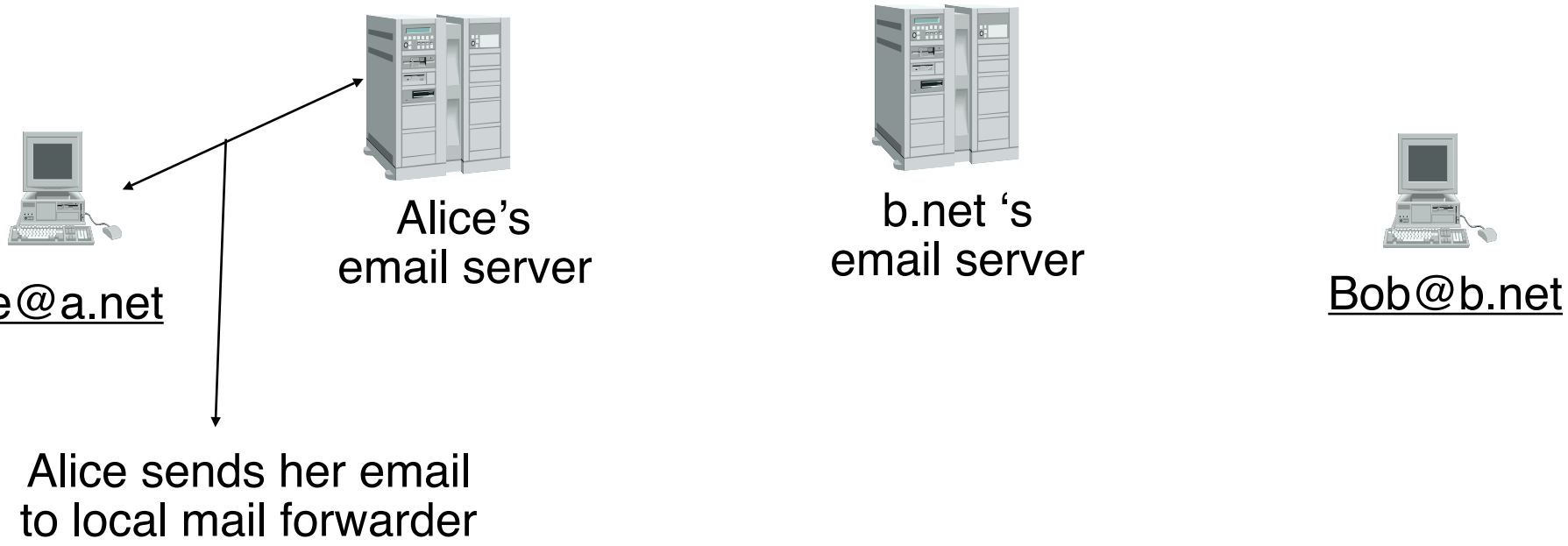

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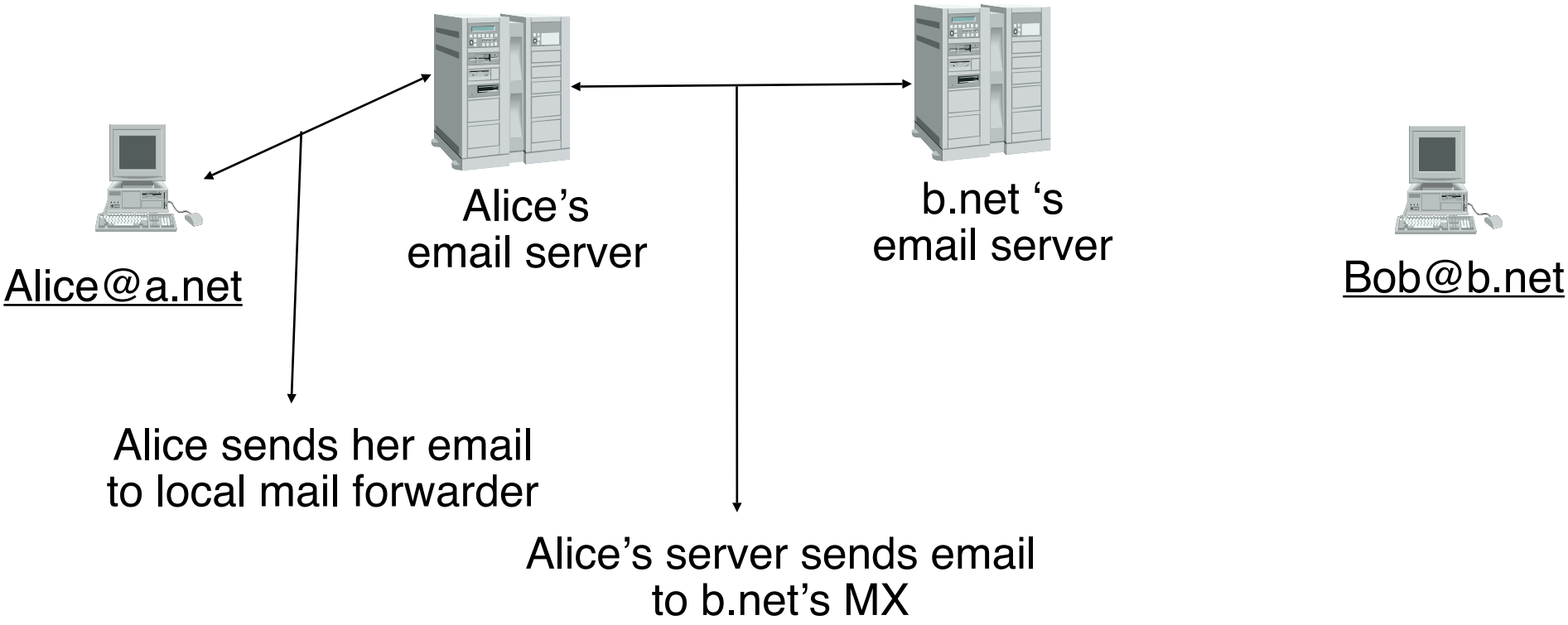

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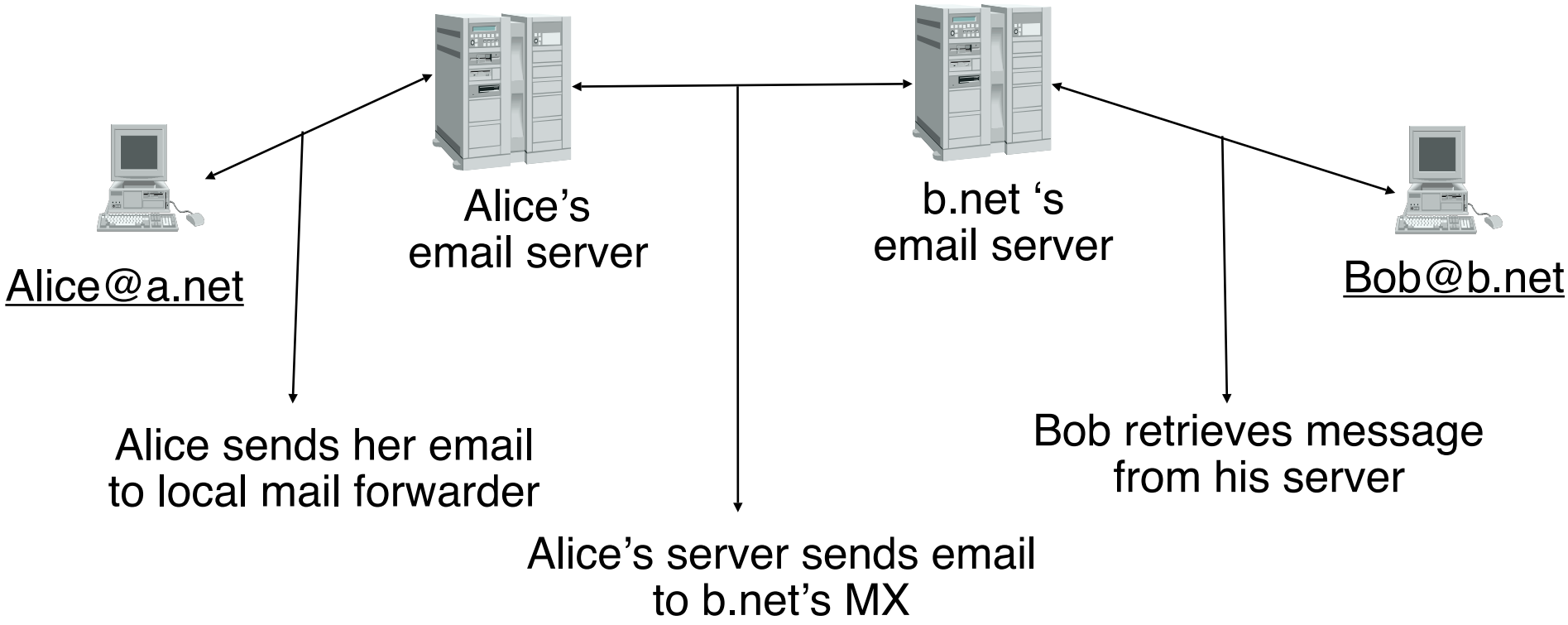
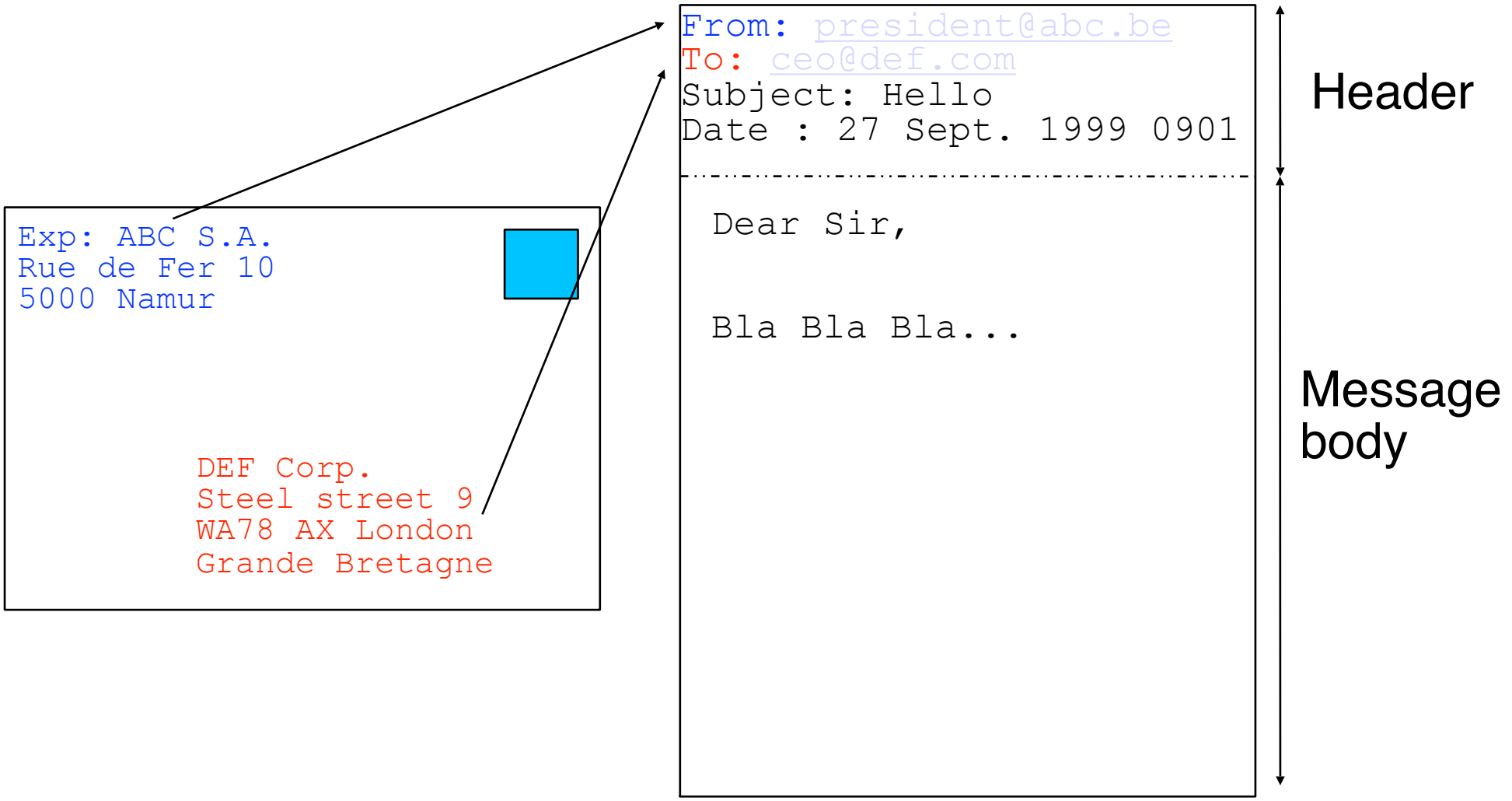


Email message format



Message format (2)

- Header format
  - Contains only US-ASCII (7bits) characters
  - At least three lines that end with <CRLF>
    - From: sender@domain
    - To:recipient@domain
    - Date: <creation date of message>
      - example : 26 Aug 199 1445 EDT
  - Optional fields
    - Subject: subject of message
    - cc: copy@domain
    - Message-ID: <number@domain>
    - Received: information on path followed by message
    - In-Reply-To: <message-ID>
  - Header ends with empty line (<CRLF>)

MIME

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- Internet email was designed for US-ASCII
  - How to transmit more complex messages ?

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- Internet email was designed for US-ASCII
  - How to transmit more complex messages ?
- Multipurpose Internet Mail Extensions
  - Improved email message format
  - Constraints
    - must remain compatible with old email servers
      - most of them only support US-ASCII and short lines
    - must support non-English text
      - character set must be beyond 7bits US-ASCII
    - must support various formats in a single message
      - message body, attachments, ...
    - must allow to transmit audio, video, ...
      - need to identify the type of content

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      - need to identify the type of content
- Solution
  - add new optional fields in header
  - add optional fields inside message body when

MIME (2)

- New header fields
  - MIME-Version:
    - version of MIME used to encode message
    - current version : 1.0
  - Content-Description:
    - comment describing the content of the message
  - Content-Type:
    - type of information inside message
  - Content-Transfer-Encoding:
    - how the message has been encoded
  - Content-Id:
    - unique identifier for the content

MIME: Content-Type

- Content-Type : type/encoding
  - type of content
    - text, image, video, application
    - multipart
  - encoding of content
    - text/plain , text/html
    - image/gif, image/jpeg
    - audio/basic
    - video/mpeg, video/quicktime
    - application/octet-stream, application/postscript
    - multipart/alternative
      - message contains several times the same information with different encodings
    - multipart/mixed
      - message contains several information of different types
        - example : text of message body and attachment

Character sets and content encoding

- How to support rich character sets ?
  - Content-Type: text/plain; charset=us-ascii
    - ASCII 7bits, default
  - Content-Type: text/plain; charset=iso-8859-1
    - Character set suitable for Western European languages, defined by ISO, 8 bits per character
    - Content-Type: text/plain; charset=unicode
    - Universal character set, defined by ISO, 16 bits per character
- How to encode non-text data ?
  - data must be encoded in US-ASCII 7 bits characters
  - Base64
  - uses ASCII characteres A...Z,a...z,0...9, "+" et "/"
    - A=0, B=1, C=2, ... +=62 et /=63
  - Each character is used to encode 6 bits
    - 24 bits from initial message -> 4 ASCII characters
  - Special character “=” used for padding

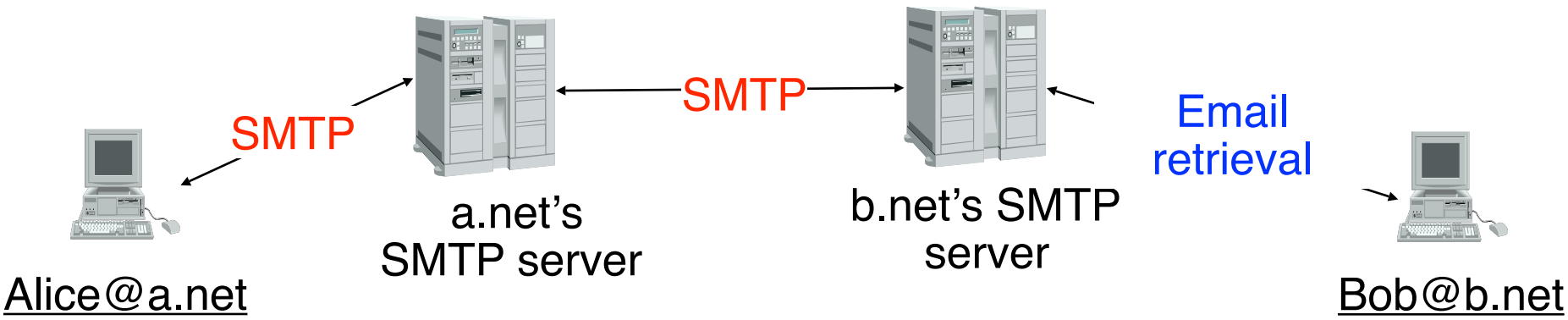
Multipart/mixed

- How to place different contents and encoding in a single message ?
  - We need a delimiter between the different content types placed inside message body

```
Date: Mon, 20 Sep 1999 16:33:16 +0200
From: Nathaniel Borenstein <nsb@bellcore.com>
To: Ned Freed <ned@innosoft.com>
Subject: Test
MIME-Version: 1.0
Content-Type: multipart/mixed; boundary="simple boundary"

preamble, to be ignored

--simple boundary
Content-Type: text/plain; charset=us-ascii

partie 1

--simple boundary
Content-Type: text/plain; charset=us-ascii

partie 2
--simple boundary
```

Email transmission

- SMTP : Simple Mail Transfer protocol
  - uses TCP service
  - Address of SMTP server
    - IP address of server + TCP + port number: 25
      - RR of type MX can be used to find the SMTP server responsible for a given domain



SMTP

- Client-server model
  - Server waits for email messages to relay/deliver
  - Client sends email messages through server
- Application-level protocol
  - client opens TCP connection
  - Client sends commands composed of
    - `command parameter <CRLF>`
      - HELO
      - MAIL FROM:
      - RCPT TO:
      - DATA
      - QUIT
  - Server answers with one-line replies
    - `numeric_code comment (text) <CRLF>`
      - 250 OK
      - 221 closing

SMTP (2)

- Three phases of SMTP
  1. Establishment of an SMTP association
     - TCP connection established upon request from client
     - Server greetings
     - HELO command from client
  2. Message transfer
     - MAIL FROM: <user@domaine>
     - RCPT TO: <user@domaine>
     - DATA
       - transmission of entire message including headers
       - one line containing only the dot "." characters marks end of message
     - Other subsequent messages can be transmitted after
  3. Release of the SMTP association
     - QUIT
     - Closing message from server
     - TCP connection is closed

Retrieval of email messages

- In the old days
  1. Destination is always connected to the Internet
     - email addresses are username@hostname
     - When an email arrives, it is stored in a file that belongs to the user, e.g. `/var/mail` on Unix

- Today
  - Most networks have one or a few SMTP servers used to receive emails, but also detect spam, viruses, ...
  - Endusers retrieve their emails from this server
    - Post Office Protocol (POP)
    - Internet Mail Access Protocol (IMAP)
    - Webmail

POP

- Goal
  - Allow authenticated users to retrieve email messages from server
- Operation
  - POP uses TCP service
  - Address of POP server
    - Host address + TCP + port number : 110
  - Client send commands
    - command : one ASCII line ending with <CRLF>
    - `USER, PASS, STAT, RETR, DELE, QUIT`
  - server replies with
    - `+OK` if command was successful
      - email messages follow some +OK replies
    - `-ERR` in case of errors

POP (2)

- Three phases of the protocol
  1. Authorisation : checking the user credentials
     - USER <username>
     - PASS <password>
  2. Transaction
     - retrieval and removal of messages
     - STAT
       - list headers of stored messages
     - RETR <n>
       - retrieval of the nth message
     - DELE <n>
       - the nth message is marked for deletion
  3. Update
     - End of the retrieval phase
       - Messages marked for deletion are removed from server
       - TCP connection is closed

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FTP : File Transfer Protocol

- Protocol from the old days
  - allows a client to send/retrieve files from a server
- Problems solved by FTP
  - User authentication
    - username, password
  - Filesystem traversal
    - browse directories on server and locate files
  - file transfer
    - to or from the server

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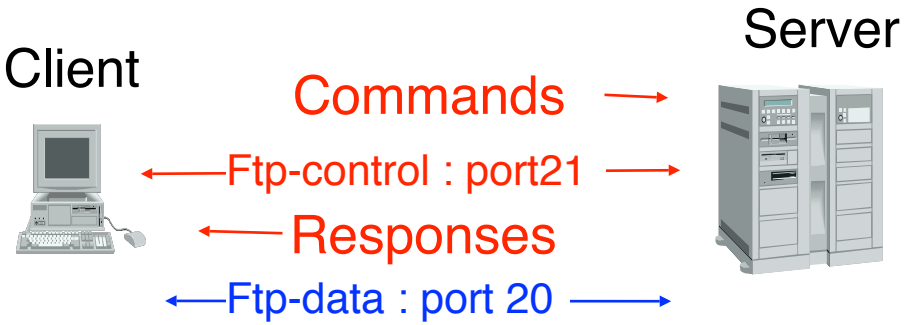
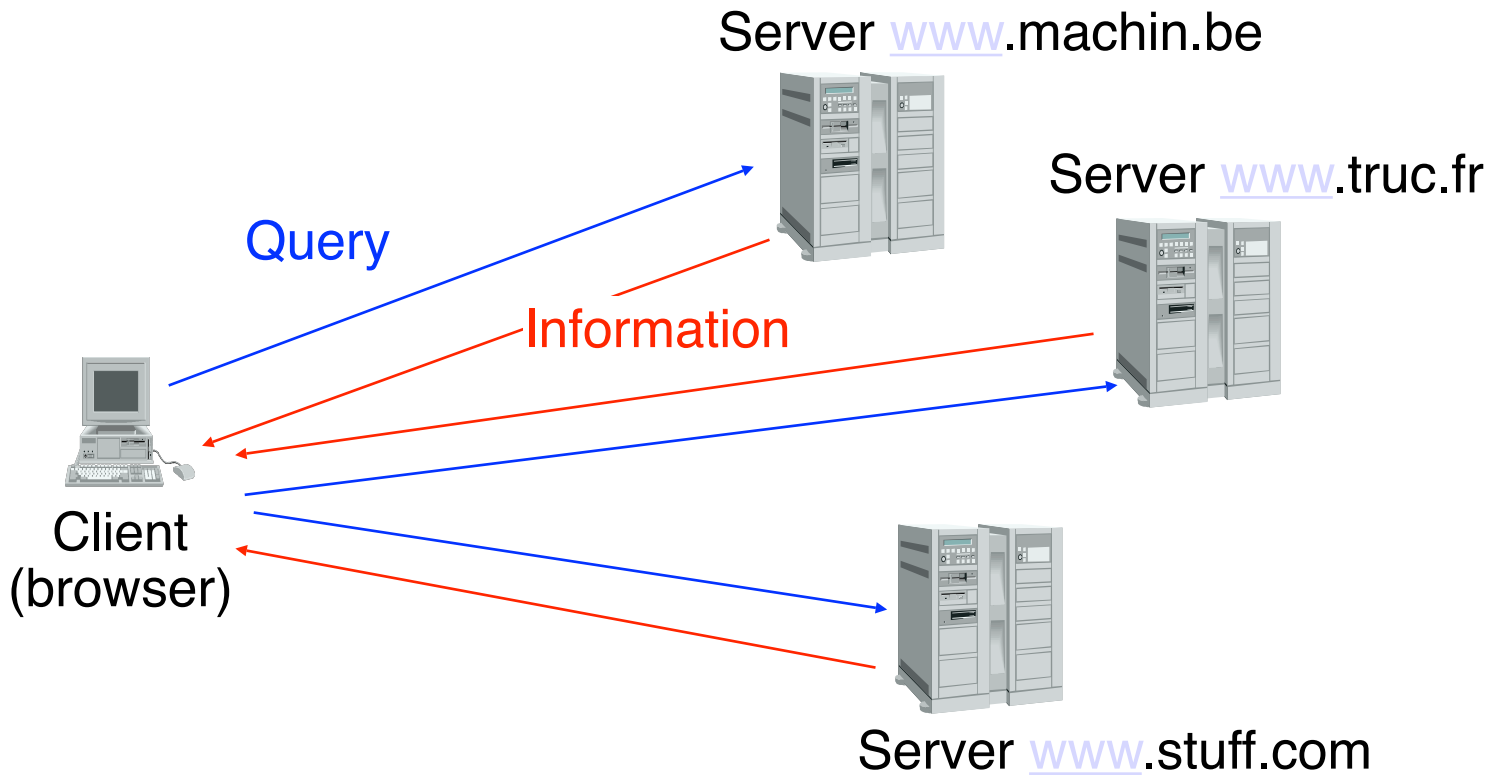


FTP : main commands

- Main commands
  - USER <user>
    - username, ftp for anonymous access
  - PASS <pass>
    - allows user to send password associated to username
  - SYST
    - information about type of server
  - CWD <path>
    - directory traversal
  - STOR <file>
    - save file in the current directory on server
  - RETR <file>
    - retrieve file from current directory on server
  - PORT <B1,B2,B3,B4,B5,B6>
    - use TCP connection on port B5*256+B6 on B1.B2.B3.B4

World Wide Web

- Goals
  - Allow browsers to browse hypertext documents stored on multiple servers



World Wide Web (2)

- The five key elements of www

1. An addressing scheme that allows to identify any document stored on a server
   - URL : Uniform Resource Locator
2. An hypertext language that allows to easily write documents with hypertext links
   - HTML : HyperText Markup Language
3. An efficient and lightweight application-level protocol to exchange documents
   - HTTP : HyperText Transfer Protocol
4. Servers
5. Clients (browsers)

Uniform Resource Locator (URL)

Uniform Resource Locator (URL)

- generic syntax : <protocol>://<document>
  - protocol used to retrieve document from server
    - http is the most common one but others are frequently used
  - document indicates the server and the location of the document
  - *<user>:<password>*@<server>*:<port>*/<path>
    - <user> : optional username
    - <password> : optional password
    - <machine> : hostname or IP address of the server that hosts the document
    - <port> : optional port number
    - <path> : document location on server
  - examples
    - http://www.info.ucl.ac.be
    - http://alice:secret@inl.info.ucl.ac.be:80/index.html

HTML

- HyperText Markup Langage
  - Language used to encode documents on the web
  - Keywords
    - <HTML>...</HTML>
    - <HEAD>...</HEAD>
    - <BODY>...</BODY>
    - <TITLE>..</TITLE>
    - <B>...</B>
    - <I>...</I>
    - <H1>...</H1>
    - <P>
    - <HR>
    - <UL>...</UL>
    - <OL>...</OL>
    - <IMG SRC="URL">
    - <A HREF="URL">*text anchor*</A>

HTML (2)

- Example

```
<HTML>

<HEAD>
<TITLE>HTML test page</TITLE>
</HEAD>

<BODY>
<IMG SRC="http://www.images.be/logo.gif">
<H1>Web servers from UCL UCL<P></H1>
<HR>
<UL>
 <LI><A HREF="http://www.uclouvain.be">UCL</A>
 <LI><A HREF="http://www.info.ucl.ac.be">CSE Dept.</A>
 <LI><A HREF="http://www.math.ucl.ac.be">Math</A>
</UL>
</BODY>

</HTML>
```

Header

Body

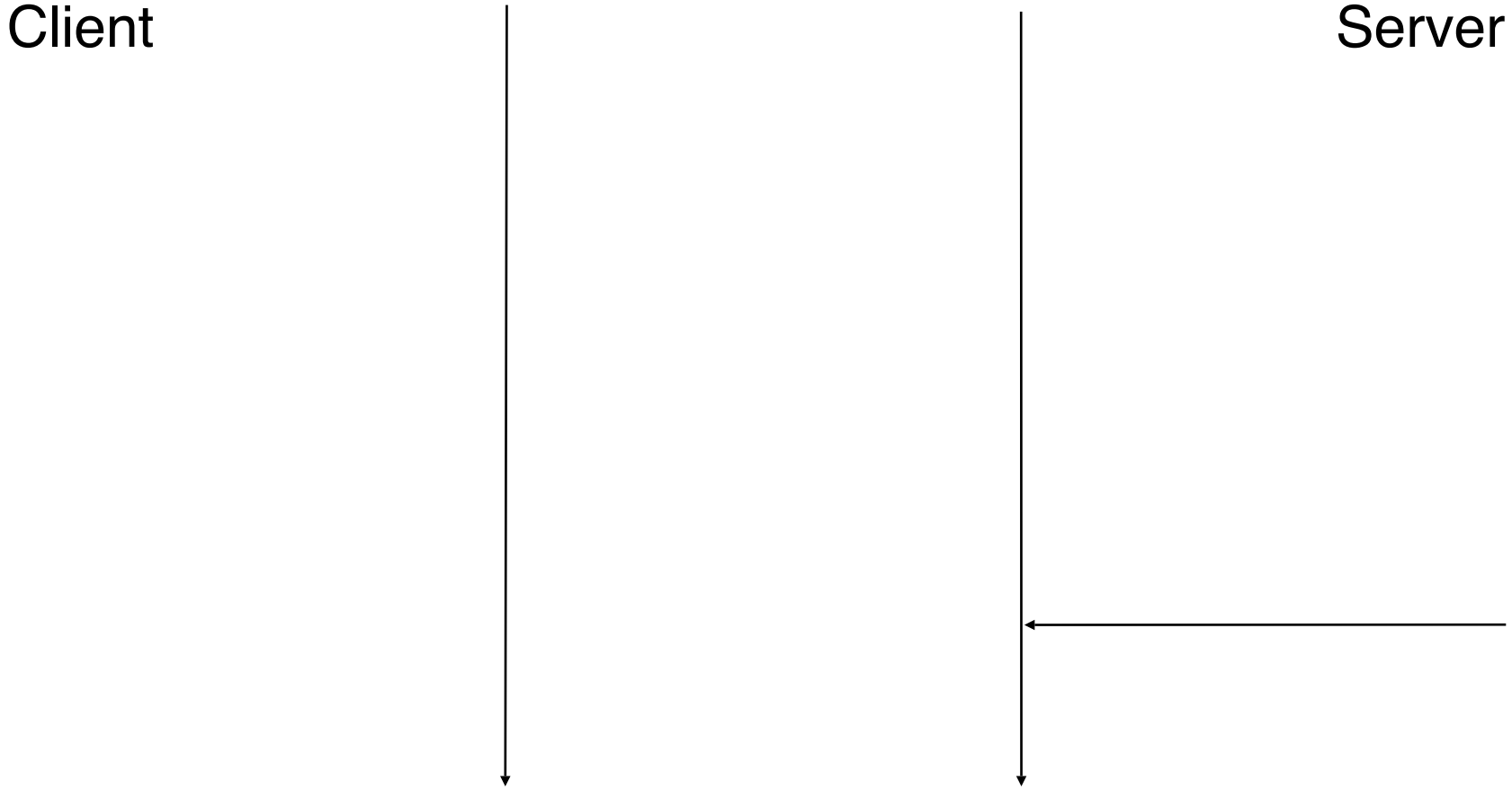
Image on remote server

First level title

External hypertext link

Information transfer www

- HTTP 1.0 - non-persistent connection
  - Principle
    - relies on TPC service (default port : 80)
    - Client sends request, server sends reply



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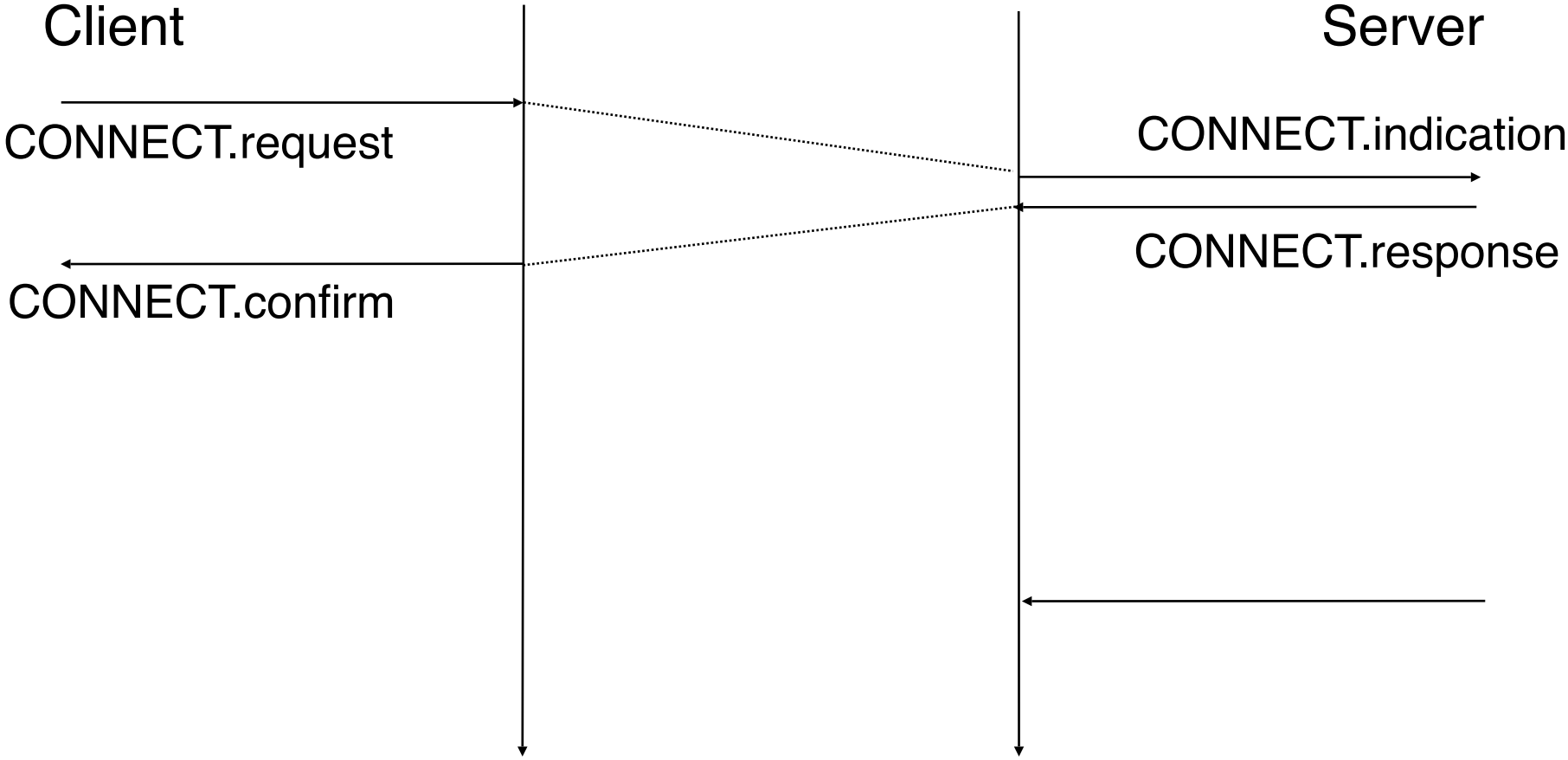

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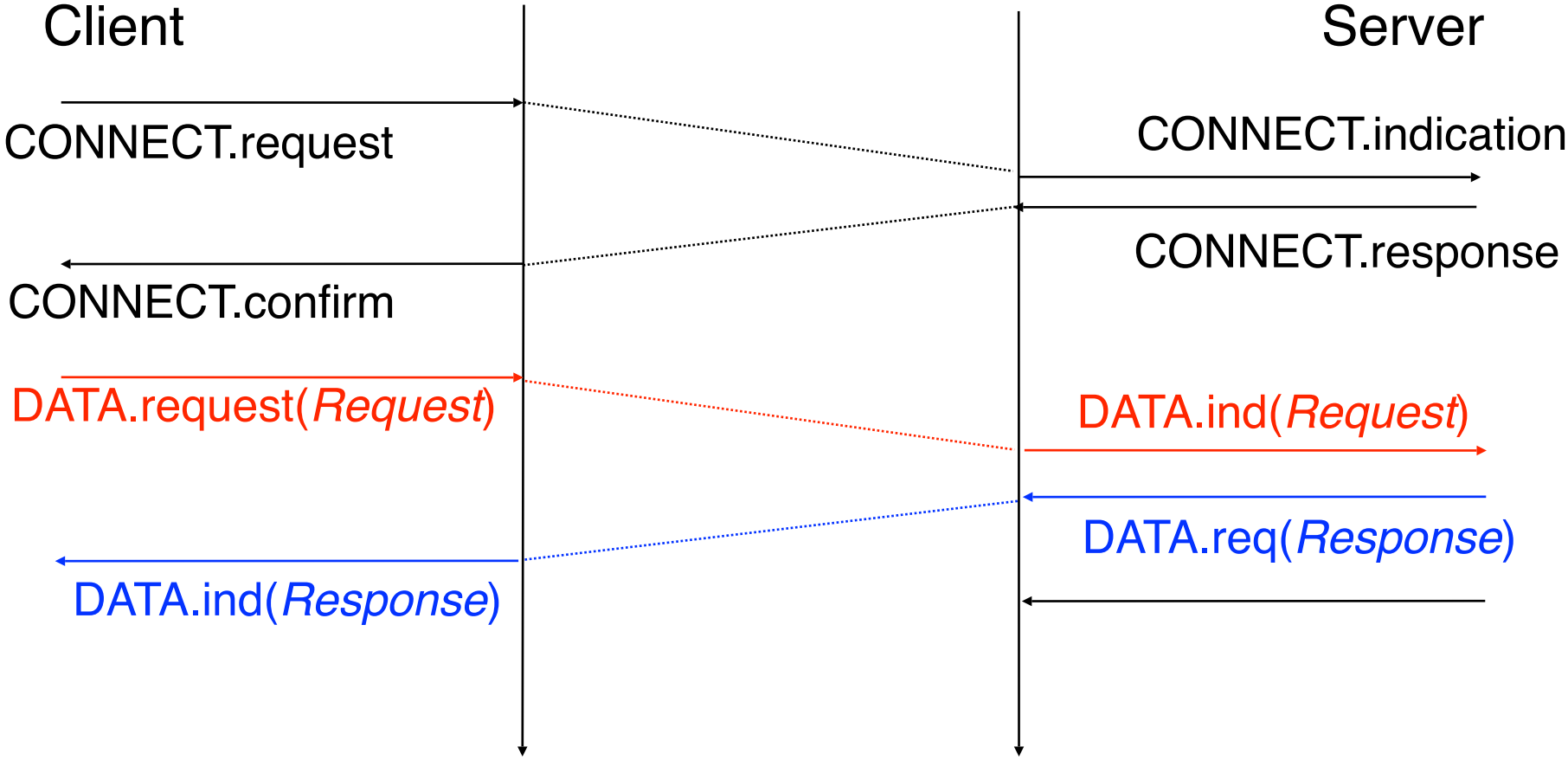
    - Client sends request, server sends reply



Information transfer www

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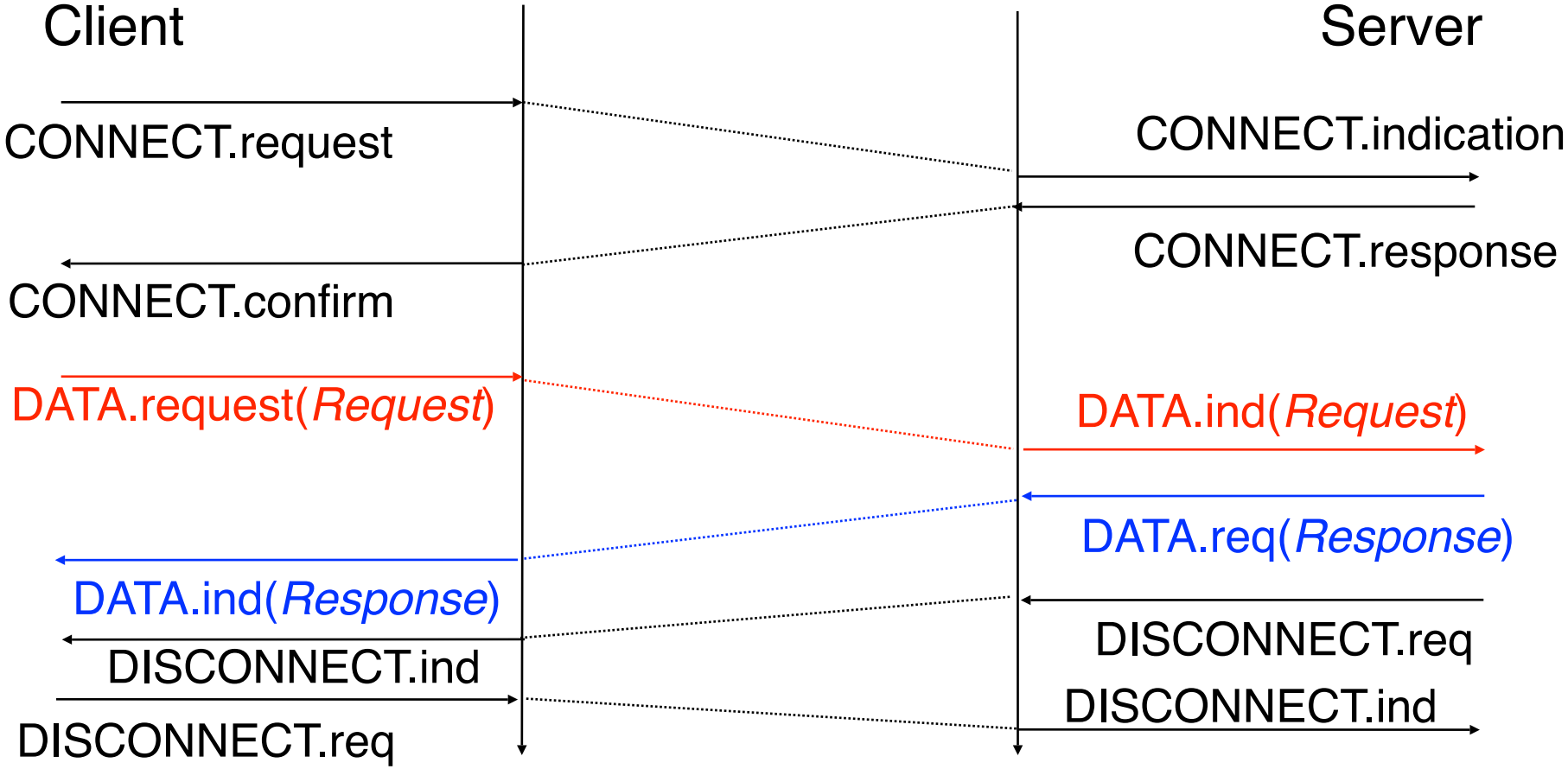


HTTP

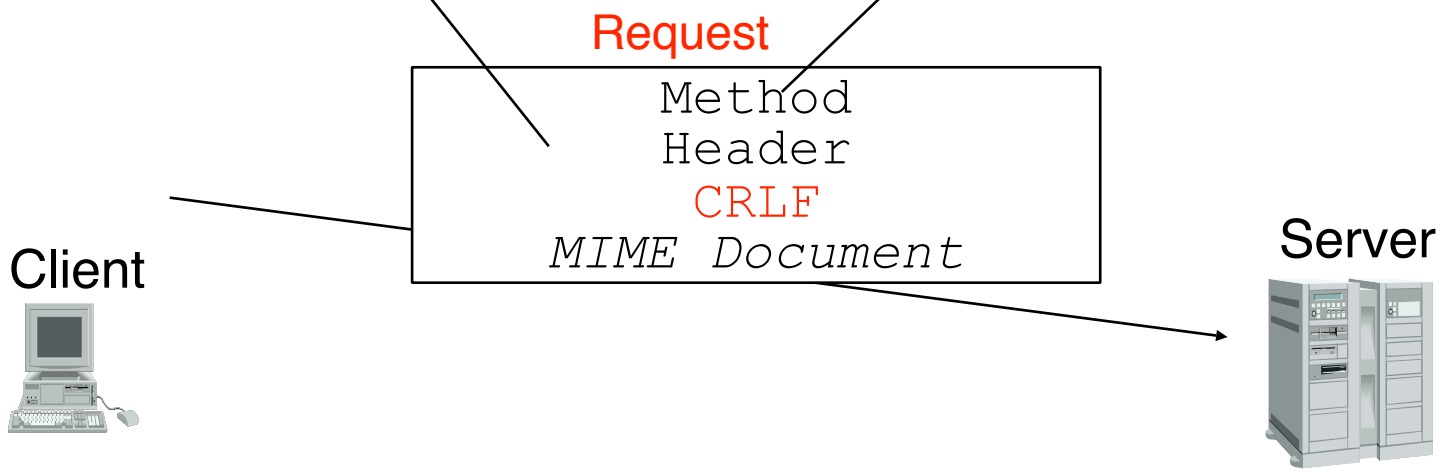
Client

Server

HTTP

Header contains additional information about request sent by client

Method
GET
POST
...



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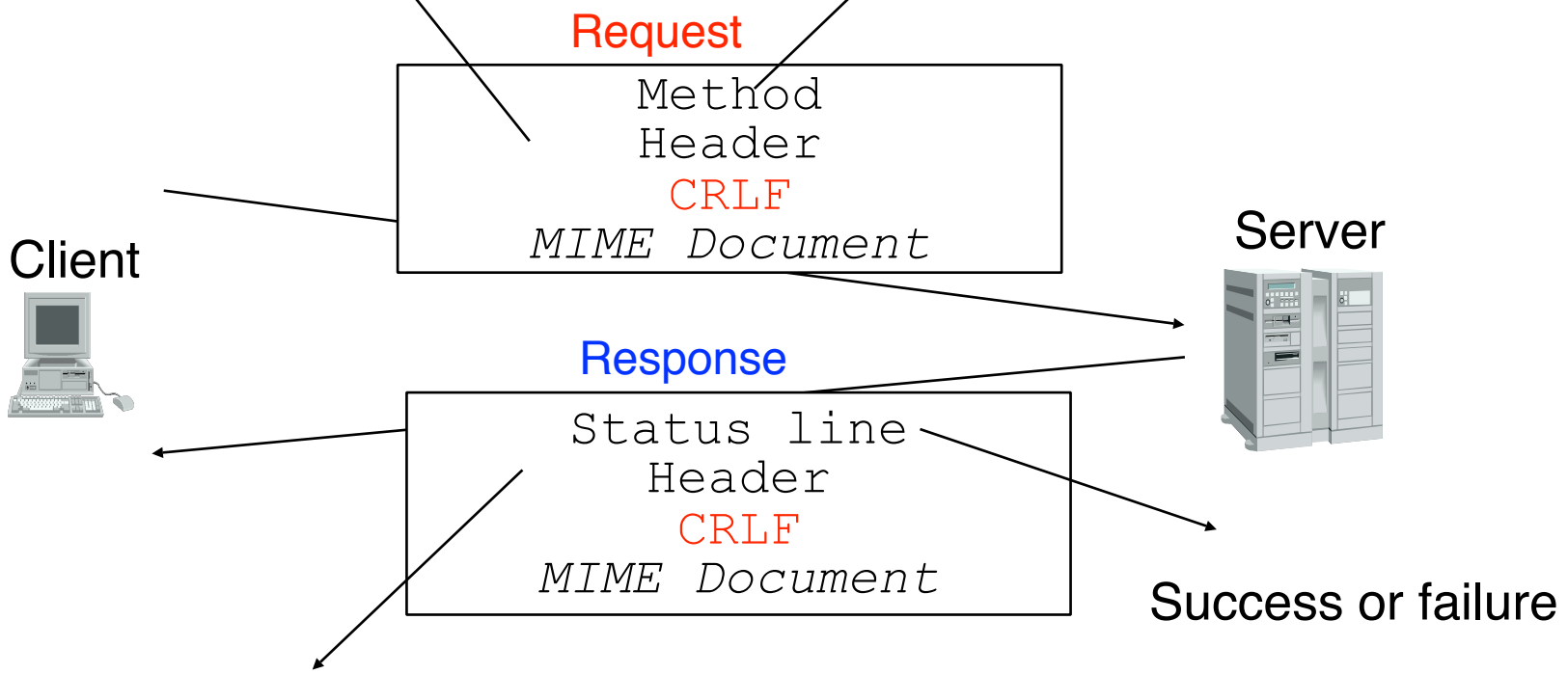

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HTTP

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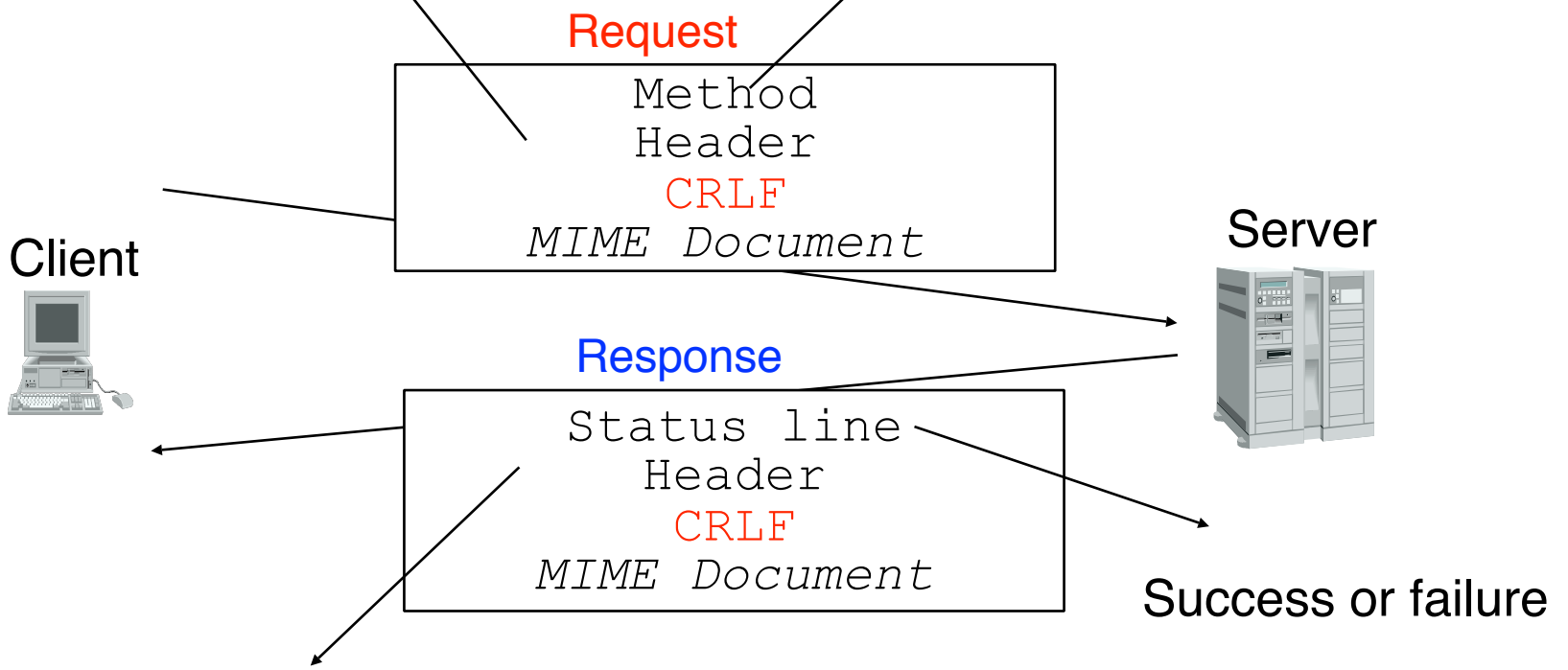


Header contains information about server and optional parameters specific to response

HTTP is a stateless protocol, server does not maintain any state from one request to another

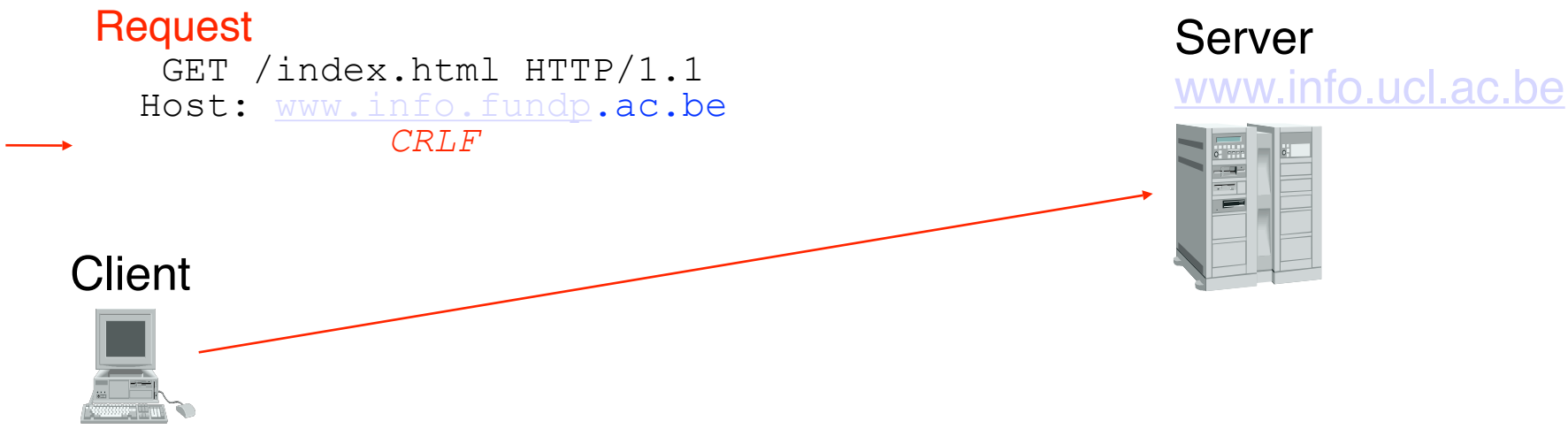
- POP, FTP, SMTP are examples of stateful protocols in contrast

HTTP : Example

Server
www.info.ucl.ac.be

Client

HTTP : Example



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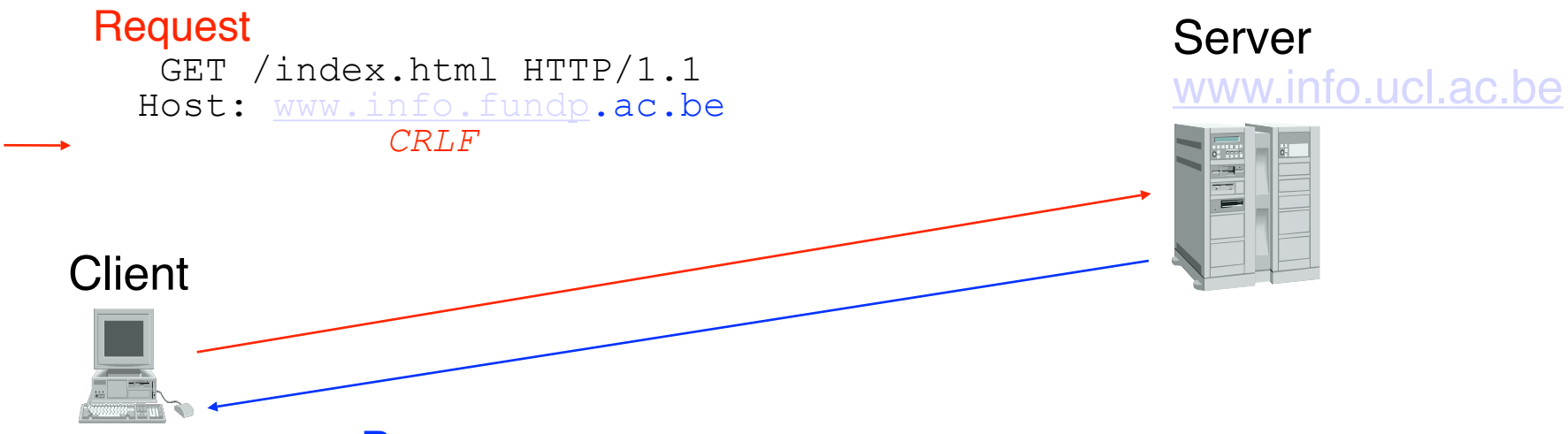

HTTP : Methods

- Methods
  - GET
    - method used to request a "document" stored on server
      - GET <document> HTTP/1.0
    - example
      - `GET /index.html HTTP/1.0`
  - POST
    - method used to send a "document" to a server
      - document is part of the request and encoded as a MIME document

HTTP : Request headers

- Request headers
  - Allow to add information about the client or the request
  - `Host: <name>`
    - Name of the server where the document is stored
  - `Authorization`
    - allows to perform access control
  - `If-Modified-Since: <date>`
    - server will only send the requested document if the document is more recent than date
  - `Referer: <url>`
    - Information, indicates the URL visited by the client before this request
  - `User-Agent: <agent>`
    - information, indicates the browser used on the client

HTTP : Status line

- Status liine
  - Format : `Version_HTTP Code Comment`
  - Success/Failure
    - `1xx` : For information (unused)
    - `2xx` : Success
      - Example : `HTTP/1.0 200 OK`
    - `3xx` : Redirection
      - Request could not be handled on local server and should be sent to another server
      - Example :
        - `HTTP/1.0 301 Moved permanently`
        - attached MIME document will contain URL of document
    - `4xx` : Client-side error
      - examples
        - syntax error, unreachable URL, unauthorised, ...
    - `5xx` : Server-side error
      - examples :
        - internal error, method not implemented on server, ...

HTTP : Response headers

- Header
  - Optional information about the server, the response or the document attached to the response
  - Date
    - date of the document attached to response
    - example : `Date: Wed, 05 Sep 2001 13:27:34 GMT`
  - Server
    - Name and version of http server used
    - example :
      `Server: Apache/1.3.20 (Unix)ApacheJServ/1.1.2 PHP/4.0.6`
  - Content-*
    - MIME header of the attached document
    - example :

```
Content-Length: 5891
Content-Type: text/html
```

HTTP 1.1

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- HTTP 1.0
  - a single TCP connection used to transmit a single document (html file, image,...)
    - the establishment and release of the TCP connection induce a significant overhead, in particular for small pages

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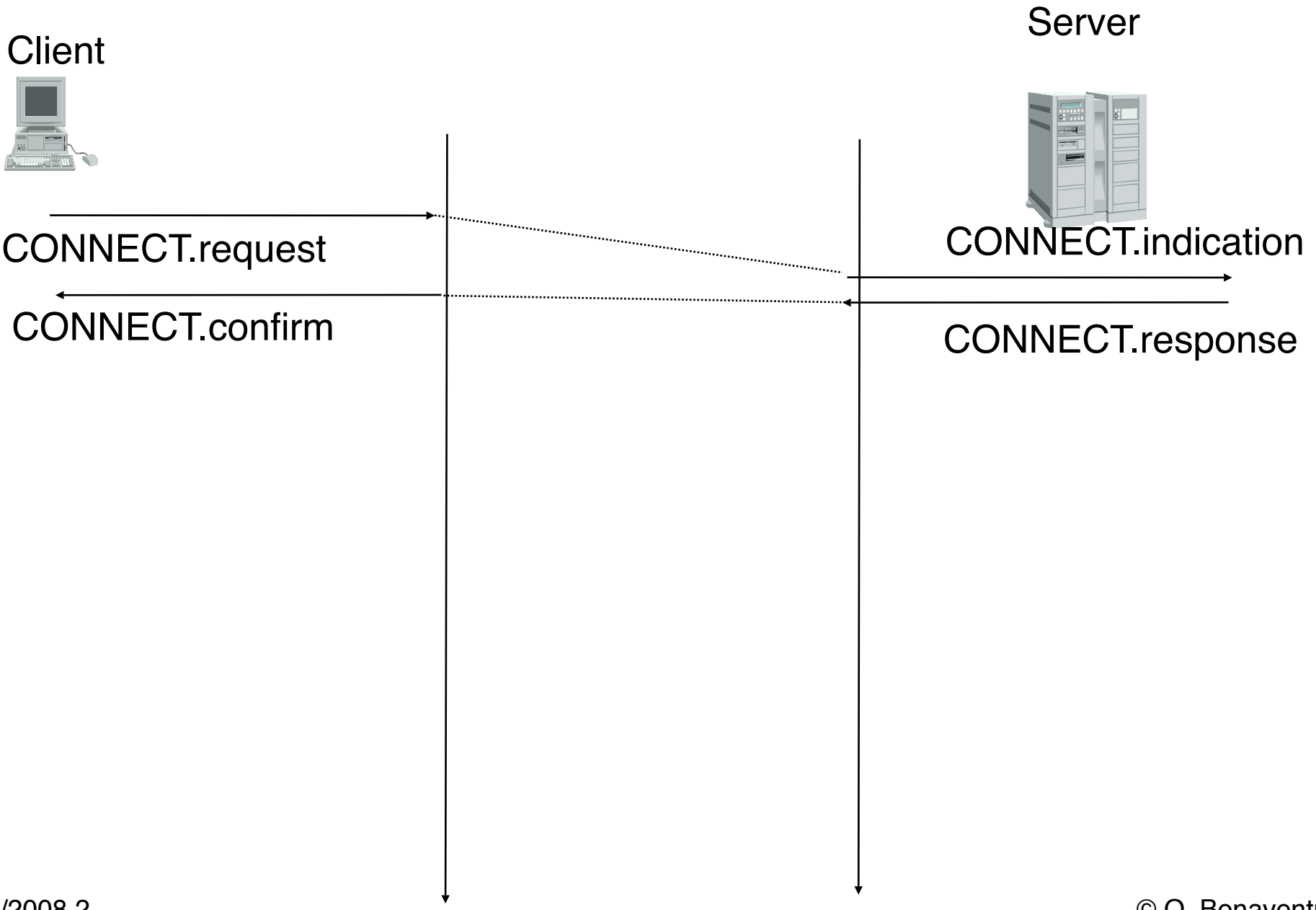
    - the establishment and release of the TCP connection induce a significant overhead, in particular for small pages
- HTTP 1.1
  - uses a single persistent TCP connection
    - This TPC connection can be used for several requests and the corresponding responses
    - the cost of establishing and releasing the TCP connection is amortised over multiple requests
    - Although HTTP 1.1 uses a single TCP connection for multiple requests, HTTP 1.1 remains stateless

HTTP 1.1 : Persistent connection

Client

Server

HTTP 1.1 : Persistent connection



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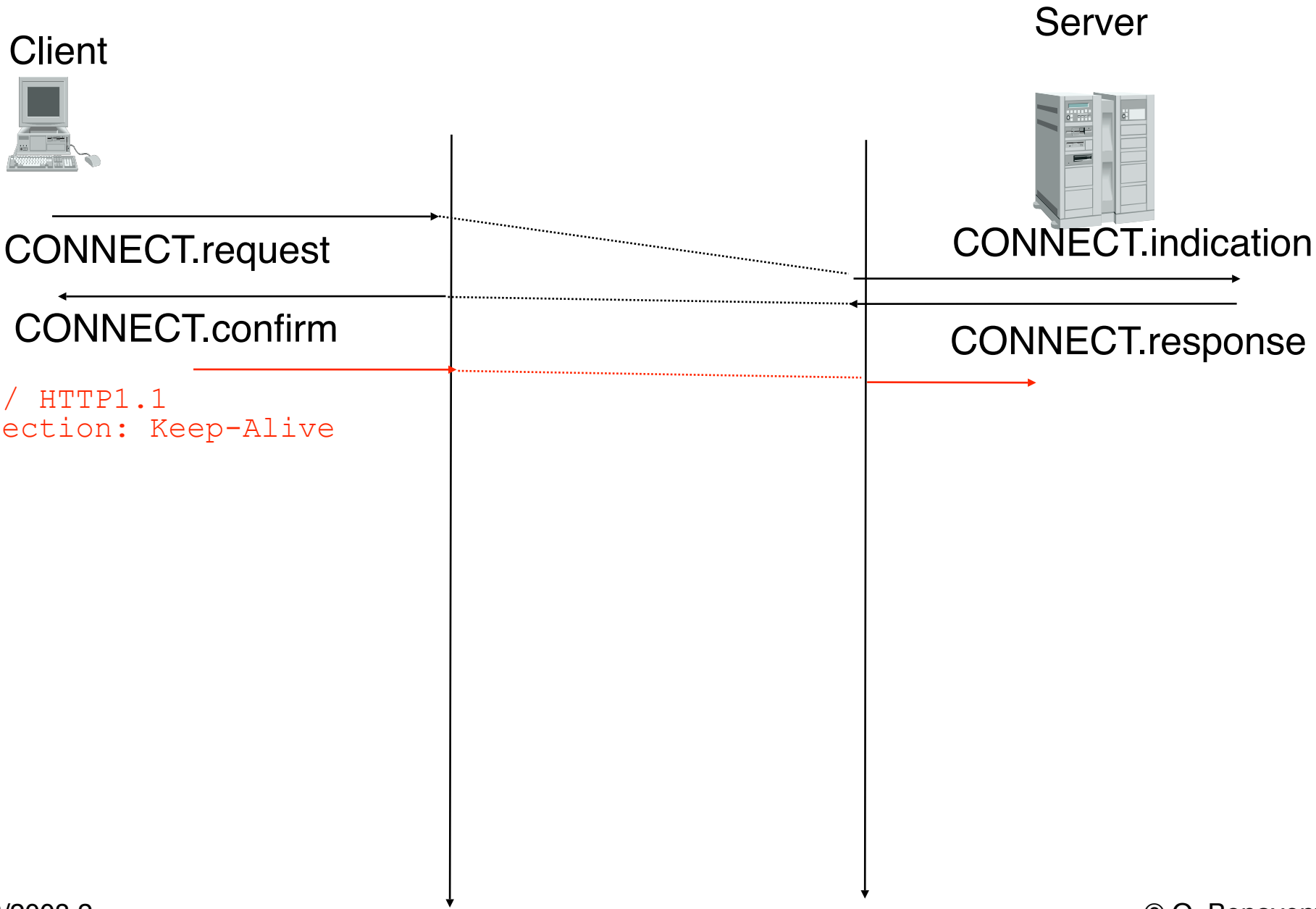

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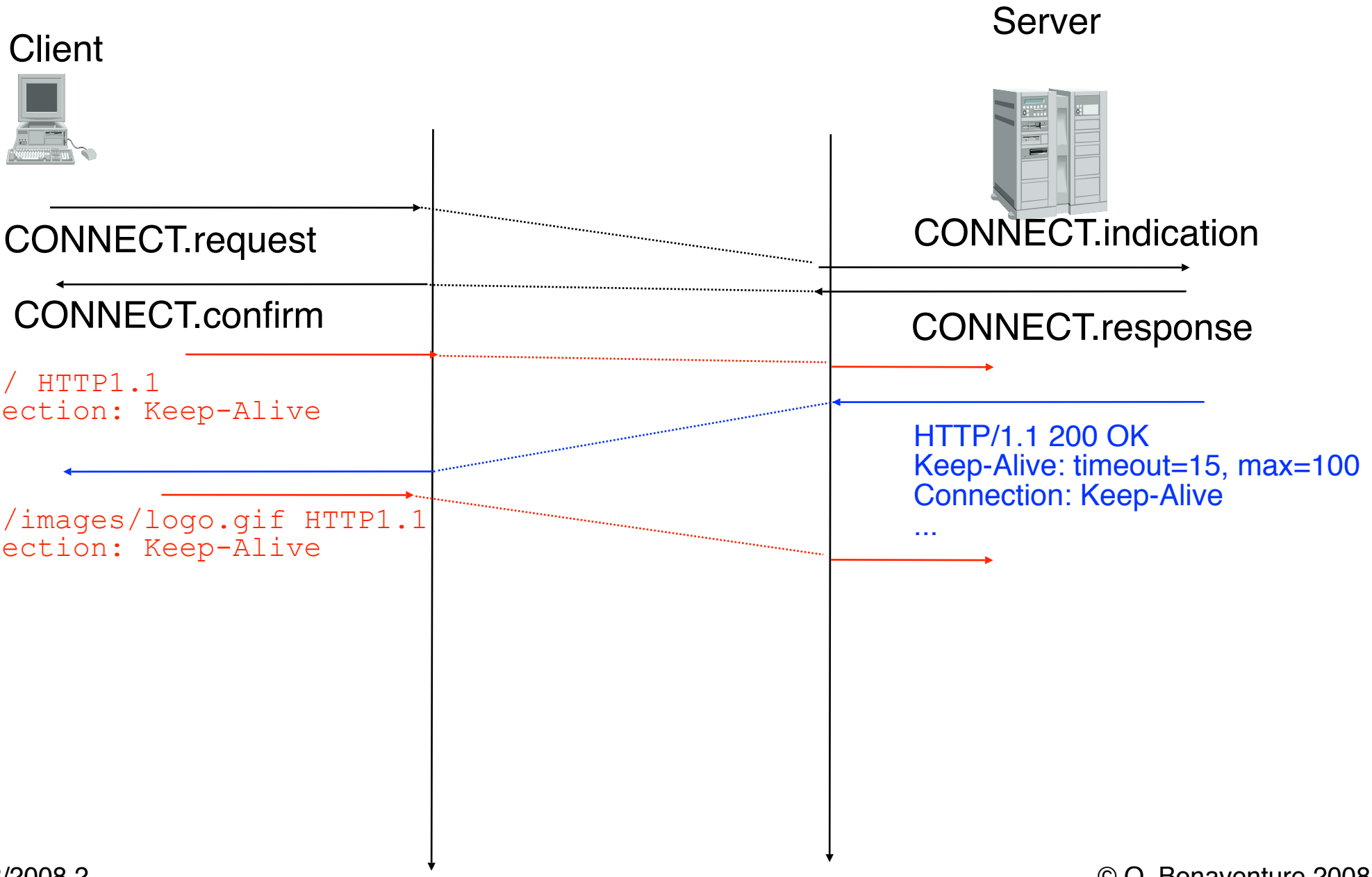

HTTP 1.1 : Persistent connection

Client

Server

CONNECT.request

CONNECT.indication

CONNECT.confirm

CONNECT.response

```
GET / HTTP1.1
Connection: Keep-Alive
...
```

HTTP/1.1 200 OK
Keep-Alive: timeout=15, max=100
Connection: Keep-Alive
...

```
GET /images/logo.gif HTTP1.1
Connection: Keep-Alive
...
```

HTTP/1.1 200 OK
Keep-Alive: timeout=15, max=99
Connection: Keep-Alive
...

HTTP 1.1 : Persistent connection

Improving performance

- Observation
  - Many pages are requested multiple times or from close endhosts
- Solution
  - local cache on each client
    - `if-modified-since` header helps
  - one cache for multiple endhosts

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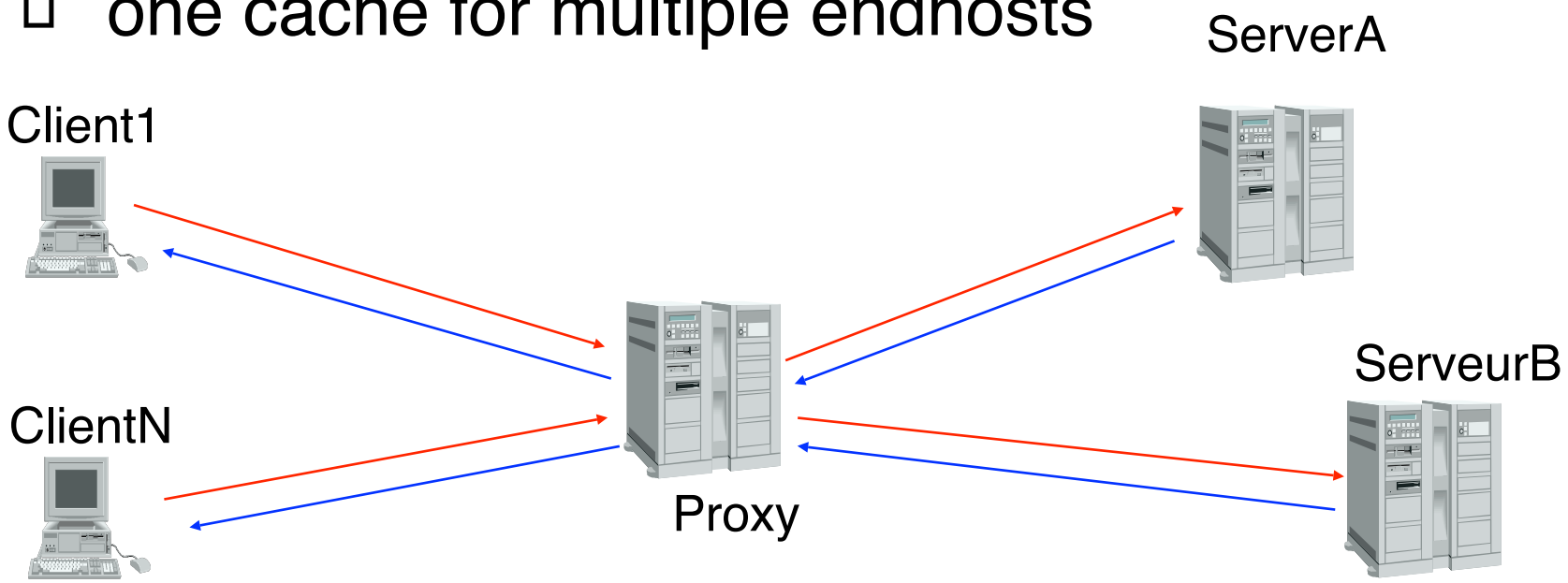

HTTP Authentication

- Example

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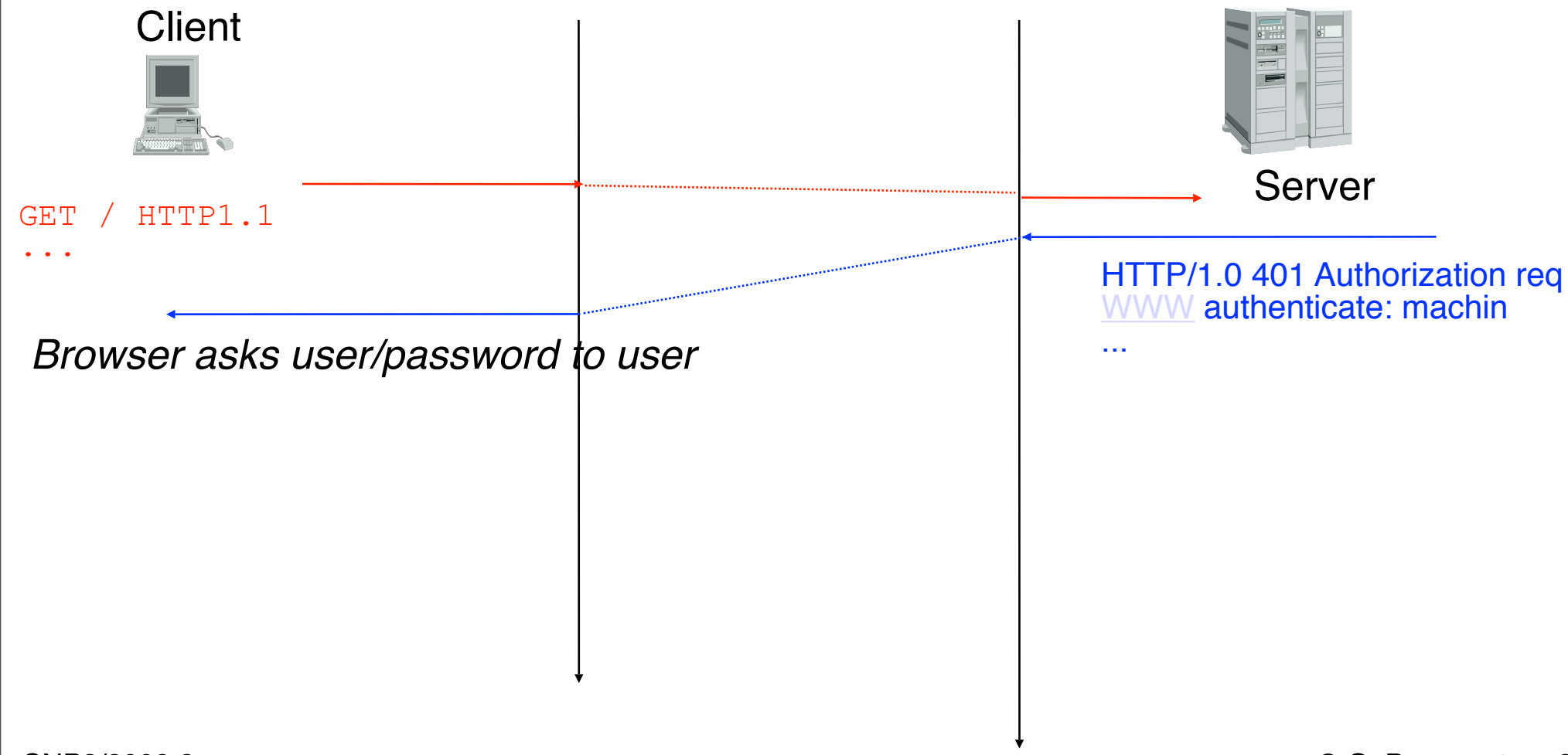

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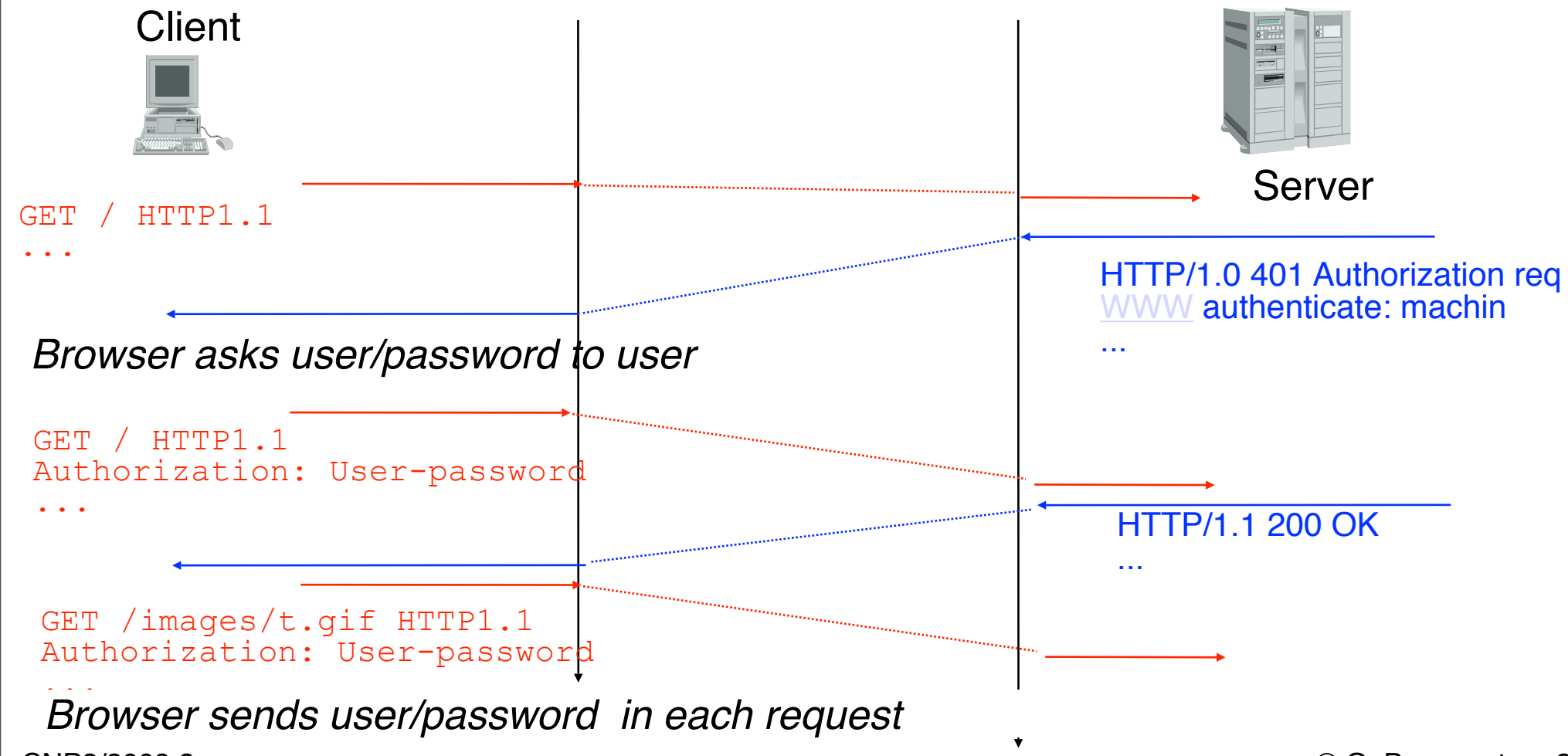


HTTP Cookies

- Example

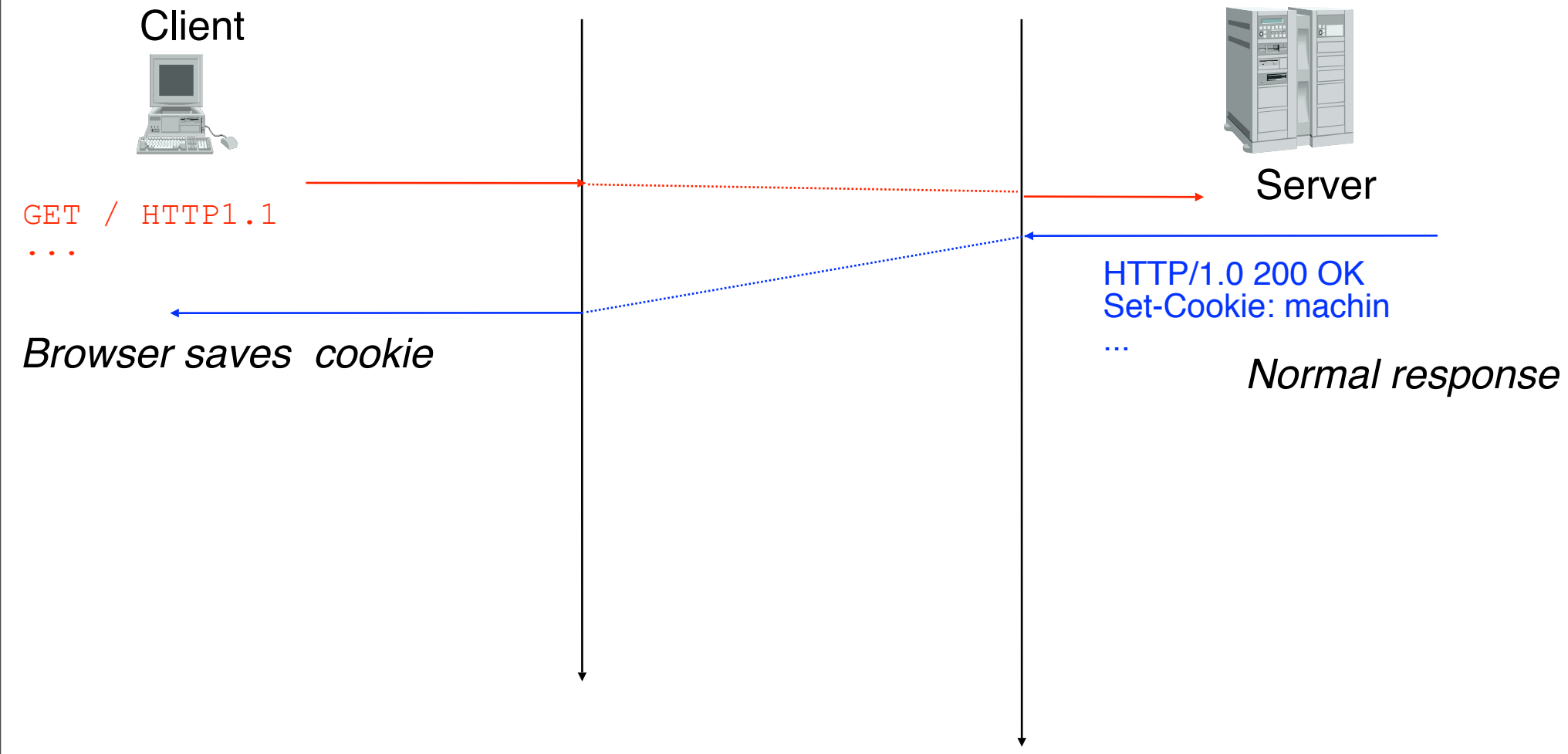
Client

Server

Normal response

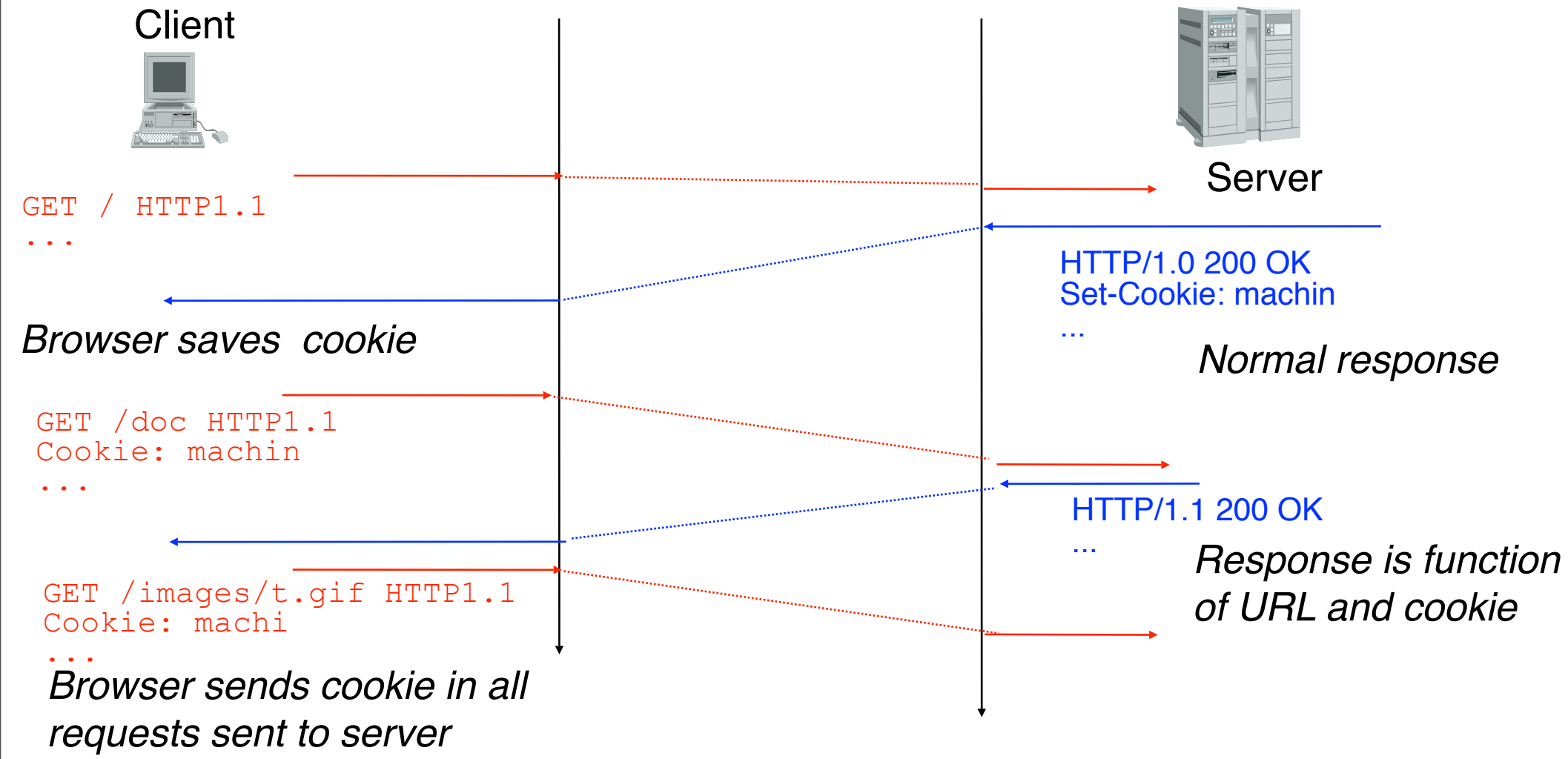
HTTP Cookies

- Example



HTTP Cookies

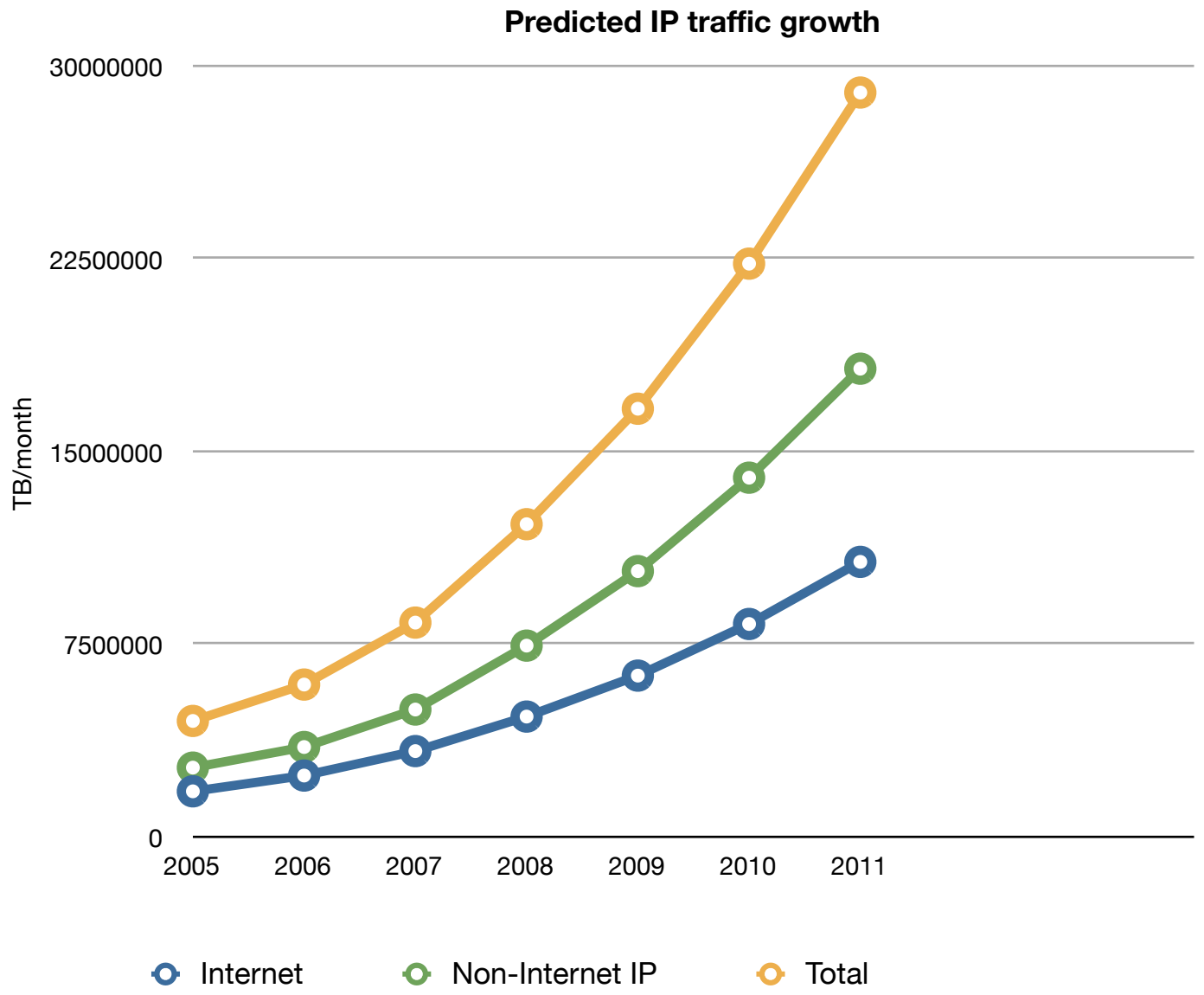
- Example



Internet applications

- Contents
  - The client-server model
  - Name to address resolution
  - email
  - world wide web
  - peer-to-peer applications

Predicted IP traffic growth



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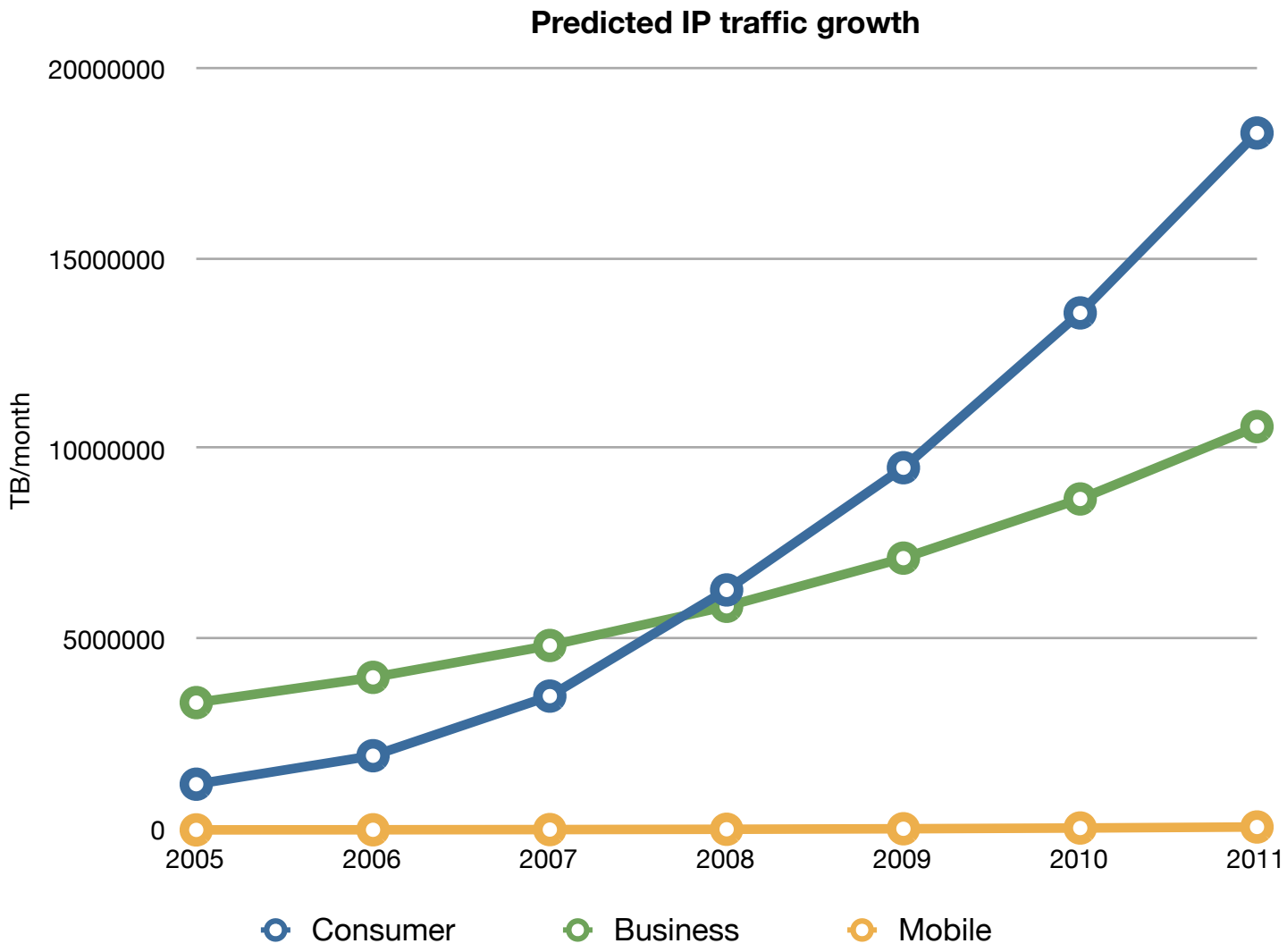
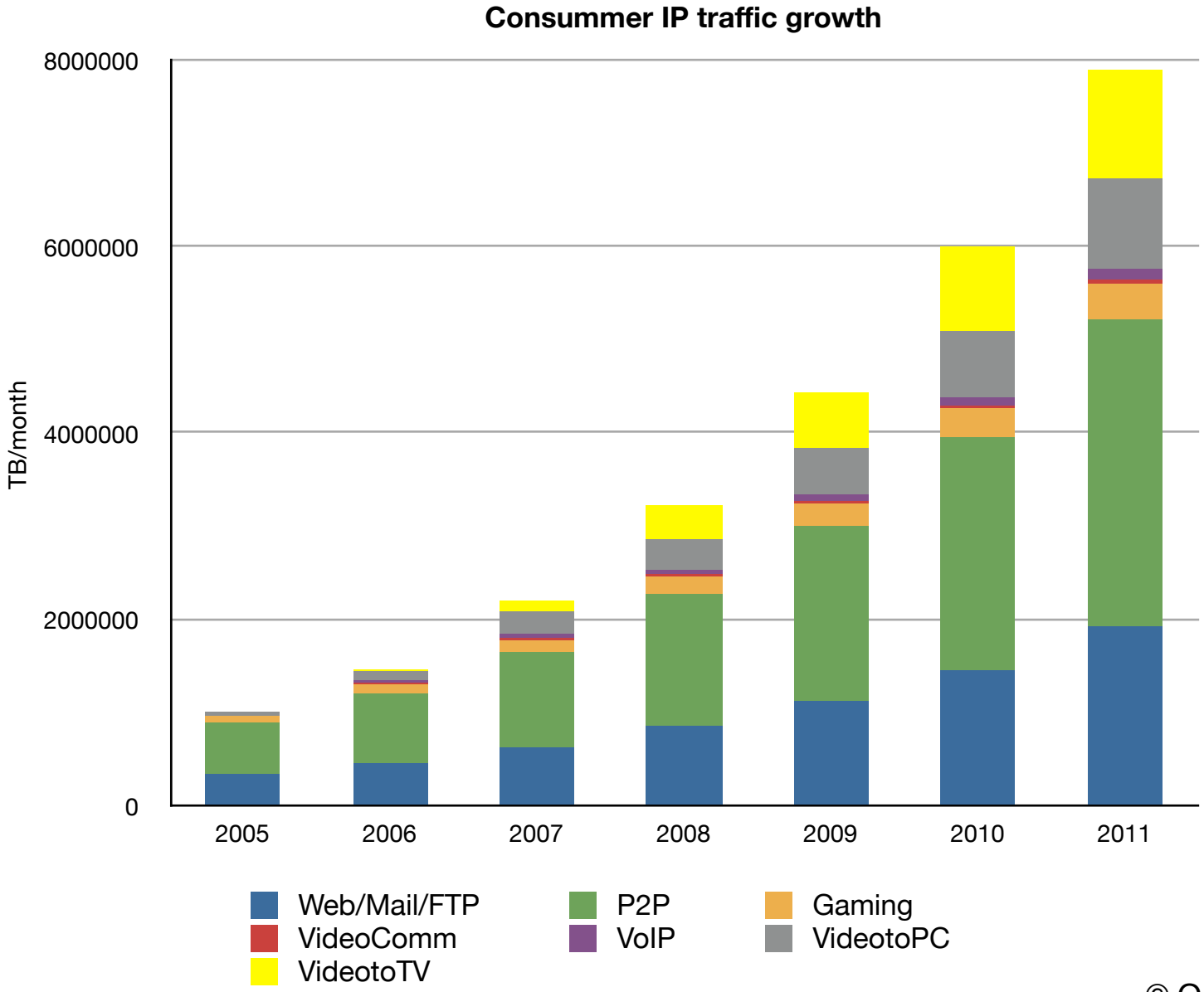


Predicted IP traffic growth (3)



Peer-to-peer file sharing

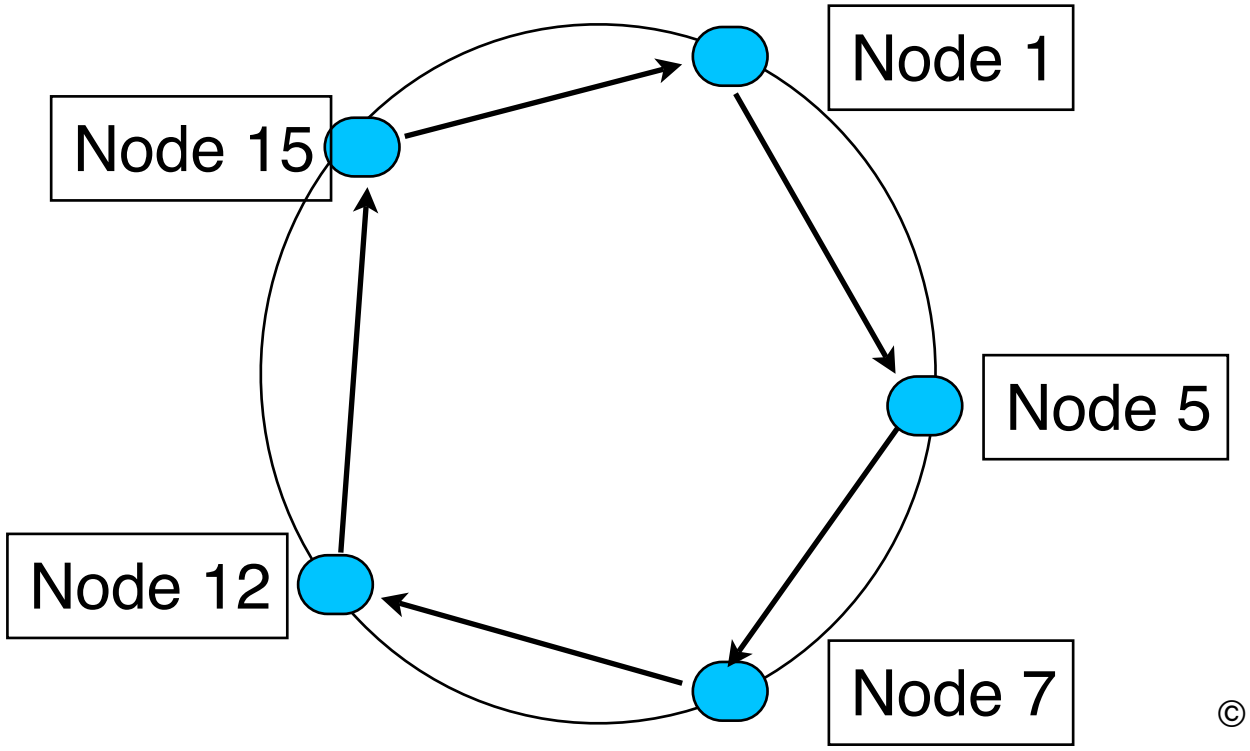
- Evolution of file sharing on the Internet
- Servers using `ftp` protocol
  - A single server that serves all files on disk
  - A set of mirror serves serving the same content
- The innovation introduced by Napster
  - How to distribute many files from many nodes ?
    - Keep the files on their source nodes
    - Central Napster server stores description and URL of each shared file
    - Users willing to obtain a file consult central server to obtain file URL and then download file from their respective source nodes
      - server remains simple and can index large number of files
      - server does not directly participate in file transfer

Peer-to-peer file sharing (2)

- Limitations of the Napster approach
  - a single server indexes all files
  - if a source node fails, then the ongoing file transfers must be restarted
    - completely or partially depending on the file transfer protocol begin used for the transfer
  - performance of file transfer is function of performance of the corresponding source node
    - if source node is connected via ADSL, performance will be severely limited
- How to improve ?
  - Divide the file in blocks
  - Each block can be served by multiple nodes
    - provides redundancy
  - Download from several nodes at the same time
    - one TCP connection may be slow and others faster

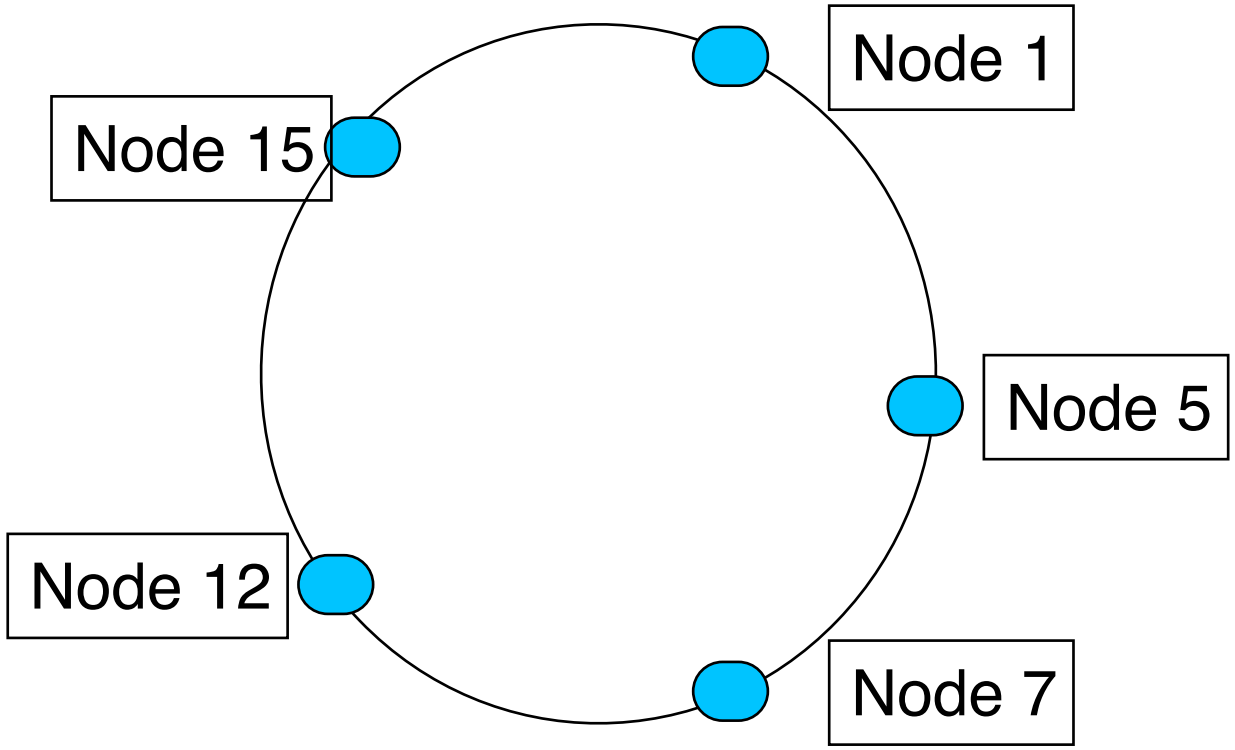
Distributed Hash Table based P2P

- How to scale file sharing to a very large number *n* of nodes ?
- Principle of the solution
  - Use a hash function such as SHA-1
  - Each node has one identifier, id=hash(IPaddress) and a pointer to its successor on the Chord ring



How to store files ?

- Principle
  - File FOOBAR is stored on the node whose id is the successor of hash("FOOBAR") on the ring
  - A node on the ring uses its successors to find the responsible node for a given file
    - Examples



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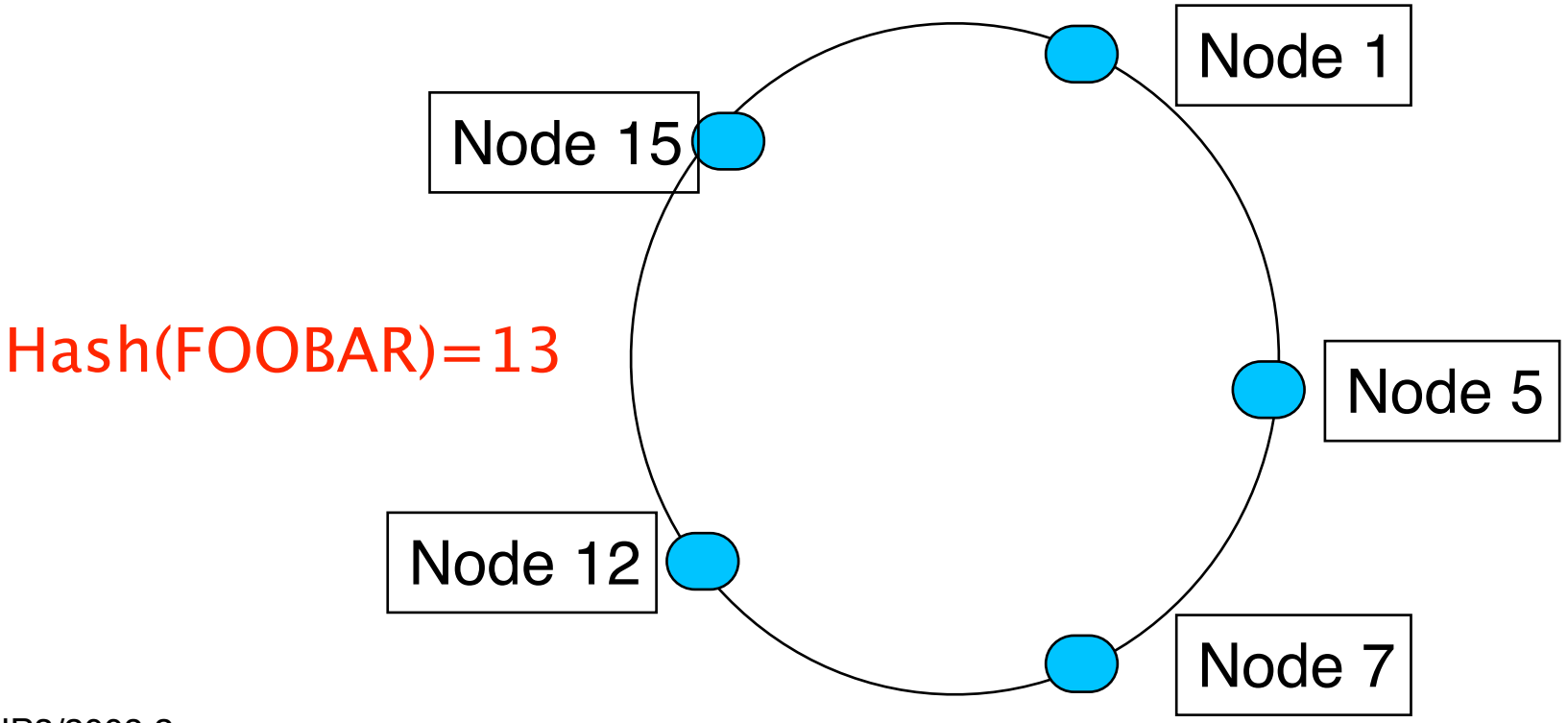

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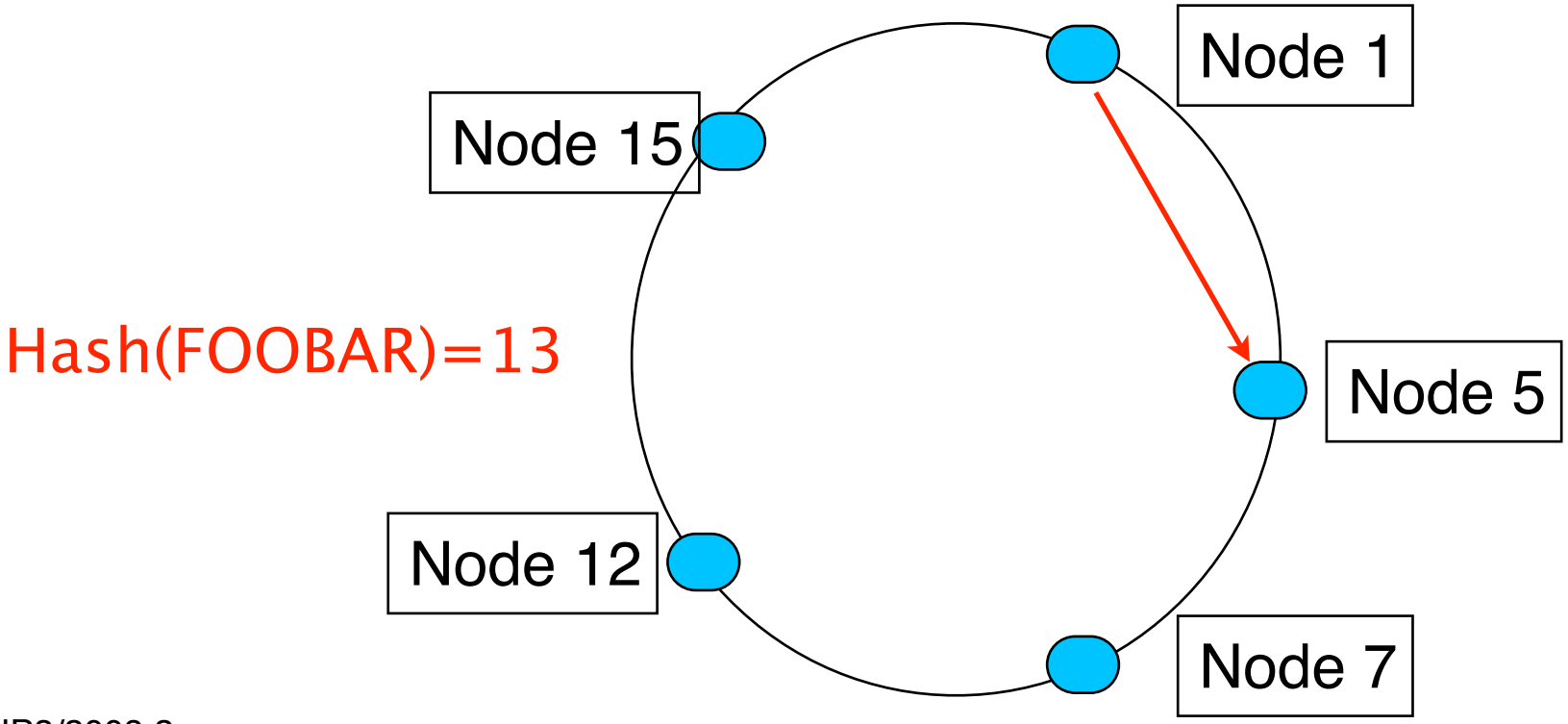

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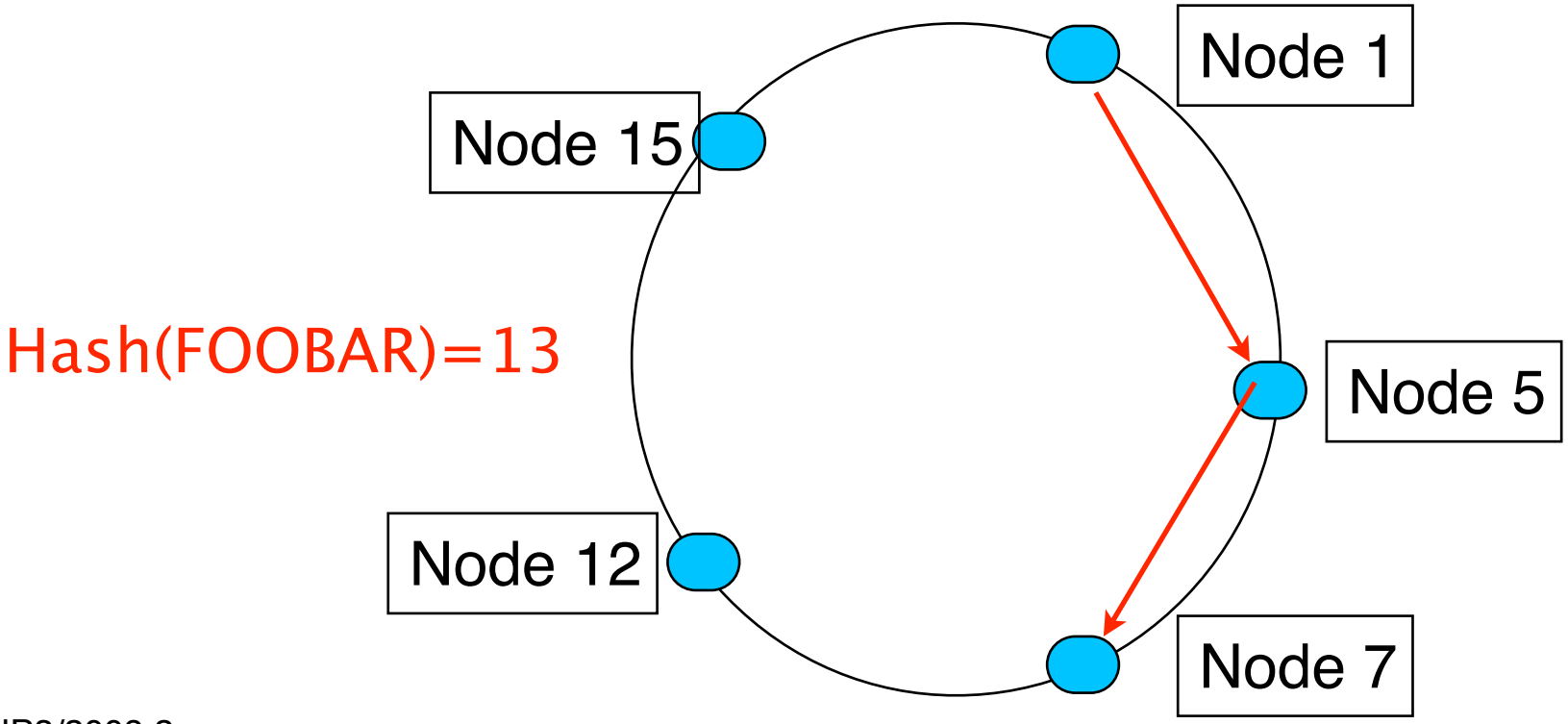

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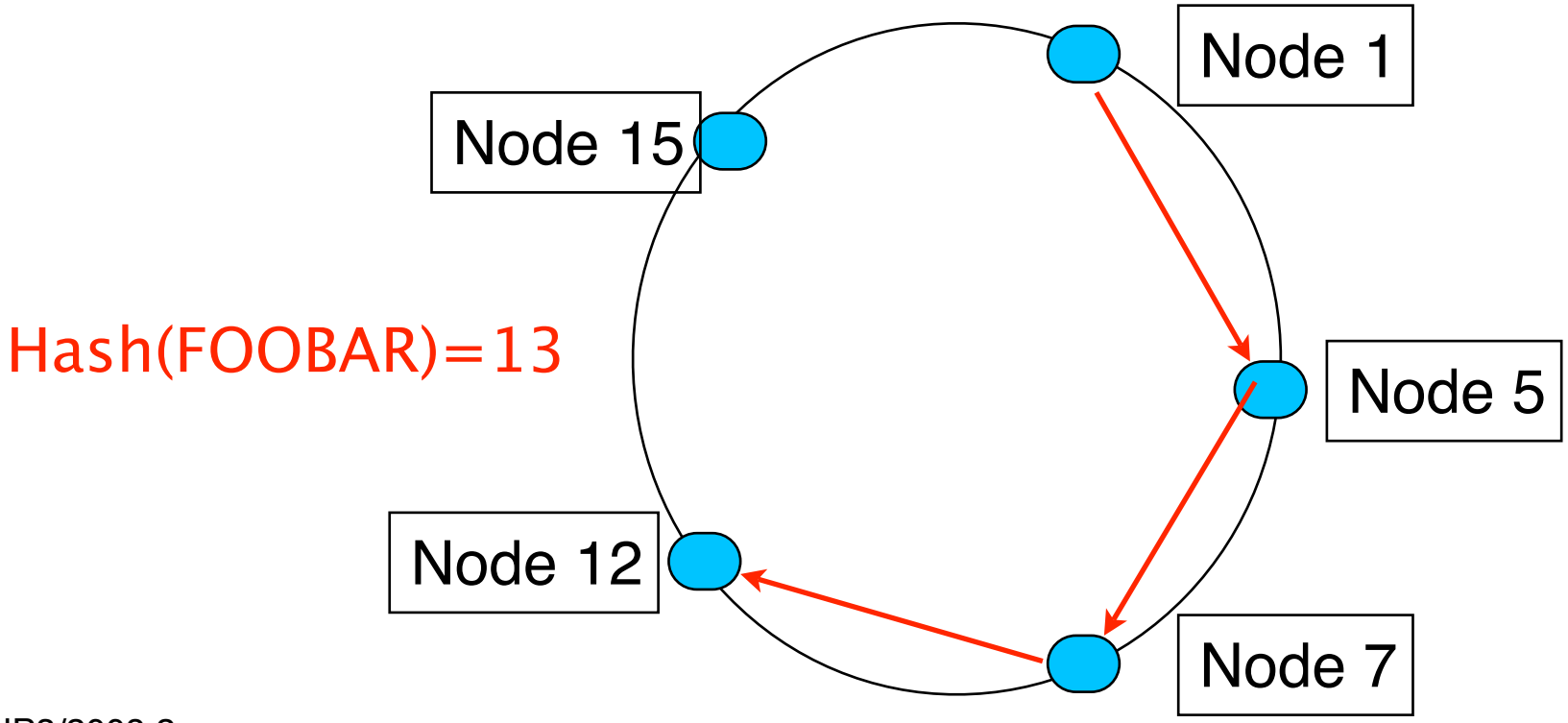

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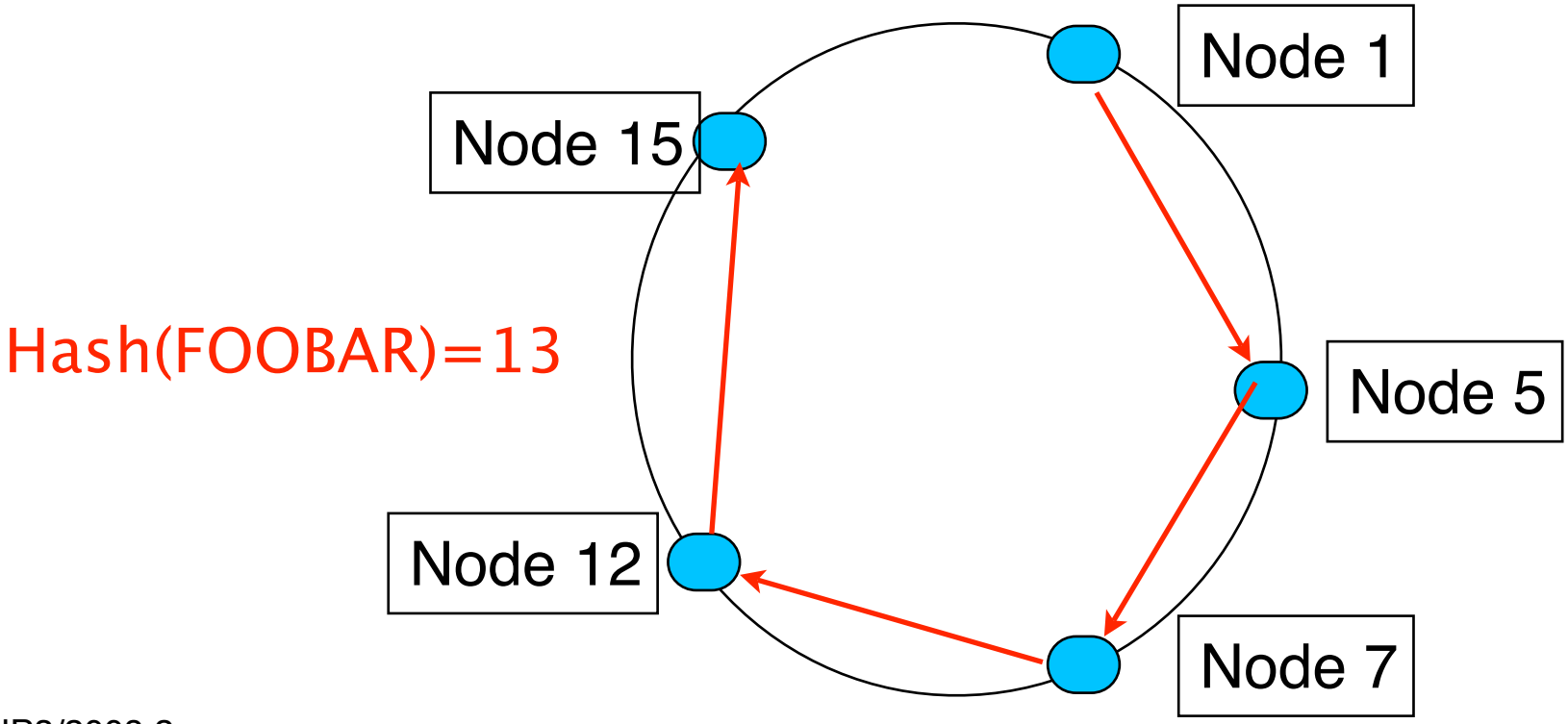

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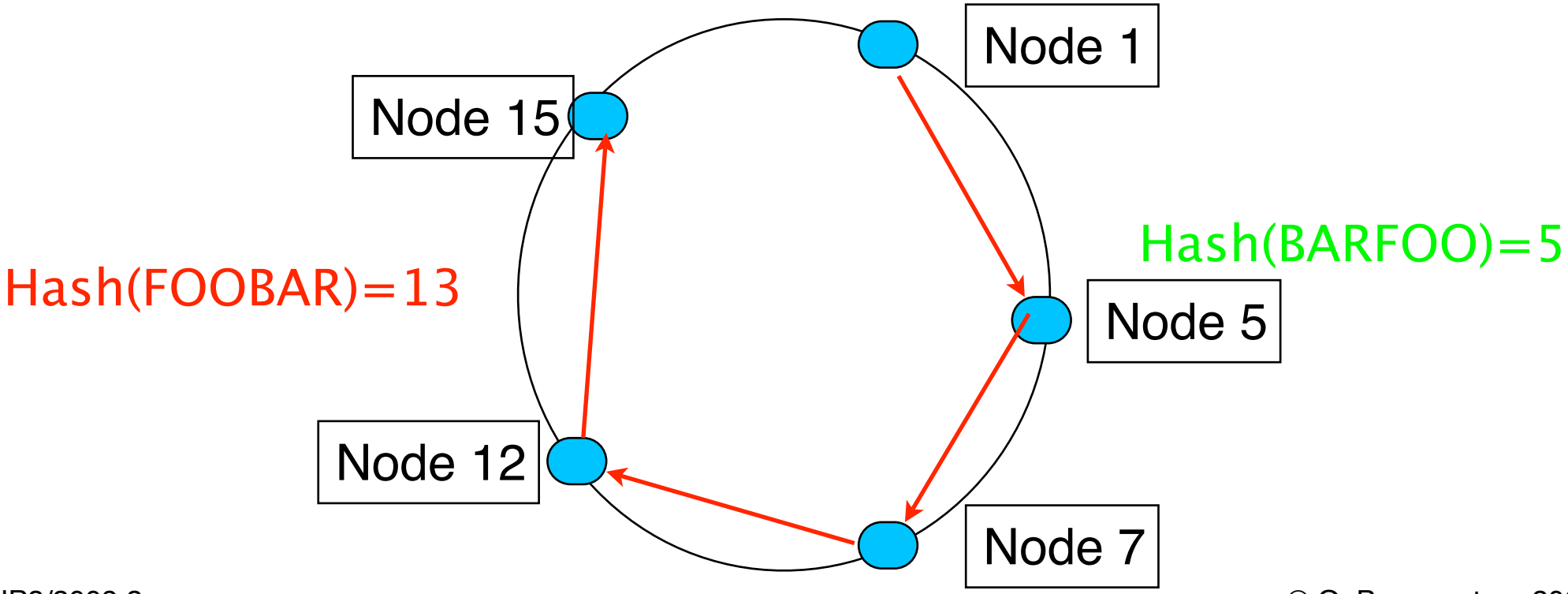

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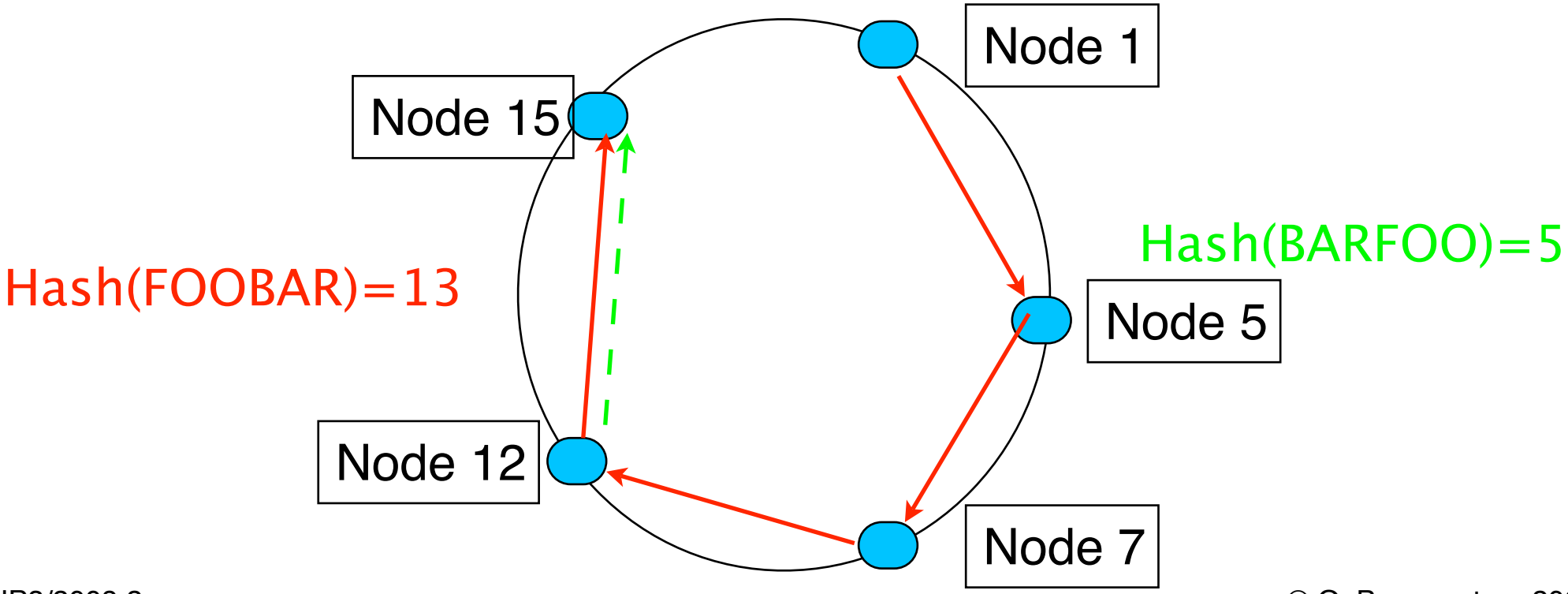

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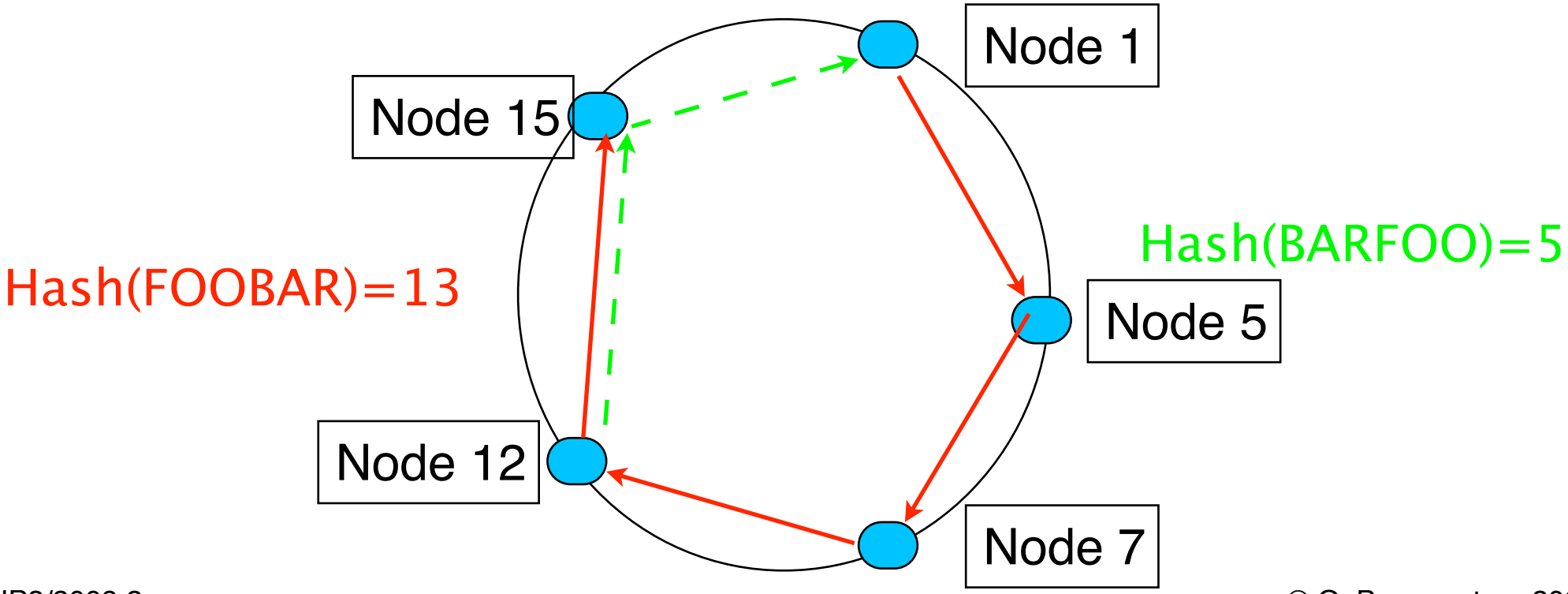

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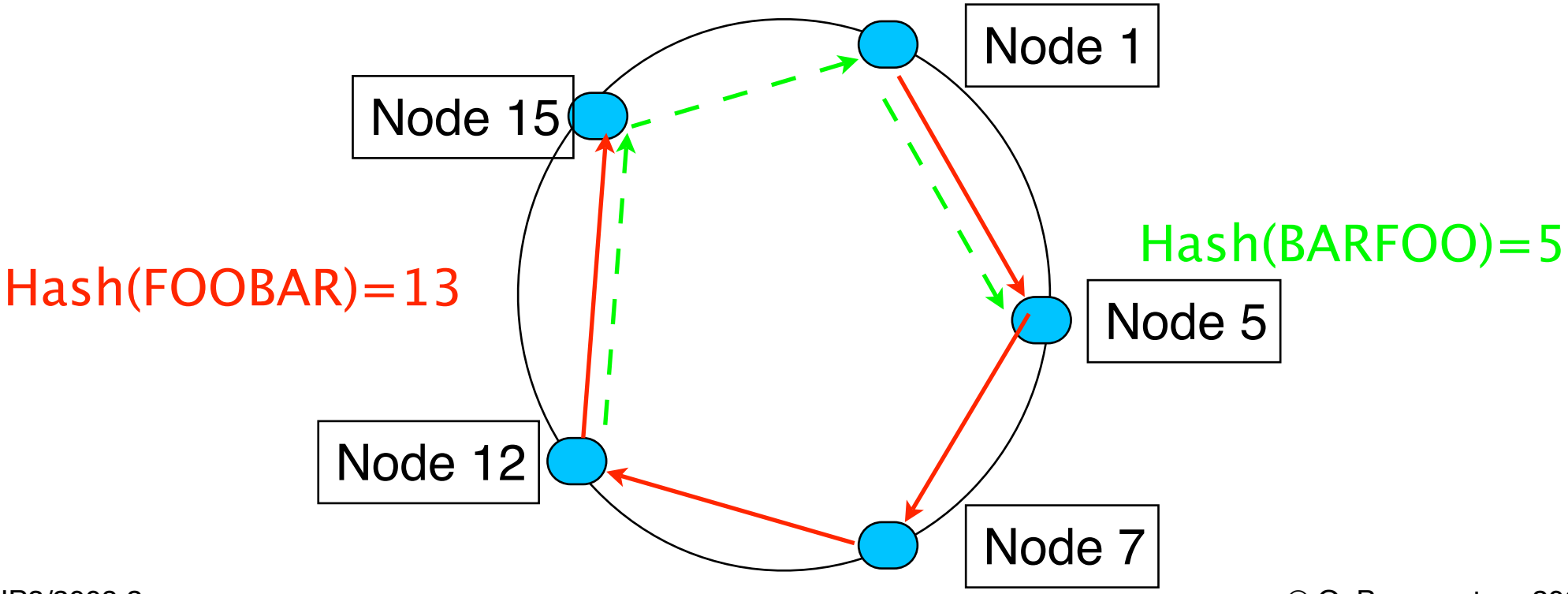

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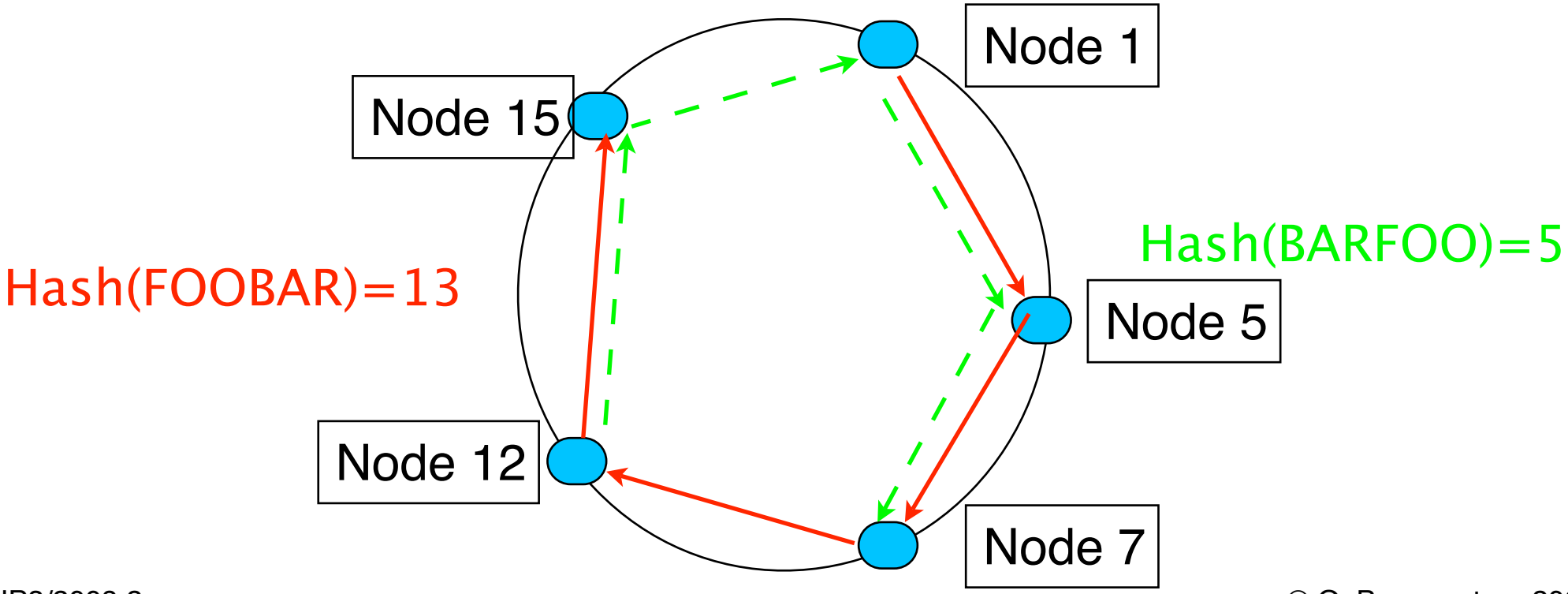

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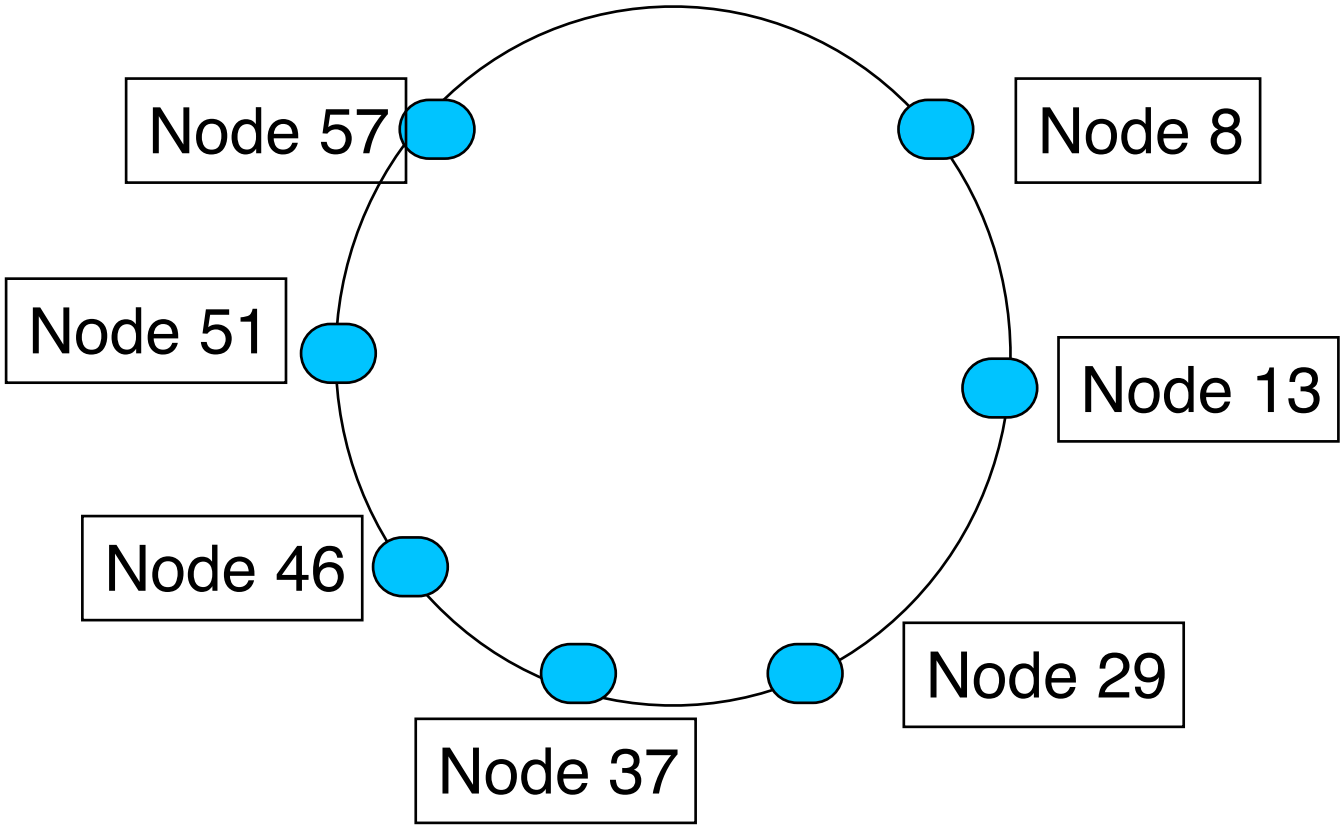
- Performance of file lookup
  - O(n)
    - worst case is to follow linked list of n nodes

How to find files faster ?

- Performance of file lookup
  - O(n)
    - worst case is to follow linked list of n nodes
- How to improve ?
  - Allow nodes to know addition pointers to other nodes on the Chord ring to speedup lookup
    - m = number of bits in the key/node identifiers
    - Each node maintains routing table of m entries
    - The ith entry in the table at node n contains the identity of the first node, s, that succeeds n by at least 2^i–1 on the identifier circle, i.e., s = successor(n + 2^i–1)
      - arithmetic modulo 2^m is used
    - A finger table entry includes both the Chord identifier and the IP address (and port number) of relevant node.

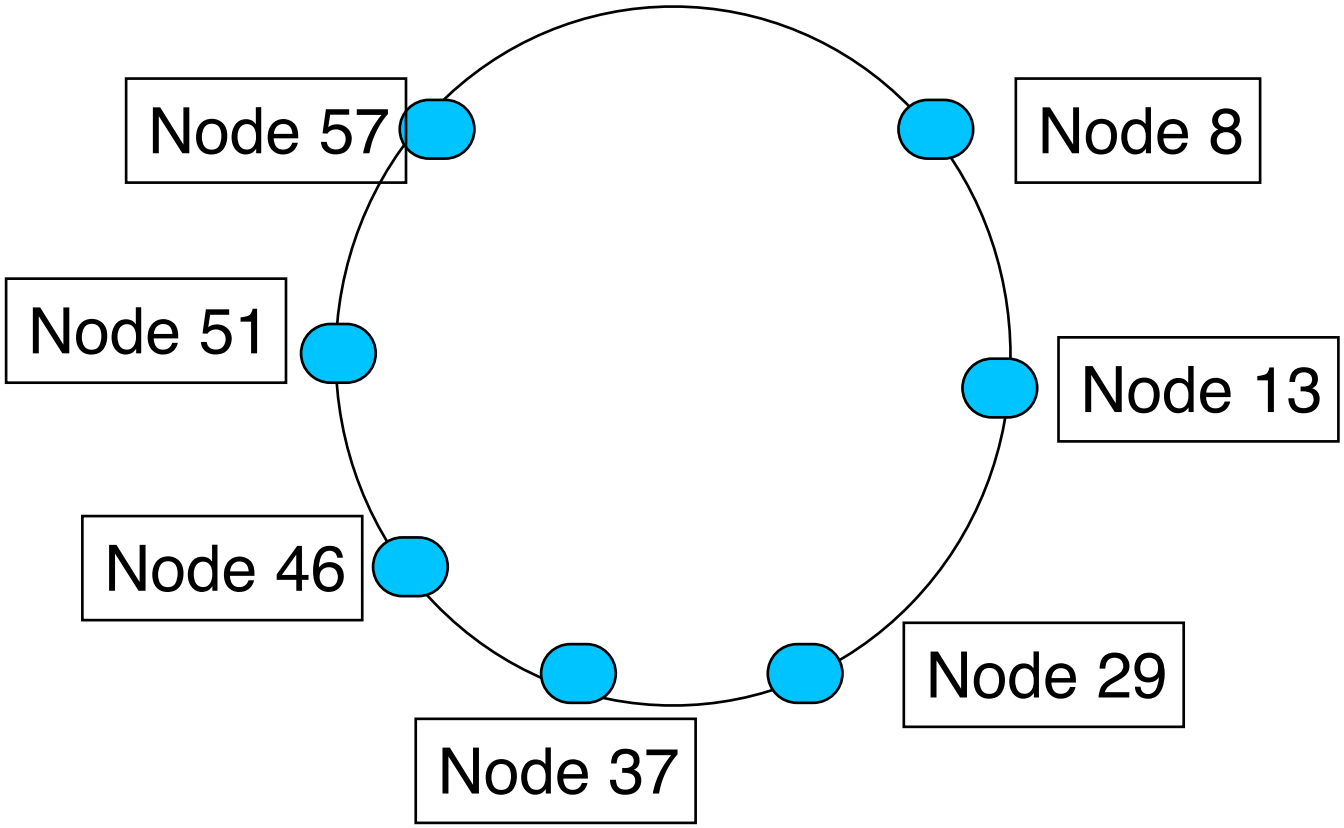
Scalable lookup with Chord



N8+1	N13
N8+2	N13
N8+4	N13
N8+8	N29
N8+16	N29
N8+32	N46

Scalable lookup with Chord

- Example
  - m=8



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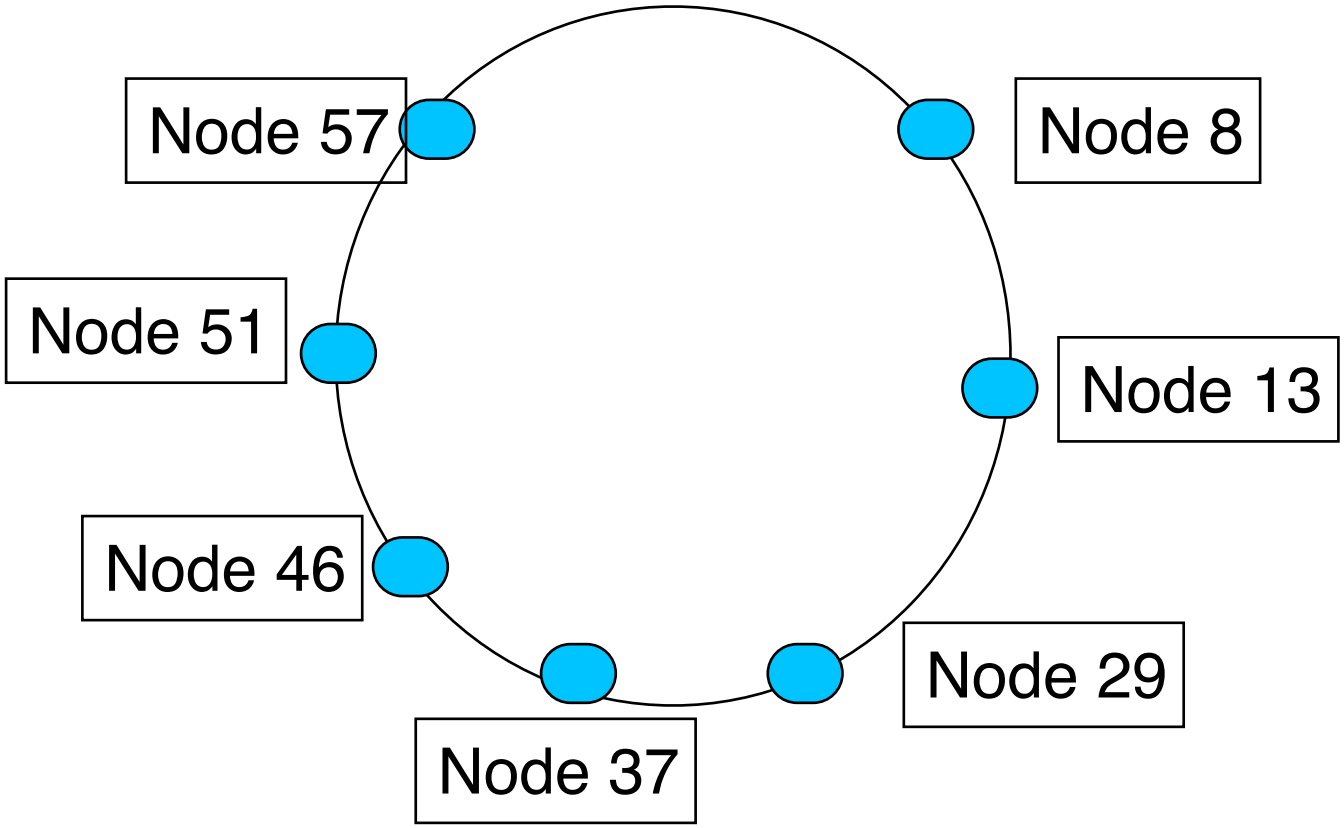

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- How to find key 53 from node 8 ?

Scalable lookup with Chord

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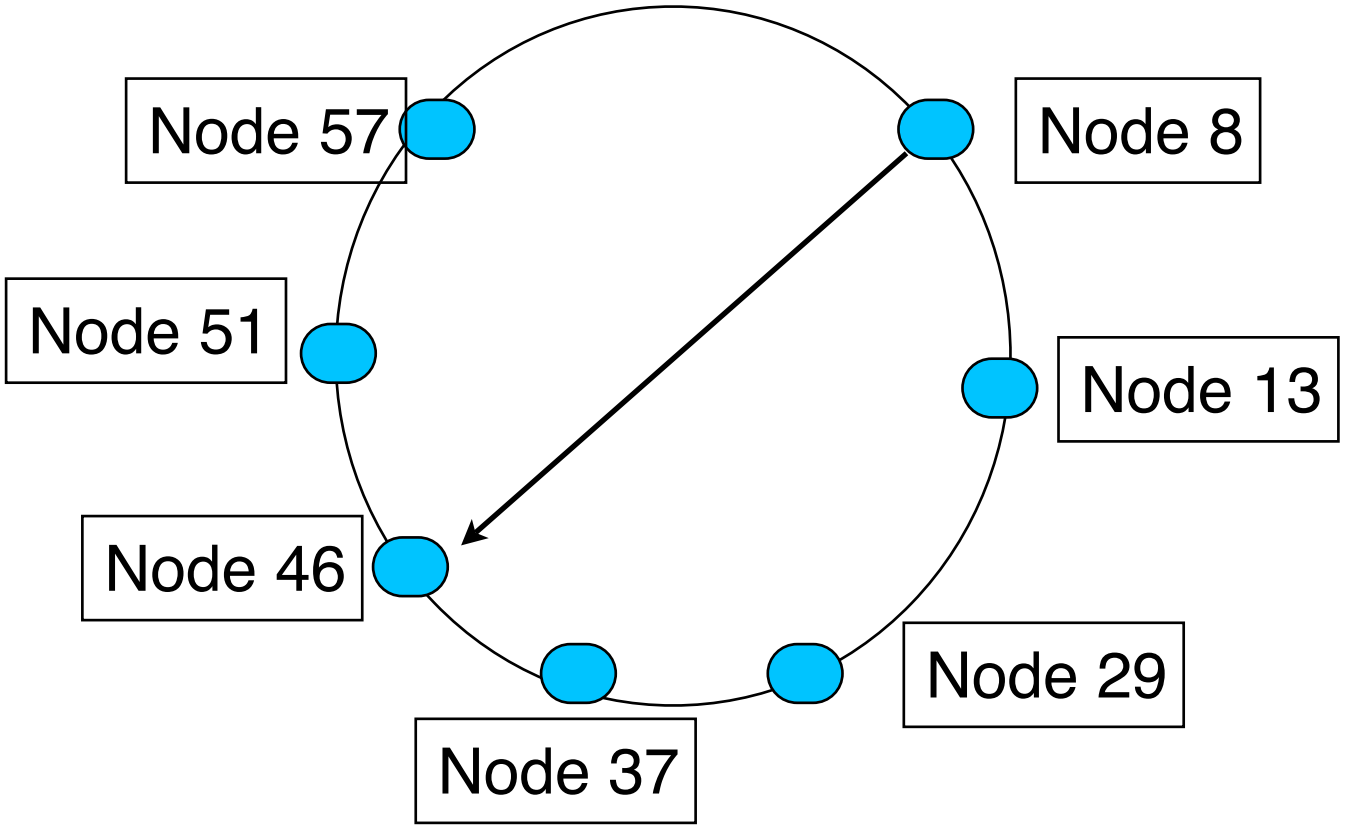

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N8+4	N13
N8+8	N29
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N8+32	N46

N46+1	N51
N46+2	N51
N46+4	N51
N46+8	N57
N46+16	N57
N46+32	N8

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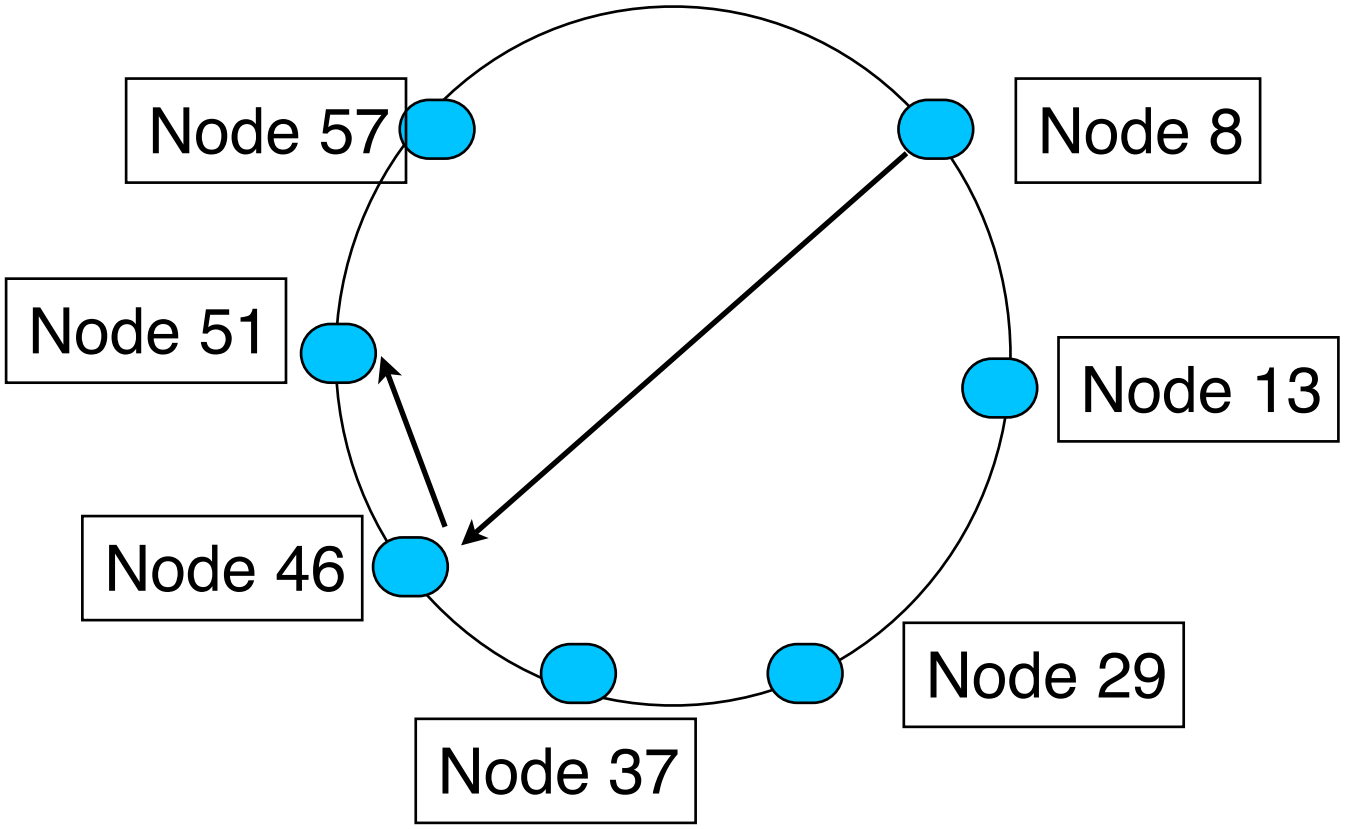

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N46+1	N51
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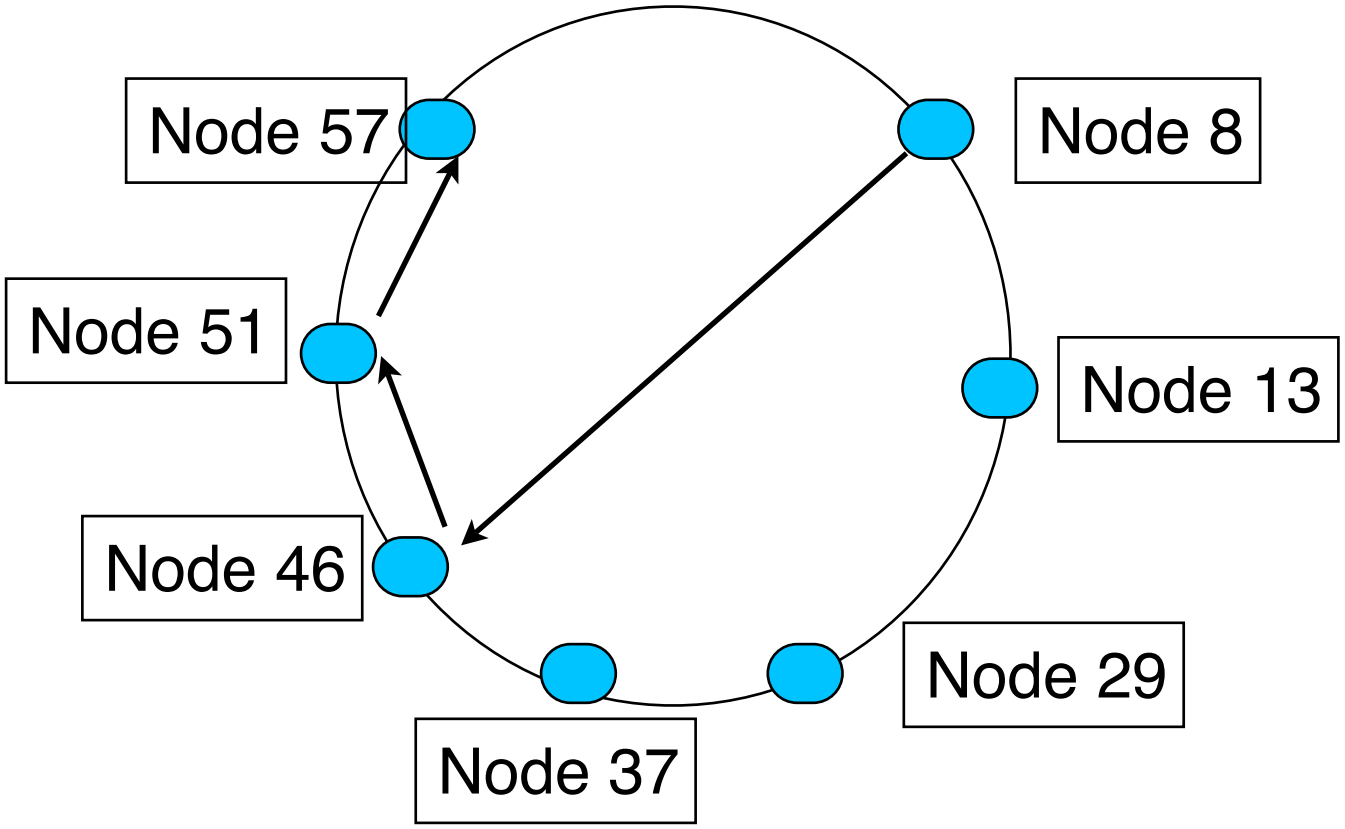

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N46+4	N51
N46+8	N57
N46+16	N57
N46+32	N8

- How to find key 53 from node 8 ?

Summary

- Client-server model
- UDP and TCP services
- Application-level protocols
  - DNS
    - relies on UDP, stateless
  - SMTP, POP, FTP
    - rely on TCP, statefull
  - HTTP
    - relies on TCP, stateless
- Peer-to-peer applications