# Fault Tolerance

# Fault Tolerance

- Fault tolerance is the ability of a distributed system to provide its services even in the presence of faults.

# Fault Tolerance

- Fault tolerance is the ability of a distributed system to provide its services even in the presence of faults.
- A distributed system should be able to recover automatically from partial failures without seriously affecting availability and performance.

# Fault Tolerance: Basic Concepts (1)

- Being fault tolerant is strongly related to what are called dependable systems Dependability implies the following:

# Fault Tolerance: Basic Concepts (1)

- Being fault tolerant is strongly related to what are called dependable systems Dependability implies the following:
  - Availability
  - Reliability
  - Safety
  - Maintainability

# Fault Tolerance: Basic Concepts (1)

- Being fault tolerant is strongly related to what are called dependable systems Dependability implies the following:
  - Availability
  - Reliability
  - Safety
  - Maintainability
- **In-class Exercise**: How is is availability different from reliability? How about a system that goes down for 1 millisecond every hour? How about a system that never goes down but has to be shut down two weeks every year?

# Fault Tolerance: Basic Concepts (2)

- A system is said to fail when it cannot meet its promises. For example, if it cannot provide a service (or only provide it partially).

# Fault Tolerance: Basic Concepts (2)

- A system is said to fail when it cannot meet its promises. For example, if it cannot provide a service (or only provide it partially).
- An error is a part of the system's state that may lead to failure. The cause of an error is called a fault.

# Fault Tolerance: Basic Concepts (2)

- A system is said to fail when it cannot meet its promises. For example, if it cannot provide a service (or only provide it partially).
- An error is a part of the system's state that may lead to failure. The cause of an error is called a fault.
- Types of faults:
  - Transient: Occurs once and then disappears. If a operation is repeated, the fault goes away.

# Fault Tolerance: Basic Concepts (2)

- A system is said to fail when it cannot meet its promises. For example, if it cannot provide a service (or only provide it partially).
- An error is a part of the system's state that may lead to failure. The cause of an error is called a fault.
- Types of faults:
  - Transient: Occurs once and then disappears. If a operation is repeated, the fault goes away.
  - Intermittent: Occurs, then vanishes of its own accord, then reappears and so on.

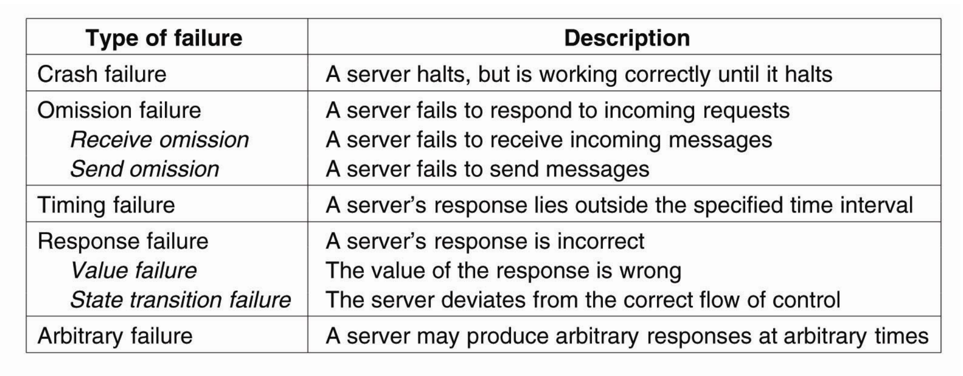
# Fault Tolerance: Basic Concepts (2)

- A system is said to fail when it cannot meet its promises. For example, if it cannot provide a service (or only provide it partially).
- An error is a part of the system's state that may lead to failure. The cause of an error is called a fault.
- Types of faults:
  - Transient: Occurs once and then disappears. If a operation is repeated, the fault goes away.
  - Intermittent: Occurs, then vanishes of its own accord, then reappears and so on.
  - Permanent: Continues to exist until the faulty component is replaced.

# Fault Tolerance: Basic Concepts (2)

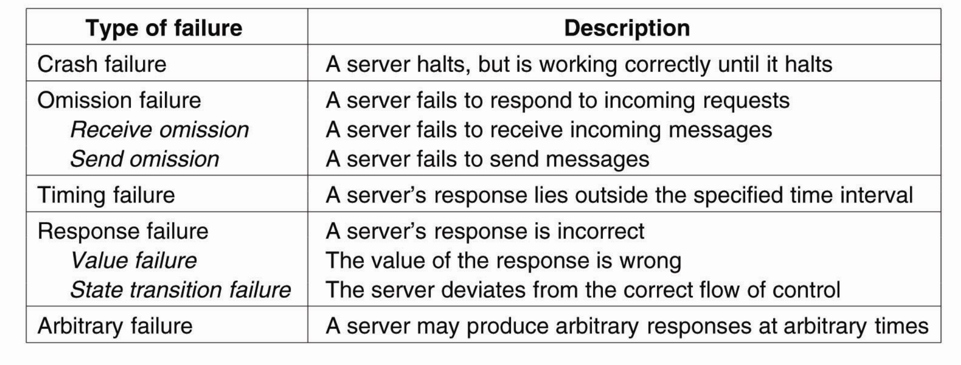
- A system is said to fail when it cannot meet its promises. For example, if it cannot provide a service (or only provide it partially).
- An error is a part of the system's state that may lead to failure. The cause of an error is called a fault.
- Types of faults:
  - Transient: Occurs once and then disappears. If a operation is repeated, the fault goes away.
  - Intermittent: Occurs, then vanishes of its own accord, then reappears and so on.
  - Permanent: Continues to exist until the faulty component is replaced.
- **In-class Exercise**: Give examples of each type of fault for your project!

# Failure Models



| Type of failure | Description |
|---|---|
| Crash failure | A server halts, but is working correctly until it halts |
| Omission failure<br>*Receive omission*<br>*Send omission* | A server fails to respond to incoming requests<br>A server fails to receive incoming messages<br>A server fails to send messages |
| Timing failure | A server's response lies outside the specified time interval |
| Response failure<br>*Value failure*<br>*State transition failure* | A server's response is incorrect<br>The value of the response is wrong<br>The server deviates from the correct flow of control |
| Arbitrary failure | A server may produce arbitrary responses at arbitrary times |

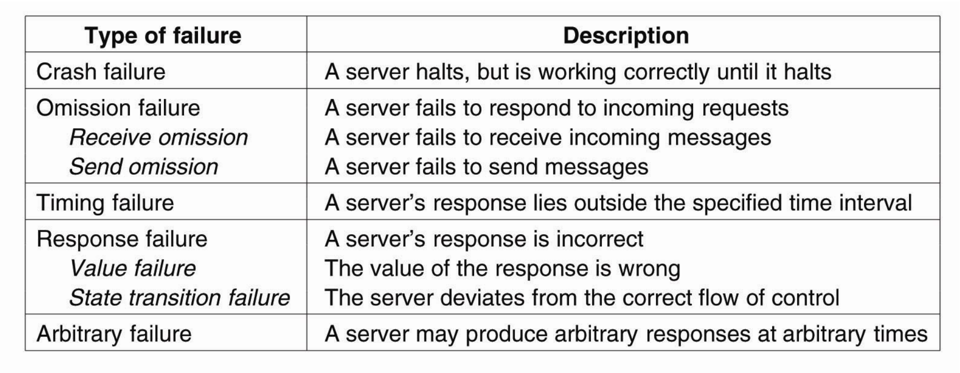
# Failure Models



| Type of failure | Description |
|---|---|
| Crash failure | A server halts, but is working correctly until it halts |
| Omission failure | A server fails to respond to incoming requests |
| *Receive omission* | A server fails to receive incoming messages |
| *Send omission* | A server fails to send messages |
| Timing failure | A server's response lies outside the specified time interval |
| Response failure | A server's response is incorrect |
| *Value failure* | The value of the response is wrong |
| *State transition failure* | The server deviates from the correct flow of control |
| Arbitrary failure | A server may produce arbitrary responses at arbitrary times |

- Fail-stop versus fail-silent.

# Failure Models



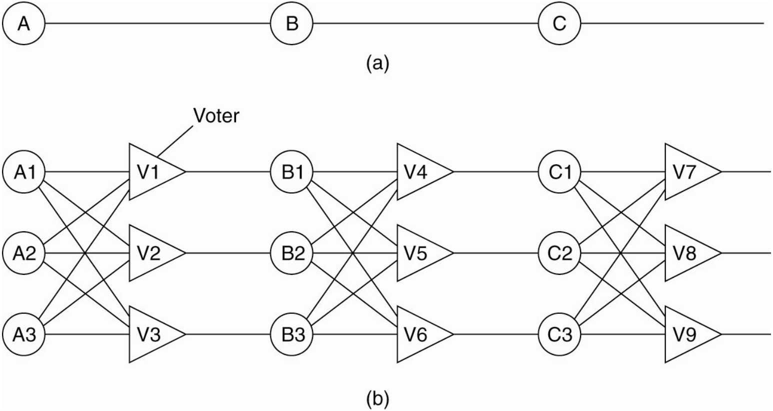
| Type of failure | Description |
|---|---|
| Crash failure | A server halts, but is working correctly until it halts |
| Omission failure | A server fails to respond to incoming requests |
| *Receive omission* | A server fails to receive incoming messages |
| *Send omission* | A server fails to send messages |
| Timing failure | A server's response lies outside the specified time interval |
| Response failure | A server's response is incorrect |
| *Value failure* | The value of the response is wrong |
| *State transition failure* | The server deviates from the correct flow of control |
| Arbitrary failure | A server may produce arbitrary responses at arbitrary times |

- Fail-stop versus fail-silent.
- Byzantine Failures:
  - Arbitrary failures where a server is producing output that it should never have produced, but which cannot be detected as being incorrect.
  - A faulty server may even be working with other servers to produce intentionally wrong answers!

# Failure Masking by Redundancy

- Information Redundancy. For example, adding extra bits (like in Hamming Codes, see the book Coding and Information Theory) to allow recovery from garbled bits.
- Time Redundancy. Repeat actions if need be.
- Physical Redundancy. Extra equipment or processes are added to make the system tolerate loss of some components.

# Failure Masking by Physical Redundancy

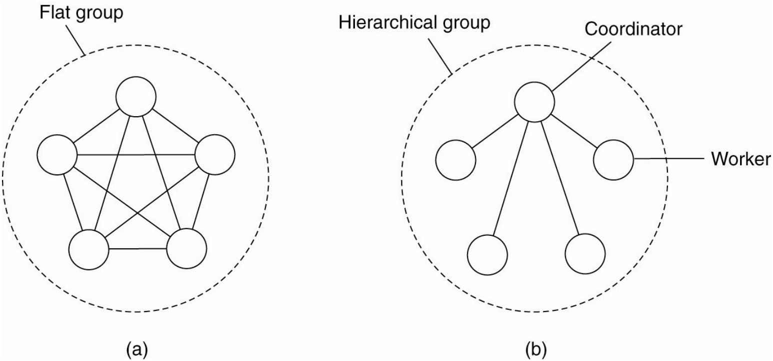


# Process Resilience

Achieved by replicating processes into groups.

- How to design fault-tolerant groups?
- How to reach an agreement within a group when some members cannot be trusted to give correct answers?

# Flat Groups Versus Hierarchical Groups



# Failure Masking Via Replication

- *Primary-backup protocol*. A primary coordinates all write operations. If it fails, then the others hold an election to replace the primary
- *Replicated-write protocols*. Active replication as well as quorum based protocols. Corresponds to a flat group

# Failure Masking Via Replication

- *Primary-backup protocol*. A primary coordinates all write operations. If it fails, then the others hold an election to replace the primary
- *Replicated-write protocols*. Active replication as well as quorum based protocols. Corresponds to a flat group
- A system is said to be *k* fault tolerant if it can survive faults in *k* components and still meet its specifications.

# Failure Masking Via Replication

- *Primary-backup protocol*. A primary coordinates all write operations. If it fails, then the others hold an election to replace the primary
- *Replicated-write protocols*. Active replication as well as quorum based protocols. Corresponds to a flat group
- A system is said to be $k$ fault tolerant if it can survive faults in $k$ components and still meet its specifications.
  - For *fail-silent* components, $k+1$ are enough to be $k$ fault tolerant.

# Failure Masking Via Replication

- *Primary-backup protocol*. A primary coordinates all write operations. If it fails, then the others hold an election to replace the primary
- *Replicated-write protocols*. Active replication as well as quorum based protocols. Corresponds to a flat group
- A system is said to be $k$ fault tolerant if it can survive faults in $k$ components and still meet its specifications.
  - For *fail-silent* components, $k+1$ are enough to be $k$ fault tolerant.
  - For *Byzantine failures*, at least $2k+1$ extra components are needed to achieve $k$ fault tolerance.

# Failure Masking Via Replication

- *Primary-backup protocol*. A primary coordinates all write operations. If it fails, then the others hold an election to replace the primary
- *Replicated-write protocols*. Active replication as well as quorum based protocols. Corresponds to a flat group
- A system is said to be *k* fault tolerant if it can survive faults in *k* components and still meet its specifications.
  - For *fail-silent* components, $k+1$ are enough to be $k$ fault tolerant.
  - For *Byzantine failures*, at least $2k+1$ extra components are needed to achieve $k$ fault tolerance.
  - Requires atomic multicasting: all requests arrive at all servers in same order. This can be relaxed to just for write operations.

# Agreement in Faulty Systems (1)

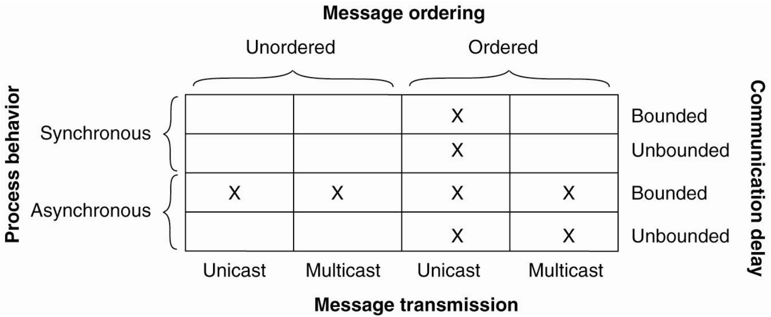
The general goal of distributed agreement algorithms is to have all the non-faulty processes reach agree consensus on some issue, and to establish that consensus within a finite number of steps.

# Agreement in Faulty Systems (1)

The general goal of distributed agreement algorithms is to have all the non-faulty processes reach agree consensus on some issue, and to establish that consensus within a finite number of steps. Possible cases:

- Synchronous versus asynchronous systems
- Communication delay is bounded or not
- Message delivery is ordered or not
- Message transmission is done through unicasting or multicasting

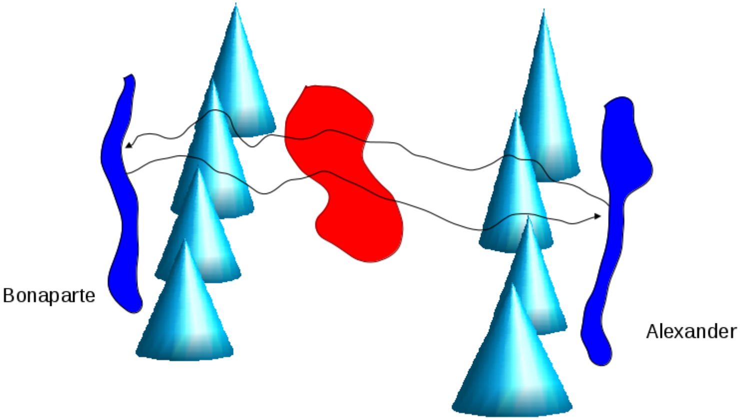
# Agreement in Faulty Systems (2)



| | | Message ordering | | | |
|---|---|---|---|---|---|
| | | Unordered | | Ordered | |
| Process behavior | Communication delay | Unicast | Multicast | Unicast | Multicast |
| Synchronous | Bounded | | | X | |
| | Unbounded | | | X | |
| Asynchronous | Bounded | X | X | X | X |
| | Unbounded | | | X | X |

Message transmission

# Agreement in Faulty Systems (3)



- Two Army Problem
- Non-faulty generals with unreliable communication.

# Agreement in Faulty Systems (3)

Byzantine Generals Problem (Lamport)

- Red army in the valley, $n$ blue generals each with their own army surrounding them.
- Communication is pairwise, instantaneous and perfect.
- However $m$ of the blue generals are traitors (faulty processes) and are actively trying to prevent the loyal generals from reaching agreement. The generals know the value $m$.

# Agreement in Faulty Systems (3)

Byzantine Generals Problem (Lamport)

- Red army in the valley, $n$ blue generals each with their own army surrounding them.
- Communication is pairwise, instantaneous and perfect.
- However $m$ of the blue generals are traitors (faulty processes) and are actively trying to prevent the loyal generals from reaching agreement. The generals know the value $m$.

**Goal**: The generals need to exchange their troop strengths. At the end of the algorithm, each general has a vector of length $n$. If $i$th general is loyal, then the $i$th element has their correct troop strength otherwise it is undefined.

# Agreement in Faulty Systems (3)

Byzantine Generals Problem (Lamport)

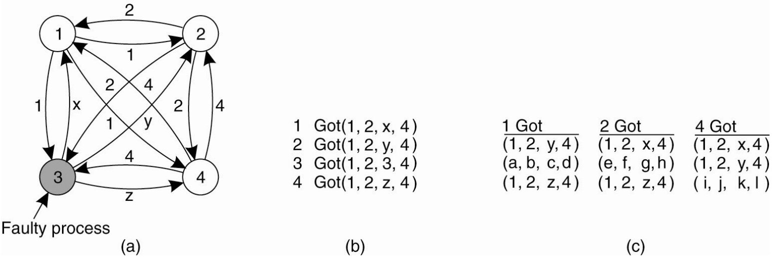
- Red army in the valley, $n$ blue generals each with their own army surrounding them.
- Communication is pairwise, instantaneous and perfect.
- However $m$ of the blue generals are traitors (faulty processes) and are actively trying to prevent the loyal generals from reaching agreement. The generals know the value $m$.

**Goal**: The generals need to exchange their troop strengths. At the end of the algorithm, each general has a vector of length $n$. If $i$th general is loyal, then the $i$th element has their correct troop strength otherwise it is undefined.

**Conditions for a solution**:

- All loyal generals decide upon the same plan of action
- A small number of traitors cannot cause the loyal generals to adopt a bad plan

# Byzantine Agreement Example (1)



1 Got(1, 2, x, 4)
2 Got(1, 2, y, 4)
3 Got(1, 2, 3, 4)
4 Got(1, 2, z, 4)

(b)

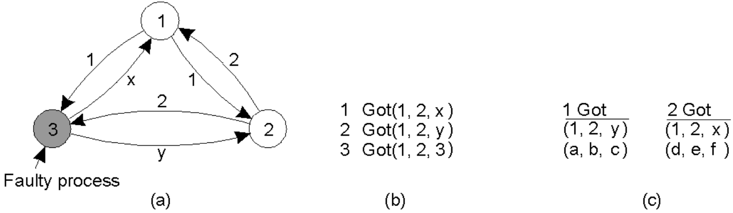
| 1 Got | 2 Got | 4 Got |
|---|---|---|
| (1, 2, y, 4) | (1, 2, x, 4) | (1, 2, x, 4) |
| (a, b, c, d) | (e, f, g, h) | (1, 2, y, 4) |
| (1, 2, z, 4) | (1, 2, z, 4) | ( i, j, k, l ) |

(c)

The Byzantine generals problem for 3 loyal generals and 1 traitor:

- The generals announce their troop strengths (let's say, in units of 1 kilo soldiers)
- The vectors that each general assembles based on previous step
- The vectors that each general receives
- If a value has a majority, then we know it correctly, else it is unknown

# Byzantine Agreement Example (2)



(a)

1 Got(1, 2, x )
2 Got(1, 2, y )
3 Got(1, 2, 3 )

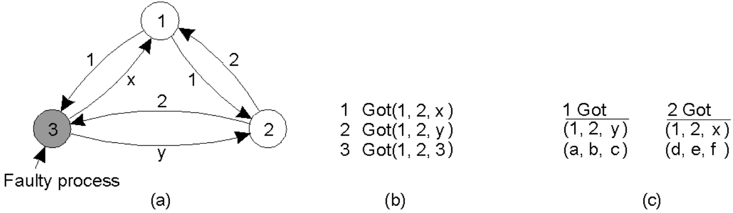
(b)

| 1 Got | 2 Got |
|---|---|
| (1, 2, y) | (1, 2, x) |
| (a, b, c) | (d, e, f ) |

(c)

- The same as in previous slide, except now with 2 loyal generals and one traitor.

# Byzantine Agreement Example (2)



1 Got(1, 2, x )
2 Got(1, 2, y )
3 Got(1, 2, 3 )

(b)

| 1 Got | 2 Got |
|---|---|
| (1, 2, y ) | (1, 2, x ) |
| (a, b, c ) | (d, e, f ) |

(c)

- The same as in previous slide, except now with 2 loyal generals and one traitor.
- For *m* faulty processes, we need a total of $3m+1$ processes to reach agreement.

# Reliable Client-Server Communication

RMI semantics in the presence of failures.

# Reliable Client-Server Communication

RMI semantics in the presence of failures.

- The client is unable to locate the server.

# Reliable Client-Server Communication

RMI semantics in the presence of failures.

- The client is unable to locate the server.
- The request message from the client to the server is lost.

# Reliable Client-Server Communication

RMI semantics in the presence of failures.

- The client is unable to locate the server.
- The request message from the client to the server is lost.
- The server crashes after receiving a request.

# Reliable Client-Server Communication

RMI semantics in the presence of failures.

- The client is unable to locate the server.
- The request message from the client to the server is lost.
- The server crashes after receiving a request.
- The reply message from the server to the client is lost.

# Reliable Client-Server Communication

RMI semantics in the presence of failures.

- The client is unable to locate the server.
- The request message from the client to the server is lost.
- The server crashes after receiving a request.
- The reply message from the server to the client is lost.
- The client crashes after sending a request.

# RPC Semantics in the Presence of Failures

- RPC failures
  - Client cannot locate server: Raise an exception or send a signal to client leading to loss in transparency

# RPC Semantics in the Presence of Failures

- RPC failures
  - Client cannot locate server: Raise an exception or send a signal to client leading to loss in transparency
  - Lost request messages: Start a timer when sending a request. If timer expires before a reply is received, send the request again. Server would need to detect duplicate requests

# RPC Semantics in the Presence of Failures

- RPC failures
  - Client cannot locate server: Raise an exception or send a signal to client leading to loss in transparency
  - Lost request messages: Start a timer when sending a request. If timer expires before a reply is received, send the request again. Server would need to detect duplicate requests
  - Server crashes: Server crashes before or after executing the request is indistinguishable from the client side...

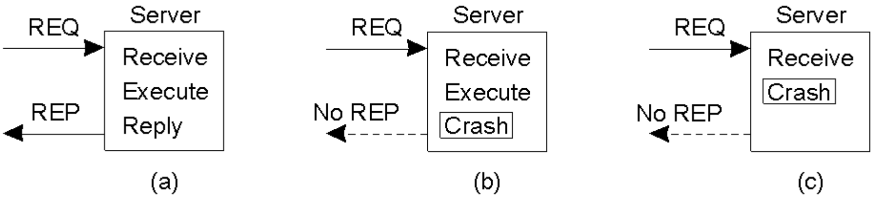
# RPC Semantics in the Presence of Failures

- RPC failures
  - Client cannot locate server: Raise an exception or send a signal to client leading to loss in transparency
  - Lost request messages: Start a timer when sending a request. If timer expires before a reply is received, send the request again. Server would need to detect duplicate requests
  - Server crashes: Server crashes before or after executing the request is indistinguishable from the client side...
- Possible RPC semantics

# RPC Semantics in the Presence of Failures

- RPC failures
  - Client cannot locate server: Raise an exception or send a signal to client leading to loss in transparency
  - Lost request messages: Start a timer when sending a request. If timer expires before a reply is received, send the request again. Server would need to detect duplicate requests
  - Server crashes: Server crashes before or after executing the request is indistinguishable from the client side...
- Possible RPC semantics
  - Exactly once semantics
  - At least once semantics
  - At most once semantics
  - Guarantee nothing semantics

# Server Crash (1)



- A server in client-server communication
  - (a) Normal case
  - (b) Crash after execution
  - (c) Crash before execution

# Server Crash (2)

- Server: Prints text on receiving request from client and sends message to client after text is printed.

# Server Crash (2)

- Server: Prints text on receiving request from client and sends message to client after text is printed.
  - Send a completion message just before it actually tells the printer to do its work
  - Or after the text has been printed

# Server Crash (2)

- Server: Prints text on receiving request from client and sends message to client after text is printed.
  - Send a completion message just before it actually tells the printer to do its work
  - Or after the text has been printed
- Client:

# Server Crash (2)

- Server: Prints text on receiving request from client and sends message to client after text is printed.
  - Send a completion message just before it actually tells the printer to do its work
  - Or after the text has been printed
- Client:
  - Never to reissue a request.

# Server Crash (2)

- Server: Prints text on receiving request from client and sends message to client after text is printed.
  - Send a completion message just before it actually tells the printer to do its work
  - Or after the text has been printed
- Client:
  - Never to reissue a request.
  - Always reissue a request.

# Server Crash (2)

- Server: Prints text on receiving request from client and sends message to client after text is printed.
  - Send a completion message just before it actually tells the printer to do its work
  - Or after the text has been printed
- Client:
  - Never to reissue a request.
  - Always reissue a request.
  - Reissue a request only if it did not receive an acknowledgment of its request being delivered to the server.

# Server Crash (2)

- Server: Prints text on receiving request from client and sends message to client after text is printed.
  - Send a completion message just before it actually tells the printer to do its work
  - Or after the text has been printed
- Client:
  - Never to reissue a request.
  - Always reissue a request.
  - Reissue a request only if it did not receive an acknowledgment of its request being delivered to the server.
  - Reissue a request only if it has not received an acknowledgment of its print request.

# Server Crash (3)

- Three events that can happen at the server:
  - Send the completion message (M)
  - Print the text (P)
  - Crash (C)

# Server Crash (3)

- Three events that can happen at the server:
  - Send the completion message (M)
  - Print the text (P)
  - Crash (C)
- These events can occur in six different orderings:

# Server Crash (4)

1. $M \rightarrow P \rightarrow C$: A crash occurs after sending the completion message and printing the text.

# Server Crash (4)

1. $M \rightarrow P \rightarrow C$: A crash occurs after sending the completion message and printing the text.
2. $M \rightarrow C (\rightarrow P)$: A crash happens after sending the completion message, but before the text could be printed.

# Server Crash (4)

1. $M \rightarrow P \rightarrow C$: A crash occurs after sending the completion message and printing the text.
2. $M \rightarrow C(\rightarrow P)$: A crash happens after sending the completion message, but before the text could be printed.
3. $P \rightarrow M \rightarrow C$: A crash occurs after sending the completion message and printing the text.

# Server Crash (4)

1. $M \to P \to C$: A crash occurs after sending the completion message and printing the text.
2. $M \to C(\to P)$: A crash happens after sending the completion message, but before the text could be printed.
3. $P \to M \to C$: A crash occurs after sending the completion message and printing the text.
4. $P \to C(\to M)$: The text printed, after which a crash occurs before the completion message could be sent.

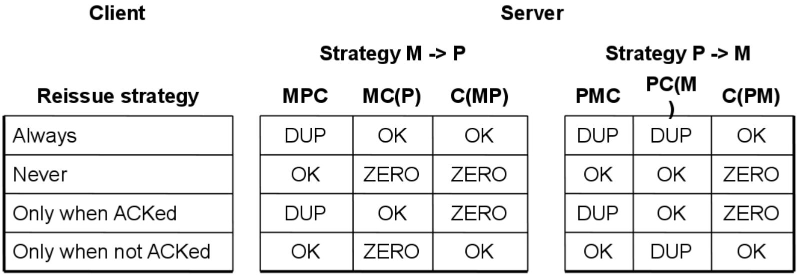
# Server Crash (4)

1. $M \to P \to C$: A crash occurs after sending the completion message and printing the text.
2. $M \to C(\to P)$: A crash happens after sending the completion message, but before the text could be printed.
3. $P \to M \to C$: A crash occurs after sending the completion message and printing the text.
4. $P \to C(\to M)$: The text printed, after which a crash occurs before the completion message could be sent.
5. $C(\to P \to M)$: A crash happens before the server could do anything.

# Server Crash (4)

1. $M \rightarrow P \rightarrow C$: A crash occurs after sending the completion message and printing the text.
2. $M \rightarrow C(\rightarrow P)$: A crash happens after sending the completion message, but before the text could be printed.
3. $P \rightarrow M \rightarrow C$: A crash occurs after sending the completion message and printing the text.
4. $P \rightarrow C(\rightarrow M)$: The text printed, after which a crash occurs before the completion message could be sent.
5. $C(\rightarrow P \rightarrow M)$: A crash happens before the server could do anything.
6. $C(\rightarrow M \rightarrow P)$: A crash happens before the server could do anything.

# Server Crash (5)



| Client | Server | | | | | |
|---|---|---|---|---|---|---|
| | Strategy M -> P | | | Strategy P -> M | | |
| Reissue strategy | MPC | MC(P) | C(MP) | PMC | PC(M<br>) | C(PM) |
| Always | DUP | OK | OK | DUP | DUP | OK |
| Never | OK | ZERO | ZERO | OK | OK | ZERO |
| Only when ACKed | DUP | OK | ZERO | DUP | OK | ZERO |
| Only when not ACKed | OK | ZERO | OK | OK | DUP | OK |

- *M*: send the completion message
- *P*: print the text
- *C*: server crash

# RPC Semantics in the Presence of Failures (2)

- Lost Reply Messages. Set a timer on client. If it expires without a reply, then send the request again. If requests are idempotent, then they can be repeated again without ill-effects

# RPC Semantics in the Presence of Failures (2)

- Lost Reply Messages. Set a timer on client. If it expires without a reply, then send the request again. If requests are idempotent, then they can be repeated again without ill-effects
- Client Crashes. Creates orphans. An orphan is an active computation on the server for which there is no client waiting. How to deal with orphans:

# RPC Semantics in the Presence of Failures (2)

- Lost Reply Messages. Set a timer on client. If it expires without a reply, then send the request again. If requests are idempotent, then they can be repeated again without ill-effects
- Client Crashes. Creates orphans. An orphan is an active computation on the server for which there is no client waiting. How to deal with orphans:
  - Extermination. Client logs each request in a file before sending it. After a reboot the file is checked and the orphan is explicitly killed off. Expensive, cannot locate grand-orphans etc.

# RPC Semantics in the Presence of Failures (2)

- Lost Reply Messages. Set a timer on client. If it expires without a reply, then send the request again. If requests are idempotent, then they can be repeated again without ill-effects
- Client Crashes. Creates orphans. An orphan is an active computation on the server for which there is no client waiting. How to deal with orphans:
  - Extermination. Client logs each request in a file before sending it. After a reboot the file is checked and the orphan is explicitly killed off. Expensive, cannot locate grand-orphans etc.
  - Reincarnation. Divide time into sequentially numbered epochs. When a client reboots, it broadcasts a message declaring a new epoch. This allows servers to terminate orphan computations.

# RPC Semantics in the Presence of Failures (2)

- Lost Reply Messages. Set a timer on client. If it expires without a reply, then send the request again. If requests are idempotent, then they can be repeated again without ill-effects
- Client Crashes. Creates orphans. An orphan is an active computation on the server for which there is no client waiting. How to deal with orphans:
  - Extermination. Client logs each request in a file before sending it. After a reboot the file is checked and the orphan is explicitly killed off. Expensive, cannot locate grand-orphans etc.
  - Reincarnation. Divide time into sequentially numbered epochs. When a client reboots, it broadcasts a message declaring a new epoch. This allows servers to terminate orphan computations.
  - Gentle Reincarnation. A server tries to locate the owner of orphans before killing the computation.

# RPC Semantics in the Presence of Failures (2)

- Lost Reply Messages. Set a timer on client. If it expires without a reply, then send the request again. If requests are idempotent, then they can be repeated again without ill-effects
- Client Crashes. Creates orphans. An orphan is an active computation on the server for which there is no client waiting. How to deal with orphans:
  - Extermination. Client logs each request in a file before sending it. After a reboot the file is checked and the orphan is explicitly killed off. Expensive, cannot locate grand-orphans etc.
  - Reincarnation. Divide time into sequentially numbered epochs. When a client reboots, it broadcasts a message declaring a new epoch. This allows servers to terminate orphan computations.
  - Gentle Reincarnation. A server tries to locate the owner of orphans before killing the computation.
  - Expiration. Each RPC is given a quantum of time to finish its job. If it cannot finish, then it asks for another quantum. After a crash, a client need only wait for a quantum to make sure all orphans are gone.

# Idempotent Operations

- An idempotent operation is one that can be repeated as often as necessary without any harm being done. E.g. reading a block from a file.

# Idempotent Operations

- An idempotent operation is one that can be repeated as often as necessary without any harm being done. E.g. reading a block from a file.
- In general, try to make RPC/RMI methods be idempotent if possible. If not, it can be dealt with in a couple of ways.

# Idempotent Operations

- An idempotent operation is one that can be repeated as often as necessary without any harm being done. E.g. reading a block from a file.
- In general, try to make RPC/RMI methods be idempotent if possible. If not, it can be dealt with in a couple of ways.
  - Use a sequence number with each request so server can detect duplicates. But now the server needs to keep state for each client....

# Idempotent Operations

- An idempotent operation is one that can be repeated as often as necessary without any harm being done. E.g. reading a block from a file.
- In general, try to make RPC/RMI methods be idempotent if possible. If not, it can be dealt with in a couple of ways.
  - Use a sequence number with each request so server can detect duplicates. But now the server needs to keep state for each client....
  - Have a bit in the message to distinguish between original and duplicate transmission