INFLUENTIAL OPERATING SYSTEMS RESEARCH

Fault Tolerant Systems

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Outline

The Tandem NonStop System

Replication for Fun and Profit

Bugs in Modern Operating Systems
Once upon a time...

• The advent of *online transaction processing*
  – 1964 – IBM SABRE for American Airlines
  – later banking, stock exchange, telephone switches ...

• New requirements
  – Large workloads and data bases (no pun intended)
  – Loss of actual money if the system goes down
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• Founded 1974
• NonStop high availability computers
• Acquired by Compaq, later by HP
Anatomy of a Failure

“Conventional, well-managed transaction processing systems fail about once very two weeks.”
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0 min: Failure
3 min: Detection
12 min: OS restarted
17 min: DB restarted
30 min: Network restarting...
8 min: Core dump complete
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Definitions

Fault Model

Defines the expected behavior of faulty components:

- **Fail-stop**: Faulty components do not produce output.
- **Soft failures**: Recovery consists of replacing hardware or restarting software.
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Metrics
Mean Time Between Failures: **MTBF**
Mean Time To Repair: **MTTR**
Definitions (2)

Availability

Do the right thing within a specified amount of time.

\[ \text{Availability} := \frac{MTBF}{MTBF + MTTR} \]
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$$\text{Availability} := \frac{MTBF}{MTBF + MTTR}$$

**Reliability**

Never do the wrong thing.
Reliability: Design Principles

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Reliability: Design Principles

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- **Redundancy**: Configure extra modules that can take over in case of failure.
NonStop: Hardware

J. Bartlett: A NonStop Kernel, SOSP 1981
NonStop: Kernel Services

Per node: memory+process manager

Fault-tolerant messaging: RPC-style programming model
  • Abort calls at any time

Packet protection
  • Sequence numbers
  • Data Checksums
  • Timeouts: resend over alternative channel
  • Batched acknowledgments: dual function as heartbeat
NonStop: Software

Software services implemented as **process pairs**

- Primary: handles all requests
- Backup: steps in if primary failure is detected
  a) Initiate restart of primary
  b) Launch new backup process
- Primary + Backup run on different processors.
- OS maintains Primary/Backup table.
NonStop: Software

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How do we keep the backup up-to-date?
NonStop: Syncing Primary+Backup

1. Lock-stepping
   - Process all requests at both partners step-by-step.
   - Will catch hardware errors, but no software ones.

2. State Checkpointing
   - Primary sends all requests and replies to backup.
   - Requires additional programming effort.

3. Delta Checkpointing
   - Instead of sending every physical request, send diffs of service state to the backup.
4. Automatic Checkpointing
   - Log all messages, only replay in case of failover.
   - If state grows to large, send physical state update.

5. Persistent Processes
   - Do not send updates at all!
   - Instead, backup wakes up in NULL state.
   - But service state needs to always be consistent!
     a) Every successful request leaves the service state consistent.
     b) Every failing request does not modify service state at all.
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But isn’t that...?
Transactions!

- Atomicity: all or nothing state modification (commit or abort)
- Consistency: always work on consistent state (even during concurrent transactions)
- Integrity: all state transformations need to be correct
- Durability: committed transactions remain persistent

Why is this good for reliability?
- No state inconsistencies
- Built-in abort + undo upon failure
- No state checkpointing between primary and backup
More Fault Models

- **Byzantine Failure**: Faulty components produce arbitrary, potentially malicious output.

- **Common Cause Failures**: Multiple components fail at the same time because they are subject to the same cause.
Software Model

An application implements a service in the form of a **state machine**.
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Can every application be implemented as a state machine?
State Machine Properties

- **Sequentiality**: Requests are processed atomically.

- **Determinism**: The same sequence of requests produces the same output.

- **Independence from time**: The timing of requests does not influence state transitions.
A system is **fault tolerant** if it satisfies its specification provided that no more than $t$ of its components become faulty during some interval of interest.

**Fault Tolerance**

- **Fail-stop**: $t+1$ replicas are needed.
- **Byzantine**: $2t+1$ replicas and majority voting.
- **Common cause**: Physically/geographically distribute replicas.
Tolerating Independent Failures

**T Fault Tolerance**

A system is **fault tolerant** if it satisfies its specification provided that no more than \( t \) of its components become faulty during some interval of interest.

**Replication**

T Fault Tolerance can be achieved by running multiple independent replicas of a state machine.

- **Fail-stop**: \( T + 1 \) replicas are needed.
- **Byzantine**: \( 2T + 1 \) replicas and majority voting
- **Common cause**: Physically/geographically distribute replicas.
Implementing State Machine Replication

• Replicas need to be coordinated:
  – **Agreement**: All replicas need to see all requests.
  – **Order**: All replicas process requests in the same order.

• Relaxations may improve performance:
  – Read-only requests in fail-stop systems need only be serviced by a single replica.
  – Commutative requests may be processed in any order.

• Coordination problems:
  – Requests may get lost.
  – Requests may overtake each other.
Implementing Ordering

It’s simple:

- Assign requests unique identifiers.
- Ensure total ordering of UIDs is possible.
- Process requests in order of their IDs.

Not quite...

- How to assign IDs?
- When does a replica know that a request reached all other replicas?
Stability

A request is defined to be **stable** at state machine $SM_i$ once no request from a correct client and bearing a lower unique identifier can be subsequently delivered to $SM_i$.

Order Implementation

A replica next processes the stable request with the smallest unique identifier.
Ordering with Logical Clocks

Assign each event $e$ a timestamp $T(e)$, so that if we have two events $e$ and $f$ and $e$ might be responsible for causing $f$, then $T(e) < T(f)$.

L. Lamport: *Time, Clocks and the Ordering of Events in a Distributed System*, CACM, 1978
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- Each process $p$ is assigned a counter $T_p$.
- Each message $m$ is augmented with the value of $T_p$ when $m$ was sent by $p$.
- $T_p$ is then updated as follows:
  1. Each event at $p$ increments $T_p$.
  2. When receiving a message, the receiver $r$ updates $T_r := \max(T_m, T_r) + 1$.

L. Lamport: *Time, Clocks and the Ordering of Events in a Distributed System*, CACM, 1978
Logical Clocks: Example

q 1

r 1

Influential Operating Systems Research
Logical Clocks: Example
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Logical Clocks and Replicas

- **FIFO Channels**: Logical clocks establish send order between any pair of processors.
Logical Clocks and Replicas

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- Replica ordering:
  - All processors periodically send heartbeat messages (broadcast!).
  - A request is stable at replica $SM_i$ if a request/heartbeat with a larger timestamp has been received by $SM_i$ from every non-faulty processor.
Things to Consider

- Can also integrate stability generation into real-time clock synchronization.
- If sync traffic is a concern, algorithms to generate UIDs with less messages exist.
- The $2T + 1$ rule for byzantine faults only works for the case of a correct voter!
  - So we might want to replicate voters see Berninck: NonStop: Advanced Architecture, DSN 2005
  - Otherwise this becomes the Byzantine Generals Problem, which is only solvable with $3T + 1$ participants see Lamport, Pease, Shostak: The Byzantine Generals Problem, 1982
N. Palix et al.: 
*Faults In Linux: Ten Years Later*,
ASPLOS 2011
Lecture on Experiments

- Document system and configuration
- Publish and keep raw data, setups, ...
- Experiments must be repeatable by others.
Repeating Experiments in the Real World

The Original:

- Static code analysis of Linux 1.0 – 2.4.
- Device drivers 3x more likely to contain bugs than rest of kernel code.

Hypothesis:
10 years of research on improving device driver quality should have had an impact.

Validation:
Repeat Chou’s experiments with Linux 2.6 kernels.
Static Source Code Analysis

Check potentially NULL pointers returned from routines.

```c
my_data_struct *foo = kmalloc(10 * sizeof(*foo), GFP_KERNEL);
foo->some_element = 23;
```

Do not use freed memory

```c
free(foo);
foo->some_element = 23;
```
Do not allocate large stack variables (>1K) on the fixed-size kernel stack.

```c
void some_function()
{
    char array[1 << 12];
    char array2[MY_MACRO(x,y)]; // not found
    ...
}
```
Inull

Do not make inconsistent assumptions about whether a pointer is NULL.

```c
void foo(char *bar)
{
    if (!bar) { // IsNull
        printk("Error: %s\n", *bar);
    } else {
        printk("Success: %s\n", *bar);
        if (!bar) { // NullRef
            panic();
        }
    }
}
```
Release acquired locks; do not double-acquire locks. Restore disabled interrupts.

```c
void foo() {
    DEFINE_SPINLOCK(l1); DEFINE_SPINLOCK(l2);
    unsigned long flags1, flags2;

    spin_lock_irqsave(&l1, flags1);
    spin_lock_irqsave(&l2, flags2);
    // double acquire:
    spin_lock_irqsave(&l1, flags1);
    ..
    spin_unlock_irqrestore(&l2, flags2);
    // unrestored interrupts for l1/flags1
    // + unreleased lock l1
}
```
Always check bounds of array indices and loop bounds derived from user data.

```c
int index = -1;
int n = copy_from_user(&index, userptr, sizeof(index));
if (!n) {
    kernel_data[index] = 0x0815;
}
```
Allocate enough memory to hold the type for which you are allocating.

```c
typedef int     myData;
typedef long long yourData;

yourData *ptr = kmalloc(sizeof(myData));
```
Lines of Code

**Figure 1.** Linux directory sizes (in MLOC)
Fault rate per subdirectory

Rate of Errors compared to Other Directories

- Block
- Free
- Inull
- Intr
- Lock
- Null
- Range
- Var

Rate
- other
- arch/i386
- net
- fs
- drivers
Fault rate per subdirectory

![Graph showing fault rate per subdirectory]
Figure 6: Faults in Linux 2.6.0 to 2.6.33
Crying for help

...Because Chou et al.'s fault finding tool and checkers were not released, and their results were released on a local web site but are no longer available, it is impossible to exactly reproduce their results on recent versions of the Linux kernel...

In laboratory sciences there is a notion of experimental protocol, giving all of the information required to reproduce an experiment...
Crying for help

...Chou et al. focus only on x86 code, finding that 70% of the Linux 2.4.1 code is devoted to drivers. Nevertheless, we do not know which drivers, file systems, etc. were included...

...Results from Chou et al.’s checkers were available at a web site interface to a database, but Chou has informed us that this database is no longer available. Thus, it is not possible to determine the precise reasons for the observed differences...
Summary

- Custom-tailoring for fault tolerance: it’s getting harder as systems grow more complex.
- Distributed systems fault tolerance: it’s running the cloud (tm).
- Device drivers are still an issue.