Mutable Protection Domains: Towards a Component-based System for Dependable and Predictable Computing

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Complexity of Embedded Systems

Traditionally simpler software stack

- limited functionality and complexity
- focused application domain

Soon cellphones will have

- 10s of millions of lines of code
- downloadable content (with real-time constraints)

Trend towards increasing complexity of embedded systems

Consequences of Complexity

Run-time interactions are difficult to predict and can cause faults

- accessing/modifying memory regions unintentionally
- corruption data-structures
- deadlocks/livelocks
- race-conditions
- ...

Faults can cause violations in correctness and predictability

Designing for Dependability and Predictability

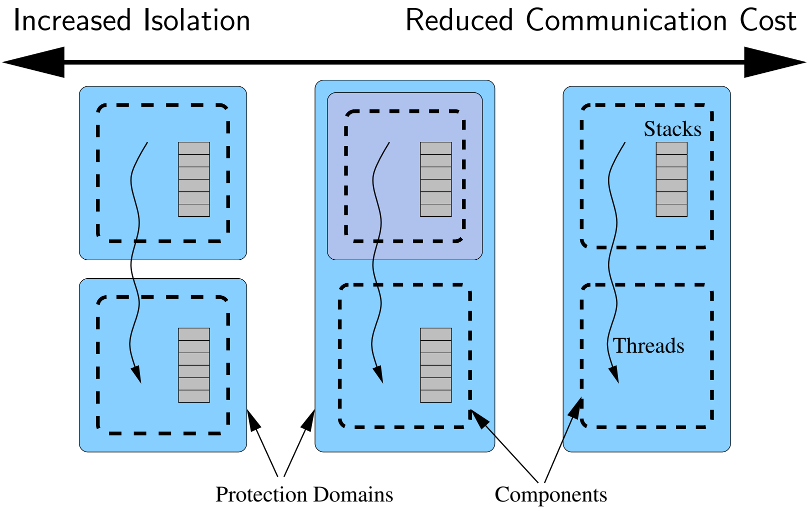
Given increasing complexity, system design must anticipate faults

Memory fault isolation: limit scope of adverse side-effects of errant software

- identify and restart smallest possible section of the system
- recover from faults with minimal impact on system goals
- employ software/hardware techniques

> Preserve system reliability and predictability in spite of misbehaving and/or faulty software

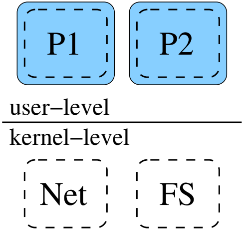
Trade-offs in Isolation Granularity



Process Isolation **User-Kernel Isolation** **Library Isolation**

Static HW Fault Isolation Approaches

What is the "best" isolation granularity?



Monolithic OSs

- provide minimal isolation to allow process independence
- large kernel not self-isolated, possibly extend-able

→ Coarse-grained isolation, **but** low service invocation cost

Static HW Fault Isolation Approaches (II)

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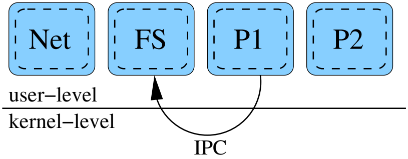

μ-kernels

- segregate system services out of the kernel, interact w/ Inter-Process Communication (IPC)
- finer-grained isolation
    - IPC overhead limits isolation granularity

→ Finer-grained fault isolation, **but** increased service invocation cost

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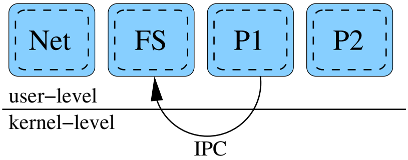

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Both characterized by a static system structure

Mutable Protection Domains (MPD)

Goal: configure system to have finest grained fault isolation while still meeting application deadlines

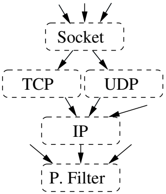
Mutable Protection Domains (MPDs)

- *dynamically* place protection domains between components in response to
  - communication overheads due to isolation
  - application deadlines being satisfied
- application close to missing deadlines
  $\longrightarrow$ lessen isolation between components
- laxity in application deadlines
  $\longrightarrow$ increase isolation between components

Mutable Protection Domains (MPD) (II)

Mutable Protection Domains appropriate for soft real-time systems

Protection domains can be made immutable where appropriate

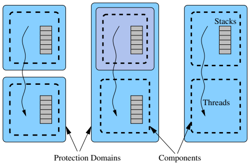


System is a collection of *components*

Arranged into a directed acyclic graph (DAG)

- nodes = components themselves
- edges = communication between them, indicative of control flow

Isolation over an edge can be configured to be one of the three isolation levels



Isolation `cost` and `benefit`

Isolation between components causes a performance penalty due to:

1. processing cost of a single invocation between those components
2. the frequency of invocations between those components

$\longrightarrow$ `cost` of each isolation level/edge

Different isolation levels yield higher dependability

- stronger isolation $\rightarrow$ higher dependability

Isolation between specific components more important

- debugging, testing, unreliable components, ...

$\longrightarrow$ `benefit` of each isolation levels/edge

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This paper studies the policies concerning when and where isolation should be present

Problem Definition

For a solution set s

where $s_i \in \{1, \ldots, \#\_\texttt{isolation\_levels}\}$

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Maximize the dependability of the system ...

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While meeting task deadlines …

while $\sum_{\forall i \in \texttt{edges}} \texttt{cost}_{is_i} \leq \texttt{surplus\_resources}$

Problem Definition

For a solution set s	where $s_i \in \{1, \ldots, \#\_\texttt{isolation\_levels}\}$
Maximize the dependability of the system …	maximize $\sum_{\forall i \in \texttt{edges}} \texttt{benefit}_{is_i}$
While meeting task deadlines …	while $\sum_{\forall i \in \texttt{edges}} \texttt{cost}_{is_i k} \leq \texttt{surplus\_resources}_k$
For each task in the system	$\forall k \in \texttt{tasks}$

Multi-Dimensional, Multiple-Choice Knapsack

$$\text{maximize} \sum_{\forall i \in \texttt{edges}} \texttt{benefit}_{is_i}$$

$$\text{subject to} \sum_{\forall i \in \texttt{edges}} \texttt{cost}_{is_i k} \leq \texttt{surplus\_resources}_k, \ \forall k \in \texttt{tasks}$$

$$s_i \in \{1, \ldots, \texttt{max\_isolation\_level}\}, \ \forall i \in \texttt{edges}$$

This problem is a multi-dimensional, multiple-choice knapsack problem (MMKP)

- multi-dimensional - multiple resource constraints
- multiple-choice - configure each edge in one of the isolation levels

NP-Hard problem

- heuristics, pseudo-poly dynamic prog., branch-bound

One-Dimensional Knapsack Problem

Effective and inexpensive greedy solutions to one-dimensional knapsack problem exist

- sort isolation levels/edges based on *benefit density*, ratio of benefit to cost
- increase isolation by including isolation levels/edges from head until resources are expended
- ...but we have multiple dimensions of cost

Solutions - Reducing Resource Dimensions

Compute an *aggregate cost* for each edge

- single value representing a combination of the costs for all tasks for an edge: $\forall k, \texttt{cost}_{is_i k} \rightarrow \texttt{agg\_cost}_{is_i}$
- some tasks very resource constrained, some aren't
- intelligently weight costs for task k to compute aggregate cost

Solutions - HEU

1. compute aggregate cost for each isolation level/edge
2. include isolation level/edge with best benefit density in solution configuration
3. goto 1 until resources expended

Fine-grained refinement of aggregate cost

- recompute once every time an isolation level/edge is added to the current solution configuration

Solutions - *coarse* and *oneshot* Refinement

1. compute aggregate cost for each isolation level/edge
2. sort by benefit density
3. include isolation level/edge from head
4. goto 3, until resources expended
5. recompute aggregate costs based on resource surpluses with solution configuration
6. goto 2 N times and return highest benefit configuration

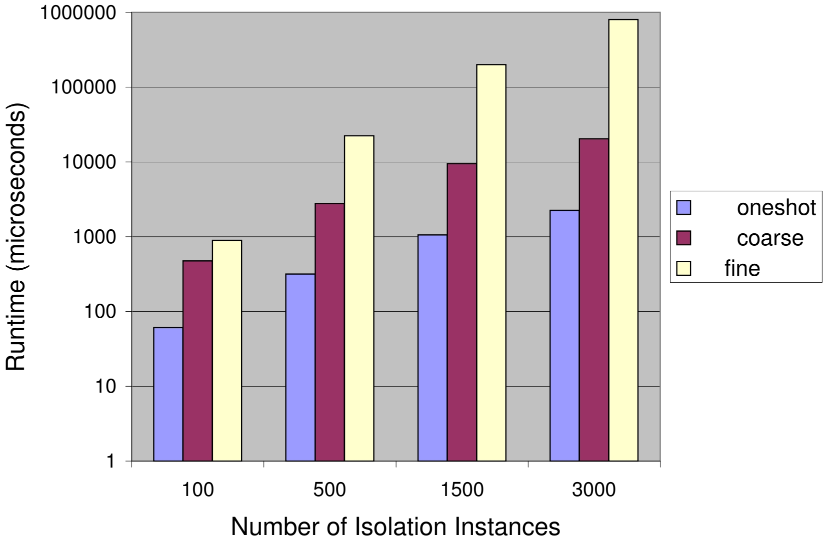
$N > 1$: *coarse-grained* refinement

- recompute once per total configuration found
- execution time linearly increases with N

$N = 1$: *oneshot*

- very quick
- no aggregate cost refinement

Solution Runtimes



System Dynamics

System is dynamic

- changing communication costs over edges as threads alter execution paths between components
- changing resource availabilities as threads vary intra-component execution time
- per-invocation cost overheads vary
  - different cache working sets, invocation argument size, . . .

System must refine the system isolation configuration as these variables change

Solutions over time

System dynamics require re-computation of system configuration

1. disregard current system state, recompute entirely new system configuration
   - traditional knapsack (MMKP) approach: *ks*

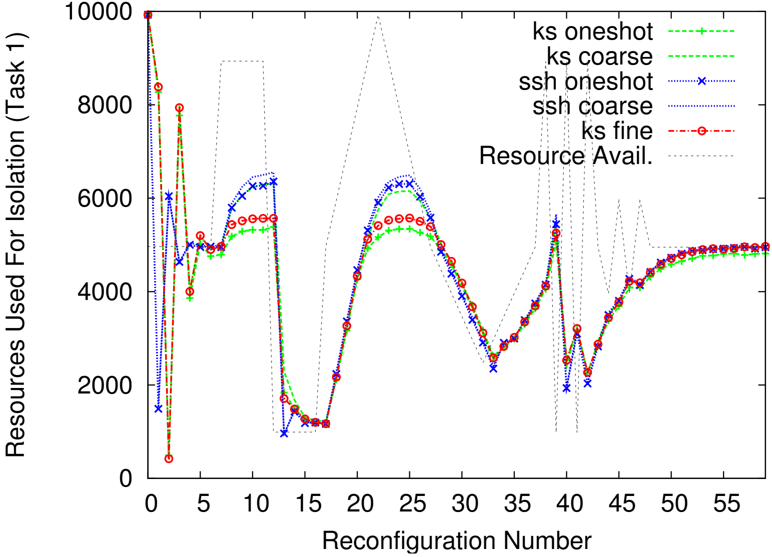
2. solve for the next system configuration starting from the current system configuration

   Successive State Heuristic (*ssh*)
   - modifies *coarse* and *oneshot* to start from the current system configuration
   - aim to reduce isolation changes to existing configuration

Experimental Simulations

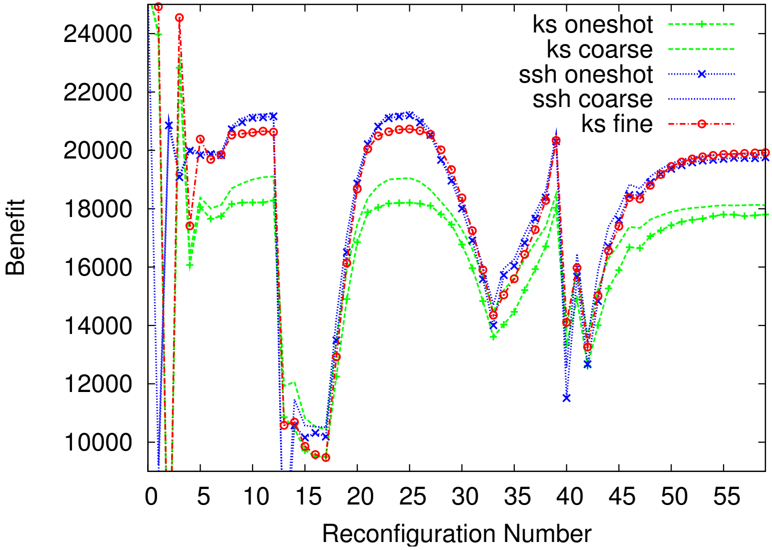
Simulate a system with

- widely varying resource surplus for 3 tasks
- changing communication costs
- 200 edges, 3 isolation levels



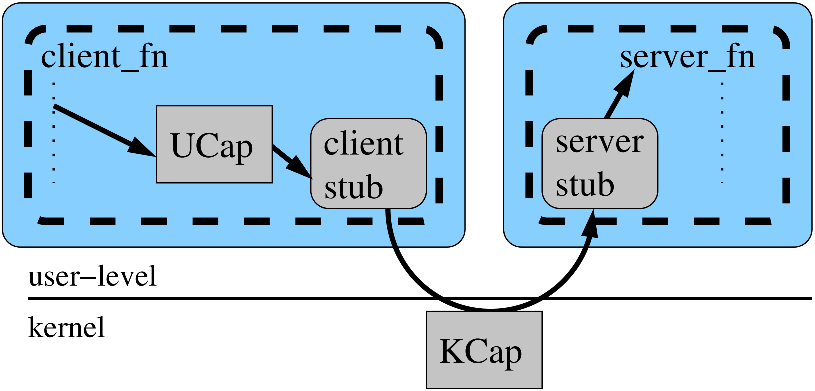
Resources Used For Isolation (Task 1)
Reconfiguration Number
ks oneshot
ks coarse
ssh oneshot
ssh coarse
ks fine
Resource Avail.
0
2000
4000
6000
8000
10000
0
5
10
15
20
25
30
35
40
45
50
55

System Isolation-Derived Benefit



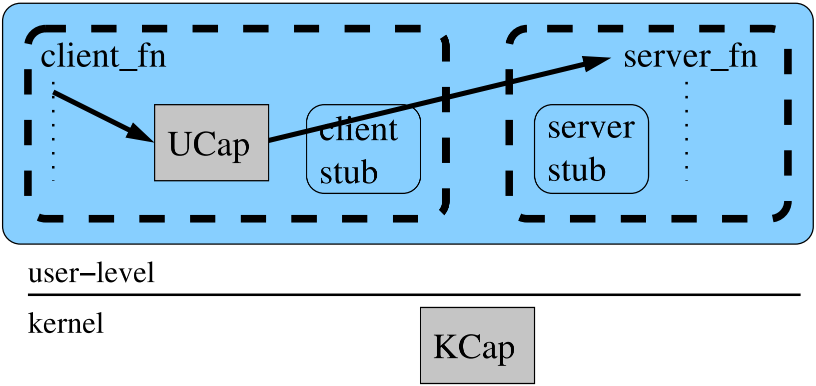
OS Support for MPD

Composite: component-based OS designed to support MPD



OS Support for MPD (II)

Composite: component-based OS designed to support MPD



OS Support for MPD (III)

Switching between the two isolation levels requires changing `UCap`, `KCap`, and protection domains

Prototype running on x86 Pentium IV @ 2.4 Ghz

- Invocation via kernel - 1510 cycles (0.63 μsecs)
- Direct invocation - 55 cycles (0.023 μsecs)

Conclusions

Solution to MMKP based on lightweight successive refinement given dynamic changes in system behavior

- possibly useful in e.g. QRAM

Mutable Protection Domains

- dynamically reconfigure protection domains to maximize fault isolation while meeting application deadlines
- makes the performance/predictability $\leftrightarrow$ fault isolation tradeoff explicit