Enhancing the Dependability of Extreme-Scale Applications*

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Clusters, Clouds, and Grids for Scientific Computing

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Contents

Extreme Scale Systems

Aggressive Strawman Design (*Bill Dally, Peter Kogge*)

- **166 million cores, 742 cores/chip**
- **Cost of data access and synchronization (in terms of energy) by far dominates the cost of computation**

Linpack Study (Peter Kogge):

475pJ data access (average) for 1 FLOPS (10pJ)

- **Memory Capacity: 0.0036 B/FLOPS, 20 MB/core**
- **Hardware and software errors will become an issue —traditional checkpointing and recovery may become infeasible.**

Key Challenges for Extreme-Scale Systems

◆ Concurrency

◆ Power/Energy / Locality

◆ High-Level Abstractions for Programming

◆ Dependability

A Short Note on
High-Level Abstractions and Dependability

The size and complexity of the code
for a given application problem
***is* relevant for dependability**
(independent of language support for dependability)

For example…

Fortran+MPI Communication for 3D 27-point Stencil (NAS MG rprj3)

```fortran
subroutine comm3(u,n1,n2,n3,kk)
use caf_intrinsics

implicit none

include 'cafnpb.h'
include 'globals.h'

integer n1, n2, n3, kk
double precision u(n1,n2,n3)
integer axis

if( .not. dead(kk) )then
   do  axis = 1, 3
      if( nprocs .ne. 1) then
         call sync_all()
         call give3( axis, +1, u, n1, n2, n3, kk )
         call give3( axis, -1, u, n1, n2, n3, kk )
         call sync_all()
         call take3( axis, -1, u, n1, n2, n3 )
         call take3( axis, +1, u, n1, n2, n3 )
      else
         call comm1p( axis, u, n1, n2, n3, kk )
      endif
   enddo
else
   do  axis = 1, 3
      call sync_all()
      call sync_all()
   enddo
   call zero3(u,n1,n2,n3)
endif
return
end


subroutine give3( axis, dir, u, n1, n2, n3, k )
use caf_intrinsics


implicit none

include 'cafnpb.h'
include 'globals.h'

integer axis, dir, n1, n2, n3, k, ierr
double precision u( n1, n2, n3 )

integer i3, i2, i1, buff_len,buff_id

buff_id = 2 + dir
buff_len = 0

if( axis .eq.  1 )then
   if( dir .eq. -1 )then

      do  i3=2,n3-1
         do  i2=2,n2-1
            buff_len = buff_len + 1
            buff(buff_len,buff_id ) = u( 2,  i2,i3)
         enddo
      enddo

      buff(1:buff_len,buff_id+1)[nbr(axis,dir,k)] =
>     buff(1:buff_len,buff_id)

   else if( dir .eq. +1 ) then

      do  i3=2,n3-1
         do  i2=2,n2-1
            buff_len = buff_len + 1
            buff(buff_len, buff_id ) = u( n1-1, i2,i3)
         enddo
      enddo

      buff(1:buff_len,buff_id+1)[nbr(axis,dir,k)] =
>     buff(1:buff_len,buff_id)

   endif
endif

if( axis .eq.  2 )then
   if( dir .eq. -1 )then

      do  i3=2,n3-1
         do  i1=1,n1
            buff_len = buff_len + 1
            buff(buff_len, buff_id ) = u( i1,  2,i3)
         enddo
      enddo

      buff(1:buff_len,buff_id+1)[nbr(axis,dir,k)] =
>     buff(1:buff_len,buff_id)

   else if( dir .eq. +1 ) then

      do  i3=2,n3-1
         do  i1=1,n1
            buff_len = buff_len + 1
            buff(buff_len,  buff_id )= u( i1,n2-1,i3)
         enddo
      enddo

      buff(1:buff_len,buff_id+1)[nbr(axis,dir,k)] =
>     buff(1:buff_len,buff_id)

   endif
endif

if( axis .eq.  3 )then
   if( dir .eq. -1 )then

      do  i2=1,n2
         do  i1=1,n1
            buff_len = buff_len + 1
            buff(buff_len, buff_id ) = u( i1,i2,2)
         enddo
      enddo

      buff(1:buff_len,buff_id+1)[nbr(axis,dir,k)] =
>     buff(1:buff_len,buff_id)

   else if( dir .eq. +1 ) then

      do  i2=1,n2
         do  i1=1,n1
            buff_len = buff_len + 1
            buff(buff_len, buff_id ) = u( i1,i2,n3-1)
         enddo
      enddo

      buff(1:buff_len,buff_id+1)[nbr(axis,dir,k)] =
>     buff(1:buff_len,buff_id)

   endif
endif

return
end


subroutine take3( axis, dir, u, n1, n2, n3 )
use caf_intrinsics


implicit none

include 'cafnpb.h'
include 'globals.h'

integer axis, dir, n1, n2, n3
double precision u( n1, n2, n3 )

integer buff_id, indx

integer i3, i2, i1

buff_id = 3 + dir
indx = 0

if( axis .eq.  1 )then
   if( dir .eq. -1 )then

      do  i3=2,n3-1
         do  i2=2,n2-1
            indx = indx + 1
            u(n1,i2,i3) = buff(indx, buff_id )
         enddo
      enddo

   else if( dir .eq. +1 ) then

      do  i3=2,n3-1
         do  i2=2,n2-1
            indx = indx + 1
            u(1,i2,i3) = buff(indx, buff_id )
         enddo
      enddo

   endif
endif

if( axis .eq.  2 )then
   if( dir .eq. -1 )then

      do  i3=2,n3-1
         do  i1=1,n1
            indx = indx + 1
            u(i1,n2,i3) = buff(indx, buff_id )
         enddo
      enddo

   else if( dir .eq. +1 ) then

      do  i3=2,n3-1
         do  i1=1,n1
            indx = indx + 1
            u(i1,1,i3) = buff(indx, buff_id )
         enddo
      enddo

   endif
endif

if( axis .eq.  3 )then
   if( dir .eq. -1 )then

      do  i2=1,n2
         do  i1=1,n1
            indx = indx + 1
            u(i1,i2,n3) = buff(indx, buff_id )
         enddo
      enddo

   else if( dir .eq. +1 ) then

      do  i2=1,n2
         do  i1=1,n1
            indx = indx + 1
            u(i1,i2,1) = buff(indx, buff_id )
         enddo
      enddo

   endif
endif

return
end


subroutine comm1p( axis, u, n1, n2, n3, kk )
use caf_intrinsics


implicit none

include 'cafnpb.h'
include 'globals.h'

integer axis, dir, n1, n2, n3
double precision u( n1, n2, n3 )

integer i3, i2, i1, buff_len,buff_id
integer i, kk, indx

dir = -1

buff_id = 3 + dir
buff_len = nm2

do  i=1,nm2
   buff(i,buff_id) = 0.0D0
enddo


dir = +1

buff_id = 3 + dir
buff_len = nm2

do  i=1,nm2
   buff(i,buff_id) = 0.0D0
enddo

dir = +1

buff_id = 2 + dir
buff_len = 0

if( axis .eq.  1 )then
   do  i3=2,n3-1
      do  i2=2,n2-1
         buff_len = buff_len + 1
         buff(buff_len, buff_id ) = u( n1-1, i2,i3)
      enddo
   enddo
endif

if( axis .eq.  2 )then
   do  i3=2,n3-1
      do  i1=1,n1
         buff_len = buff_len + 1
         buff(buff_len,  buff_id )= u( i1,n2-1,i3)
      enddo
   enddo
endif

if( axis .eq.  3 )then
   do  i2=1,n2
      do  i1=1,n1
         buff_len = buff_len + 1
         buff(buff_len, buff_id ) = u( i1,i2,n3-1)
      enddo
   enddo
endif

dir = -1

buff_id = 2 + dir
buff_len = 0

if( axis .eq.  1 )then
   do  i3=2,n3-1
      do  i2=2,n2-1
         buff_len = buff_len + 1
         buff(buff_len,buff_id ) = u( 2,  i2,i3)
      enddo
   enddo
endif

if( axis .eq.  2 )then
   do  i3=2,n3-1
      do  i1=1,n1
         buff_len = buff_len + 1
         buff(buff_len, buff_id ) = u( i1,  2,i3)
      enddo
   enddo
endif

if( axis .eq.  3 )then
   do  i2=1,n2
      do  i1=1,n1
         buff_len = buff_len + 1
         buff(buff_len, buff_id ) = u( i1,i2,2)
      enddo
   enddo
endif

do  i=1,nm2
   buff(i,4) = buff(i,3)
   buff(i,2) = buff(i,1)
enddo

dir = -1

buff_id = 3 + dir
indx = 0

if( axis .eq.  1 )then
   do  i3=2,n3-1
      do  i2=2,n2-1
         indx = indx + 1
         u(n1,i2,i3) = buff(indx, buff_id )
      enddo
   enddo
endif

if( axis .eq.  2 )then
   do  i3=2,n3-1
      do  i1=1,n1
         indx = indx + 1
         u(i1,n2,i3) = buff(indx, buff_id )
      enddo
   enddo
endif

if( axis .eq.  3 )then
   do  i2=1,n2
      do  i1=1,n1
         indx = indx + 1
         u(i1,i2,n3) = buff(indx, buff_id )
      enddo
   enddo
endif



dir = +1

buff_id = 3 + dir
indx = 0

if( axis .eq.  1 )then
   do  i3=2,n3-1
      do  i2=2,n2-1
         indx = indx + 1
         u(1,i2,i3) = buff(indx, buff_id )
      enddo
   enddo
endif

if( axis .eq.  2 )then
   do  i3=2,n3-1
      do  i1=1,n1
         indx = indx + 1
         u(i1,1,i3) = buff(indx, buff_id )
      enddo
   enddo
endif

if( axis .eq.  3 )then
   do  i2=1,n2
      do  i1=1,n1
         indx = indx + 1
         u(i1,i2,1) = buff(indx, buff_id )
      enddo
   enddo
endif

return
end
```

Chapel 3D NAS MG Stencil rprj3

```
function rprj3(S,R) {
  const Stencil: domain(3) = [-1..1, -1..1, -1..1],         // 27-points
        w: [0..3]real = (/0.5, 0.25, 0.125, 0.0625/),       // weights
        w3d: [(i,j,k) in Stencil] = w((i!=0) + (j!=0) + (k!=0));

forall ijk in S.domain do
    S(ijk) = sum reduce [off in Stencil] (w3d(off) * R(ijk + R.stride*off));
}
```

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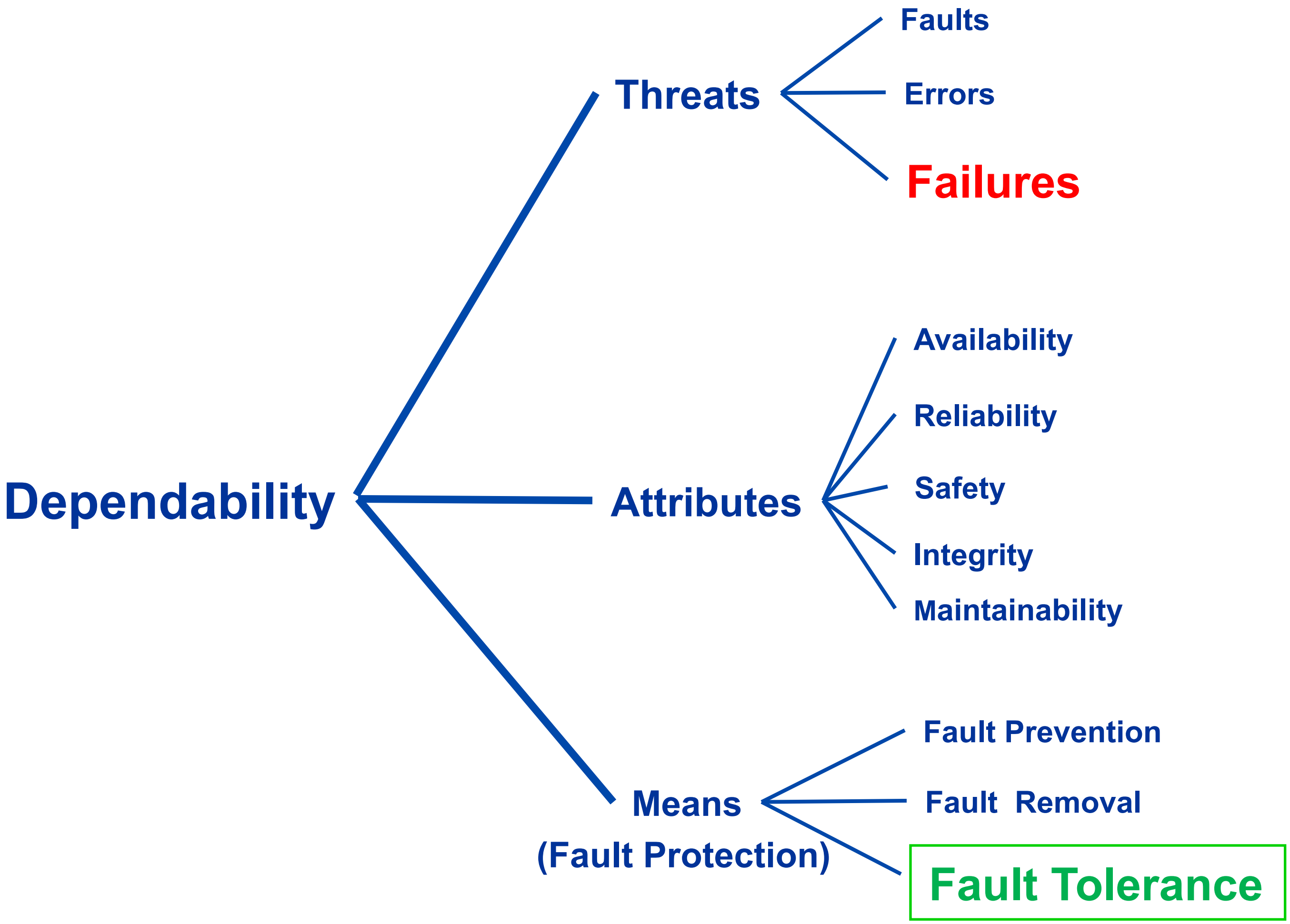
2. **Dependability**
3. Introspection Framework for Fault Tolerance
4. Generation of Fault-Tolerant Code
5. Conclusion

Dependability*

The ability of a computing system to deliver service that can be justifiably trusted



Dependability

Threats

Faults

Errors

Failures

Attributes

Availability

Reliability

Safety

Integrity

Maintainability

Means

(Fault Protection)

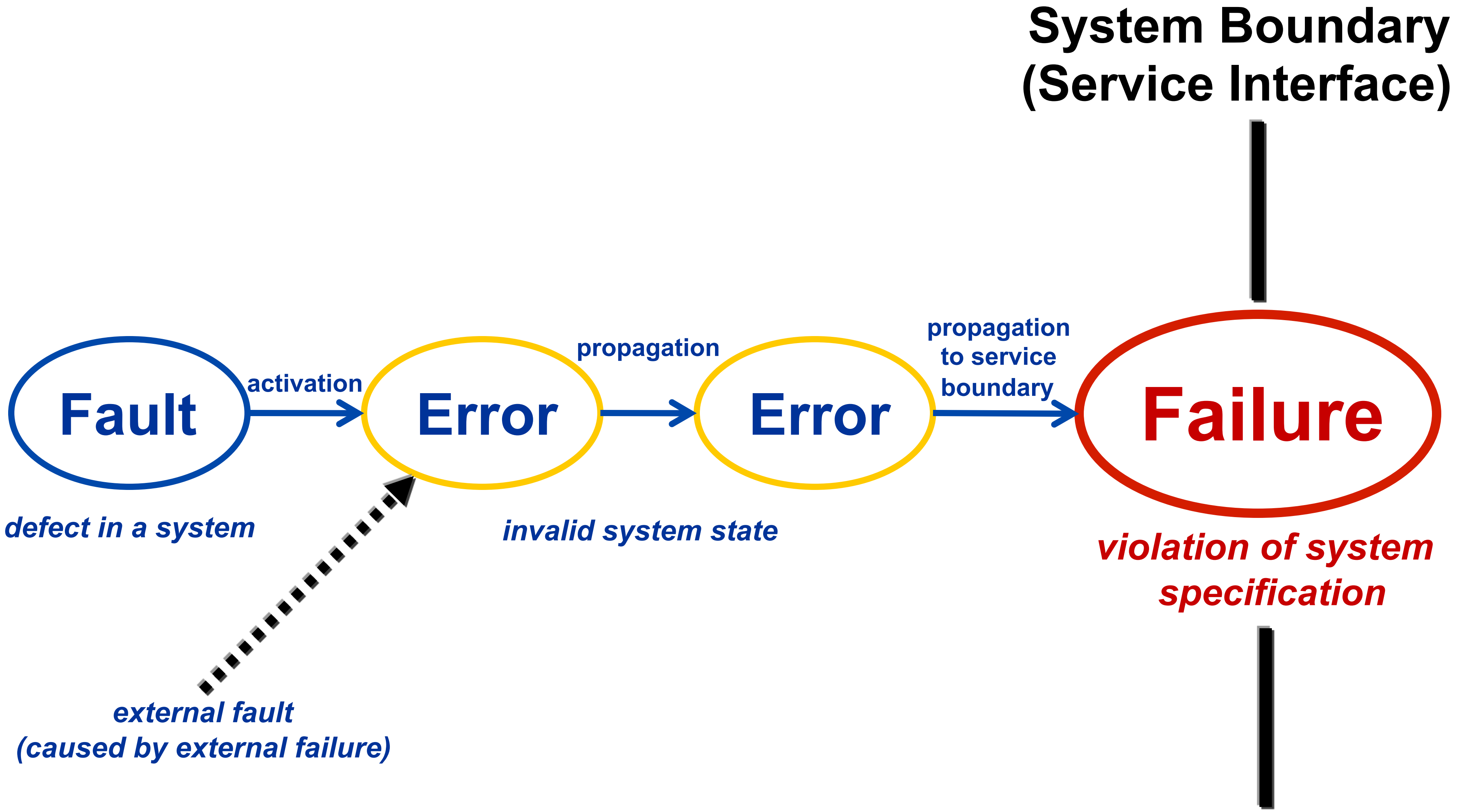
Fault Prevention

Fault Removal

Fault Tolerance

*A. Avizienis, J.-C.Laprie, B.Randell: Fundamental Concepts of Dependability. UCLA CSD Report 010028, 2000

Threats: the Fault-Error-Failure Chain



System Boundary
(Service Interface)

Fault

activation

Error

propagation

Error

propagation
to service
boundary

Failure

defect in a system

invalid system state

violation of system specification

external fault
(caused by external failure)

Fault Protection

- **Fault Prevention:** via *quality control* during design and manufacturing of hardware and software
  - ***structured programming, modularization, information hiding; firewalls***
  - ***shielding and radiation hardening***
  - *…*
- **Fault Removal:** Verification and Validation (V&V), model checking

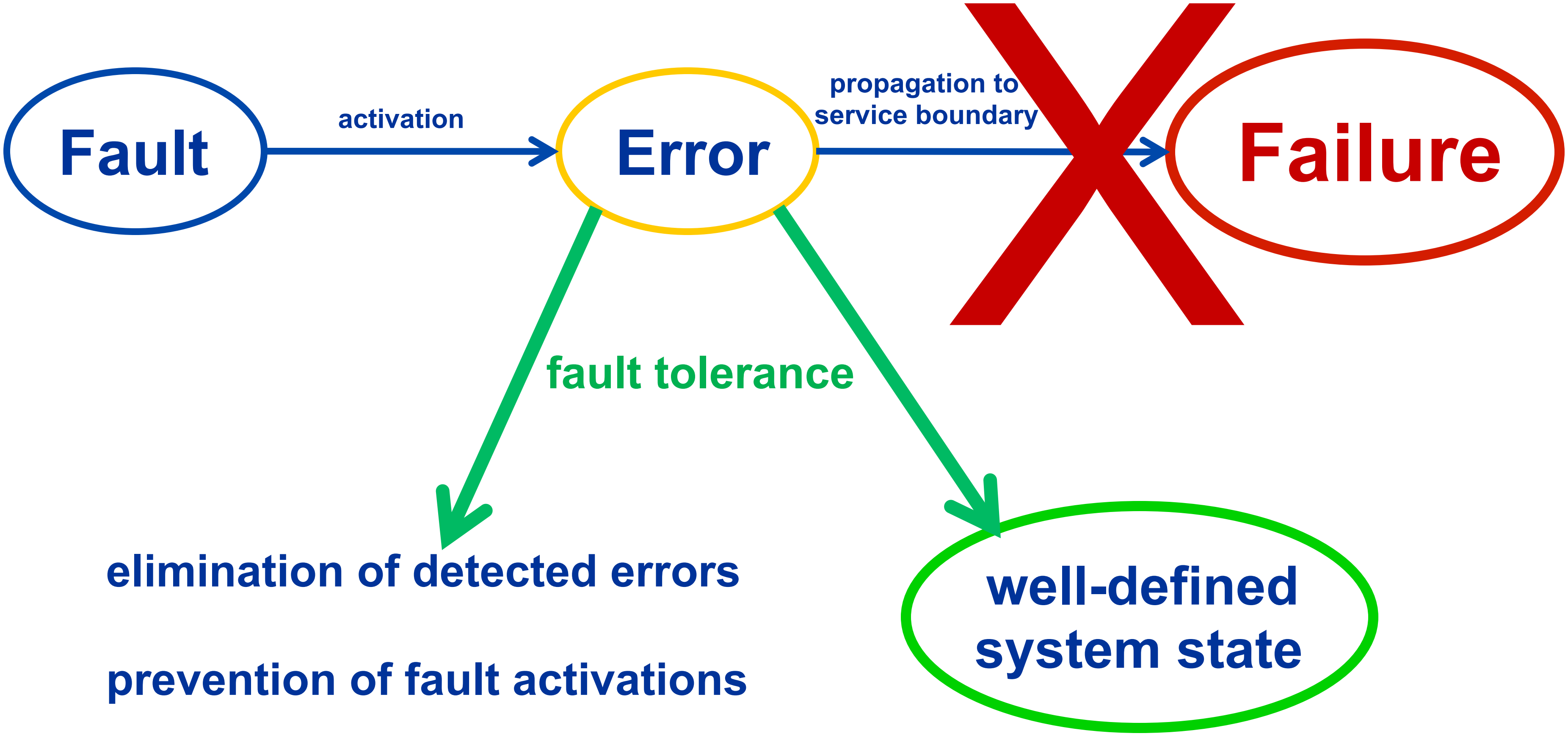
In general, ***fault prevention and removal cannot guarantee the absence of errors****—for theoretical as well as practical reasons (undecidability, NP-completeness, etc.). Even a perfectly correct program may be subject to hard and soft errors. This motivates the need for* **fault tolerance** *as a third category of fault protection.*

Fault Protection ctd.

◆ **Fault Tolerance:** *the ability to preserve the delivery of correct service (system specification) in the presence of active faults*

- ***error detection***
- ***recovery: error handling and fault handling***
- ***fault masking: redundancy-based recovery without explicit error detection (e.g., TMR)***

Fault Tolerance



Fault

activation

Error

propagation to
service boundary

Failure

fault tolerance

elimination of detected errors

prevention of fault activations

well-defined
system state

Issues in Dependability for Extreme-Scale Systems

- Extreme-scale systems will have less reliable components (due to smaller feature sizes) and a larger component count than current systems: as a consequence, errors are expected to become the norm, not an exception
- Checkpointing and recovery may become intolerably expensive—and even infeasible, depending on MTTF
- Dynamic power management may have a negative effect on hardware reliability (thermal stresses)

Issues in Multi-Core Fault Tolerance

Challenges

- **Fault in a shared component of a multi-core chip may affect the whole chip**
  - *caches, memory controller, I/O circuitry, on-chip networks*
  - *fewer natural boundaries than for traditional architectures*
  - *example: failing cache controller for L2 cache in Sun Niagara*

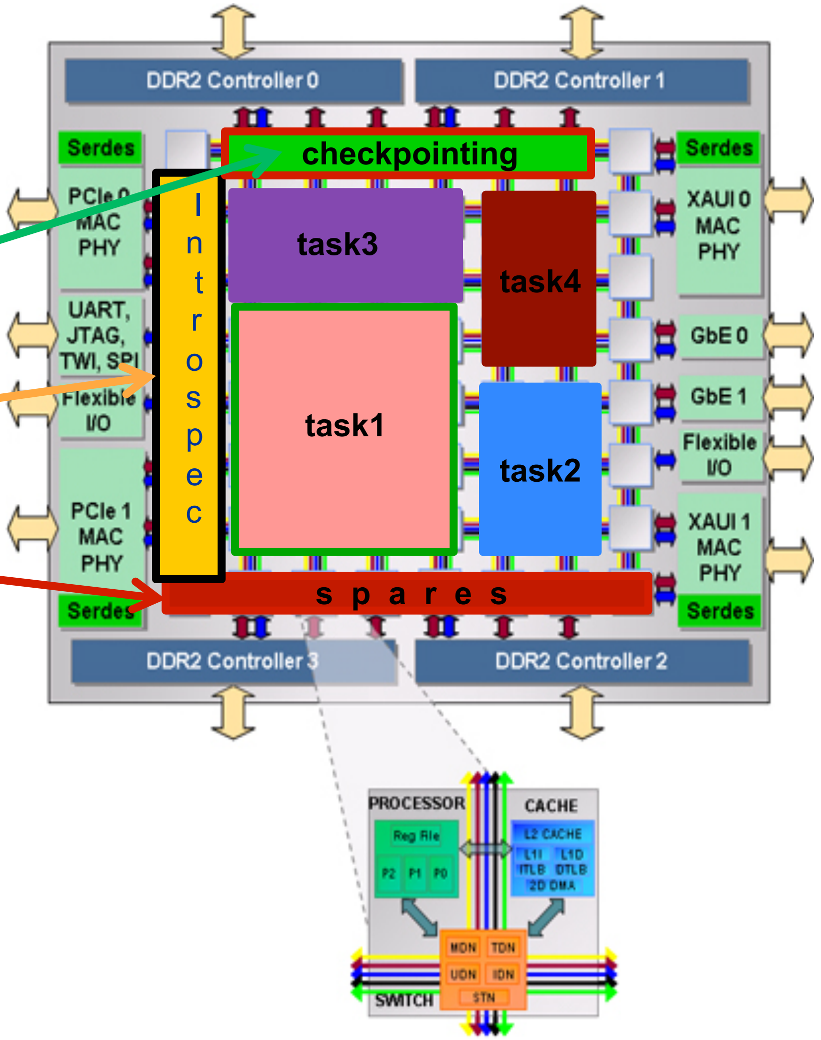
- **Possible Solution: Hardware-Supported Isolation***
  - *partition sets of components into independently configurable units*
  - *Tile64 chip supports "walling off" sets of cores*

***N.Aggarwal,P.Ranganathan,N.P.Jouppi,J.E.Smith :IEEE Computer, June 2007**

Issues in Multi-Core Fault Tolerance

Opportunities

- **Cores are becoming an inexpensive resource**
- **Use of cores for:**
  - *checkpointing*
  - *introspection support*
  - *spares*



Specification: Allocation of cores to tasks (RT Chapel)

```
const L:[n,n]locale = reshape(Locales)
on L(2..p1,2..q1)         do task1
on L(p1+1..n-1,2..q2)     do task2
on L(2..p1,q1+1..n-1)     do task3
on L(p1+1..n-1,q2+1..n-1)do task4

on L(2..n-1,1) do Introspection
on L(1,2..n-1) do Checkpointing
allocate spares to L(1..n,n)
```

Contents

Focus of Work

- Development of an *Introspection Framework* for adaptive fault tolerance
- Development of an API for expressing dependability requirements of applications
- Compiler analysis for the generation of redundant code and intelligent optimization of checkpointing
- Development of fault tolerance metrics

A Framework for Introspection

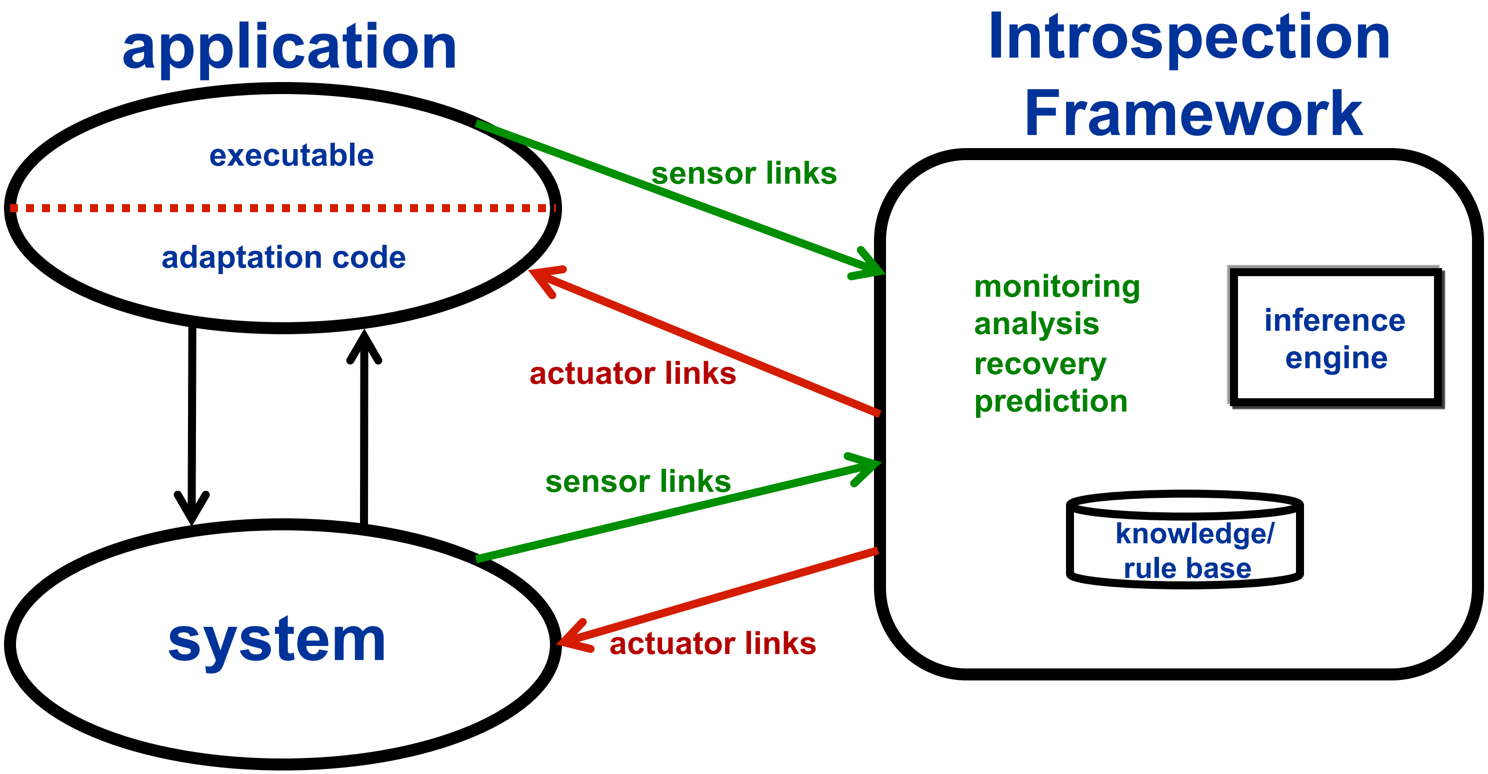
Introspection…

- provides *dynamic* monitoring, analysis, and feedback, enabling system to become self-aware and context-aware:
  - *monitoring execution behavior*
  - *reasoning about its internal state*
  - *changing the system or system state when necessary*
- exploits adaptively threads available in multi-core systems
- can be applied to a range of different scenarios, including:
  - fault tolerance
  - *performance tuning*
  - *energy and power management*
  - *behavior analysis*

Adaptive Introspection-Based Fault Tolerance

<u>**Adaptive Fault Tolerance**</u>: the capability to provide dependability based on a fault model, application requirements, and system properties

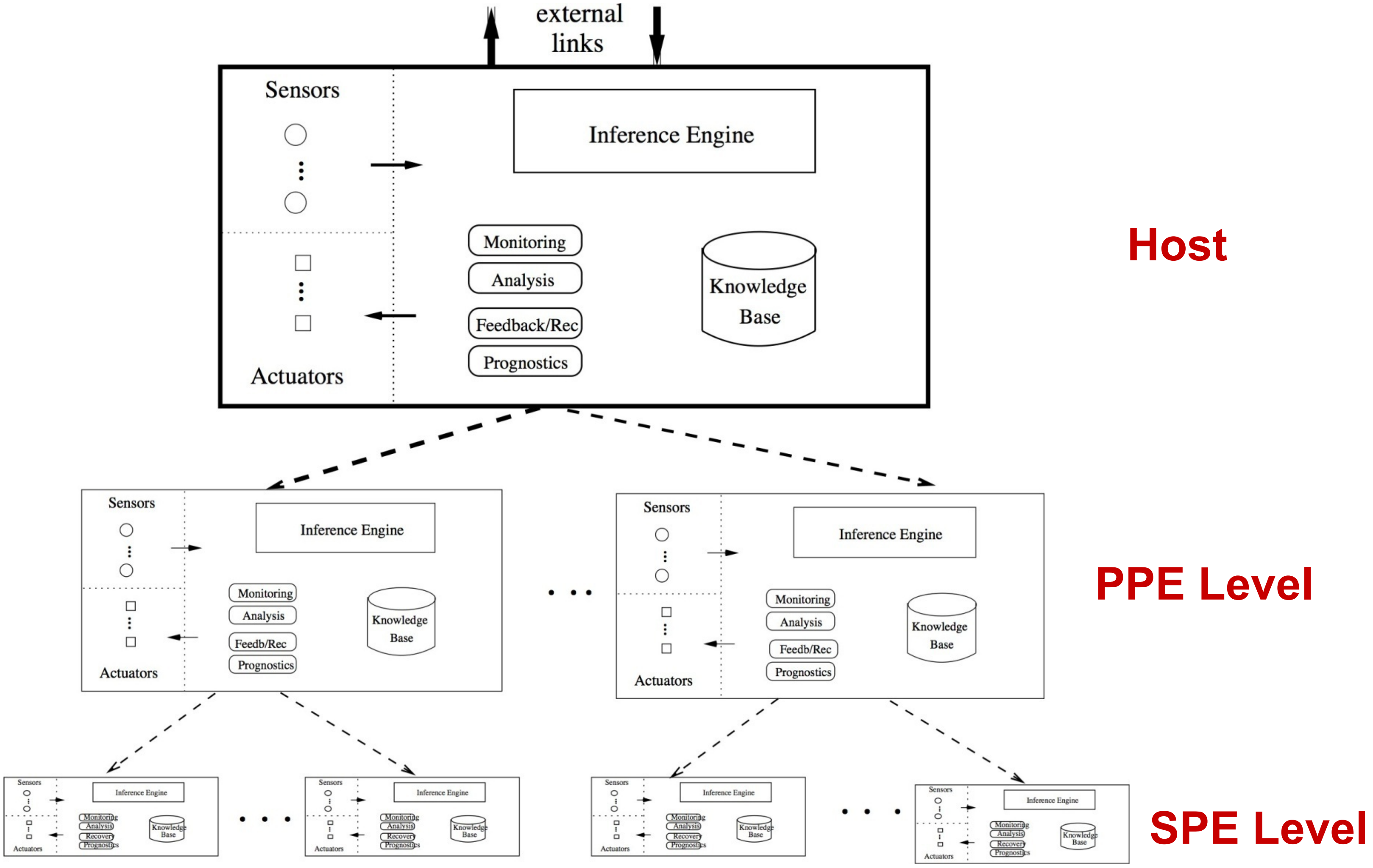
<u>**Introspection**</u> provides functionality for error detection, analysis and recovery



Introspection Framework Architecture

- The architecture of the Introspection Framework depends on the structure of the application, the mapping of application components to the hardware, and related dependability requirements
- *Introspection Modules*—the atomic components of this structure—are arranged into an *introspection graph,* which expresses a control relation in the set of modules
- Each introspection module is associated with application components and performs specialized functions related to these components
- This supports a capability for component-based fault tolerance, supporting *heterogeneity* as well as the capability to deal with errors locally, in parallel, and at the earliest possible time

Introspection-Based Fault Tolerance Architecture: Example: PS3 Cluster



Introspection Module

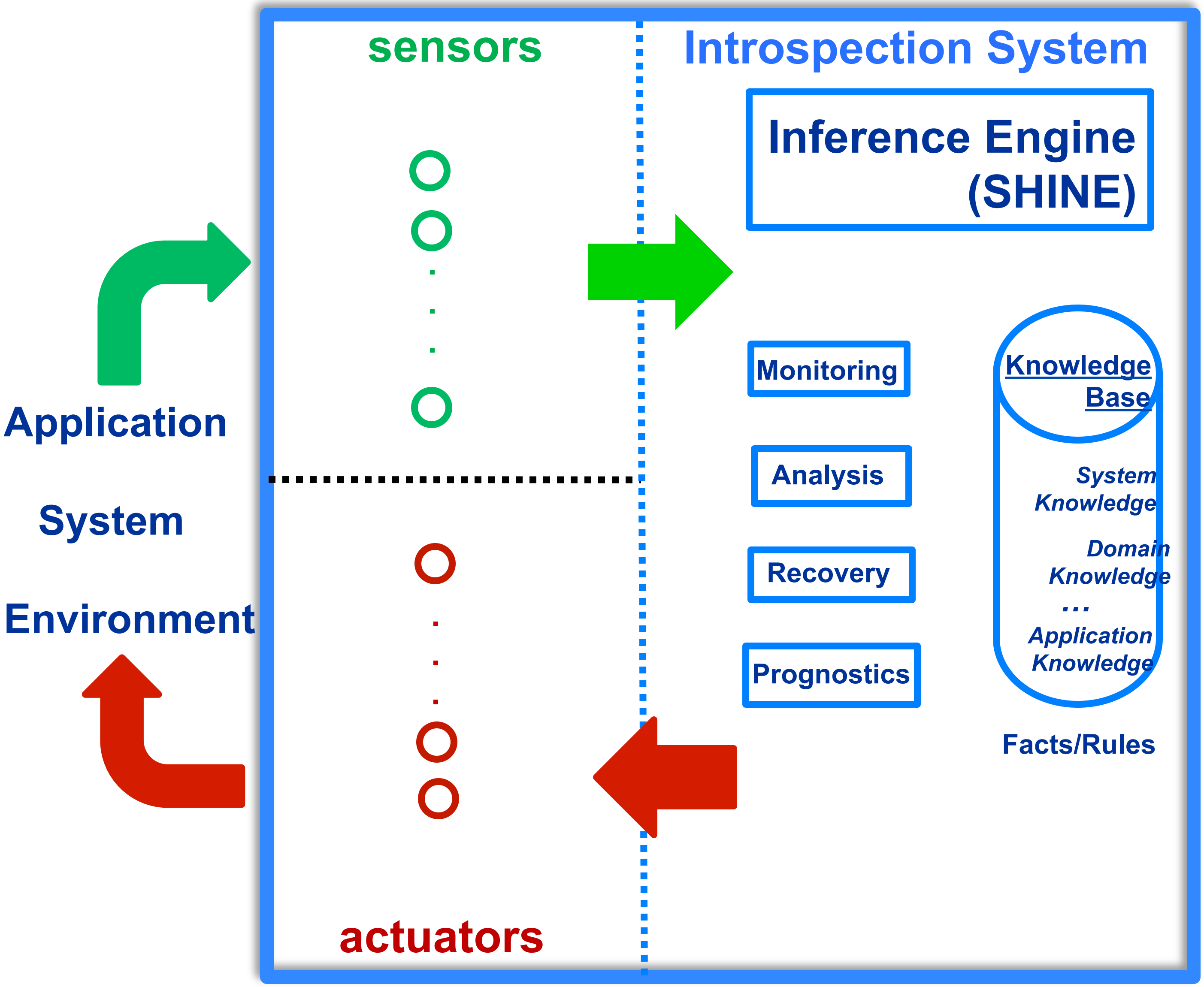
„atomic“ component of introspection

Fault Classes under Consideration

- *transient faults*
- *hard faults*
- *software design faults*

Sensors *provide input to the introspection system (e.g., state information, assertion values, hardware alarms)*

Actuators *provide feedback from the introspection system to the application (e.g., error analysis information, suggestions for recovery algorithms, modification of instrumentation)*



Application

System

Environment

sensors

Introspection System

Inference Engine (SHINE)

Monitoring

Analysis

Recovery

Prognostics

Knowledge Base

System Knowledge

Domain Knowledge

…

Application Knowledge

Facts/Rules

actuators

Introspection Complements V&V

- Introspection performs execution time monitoring, analysis, recovery
- Introspection can deal with transient errors, execution anomalies, performance problems
  - *this capability is inherently beyond the scope of V&V technology*
  - *and it can be used to deal with design errors*
- Future Goal: integration of introspection with V&V technology into a comprehensive program development scheme

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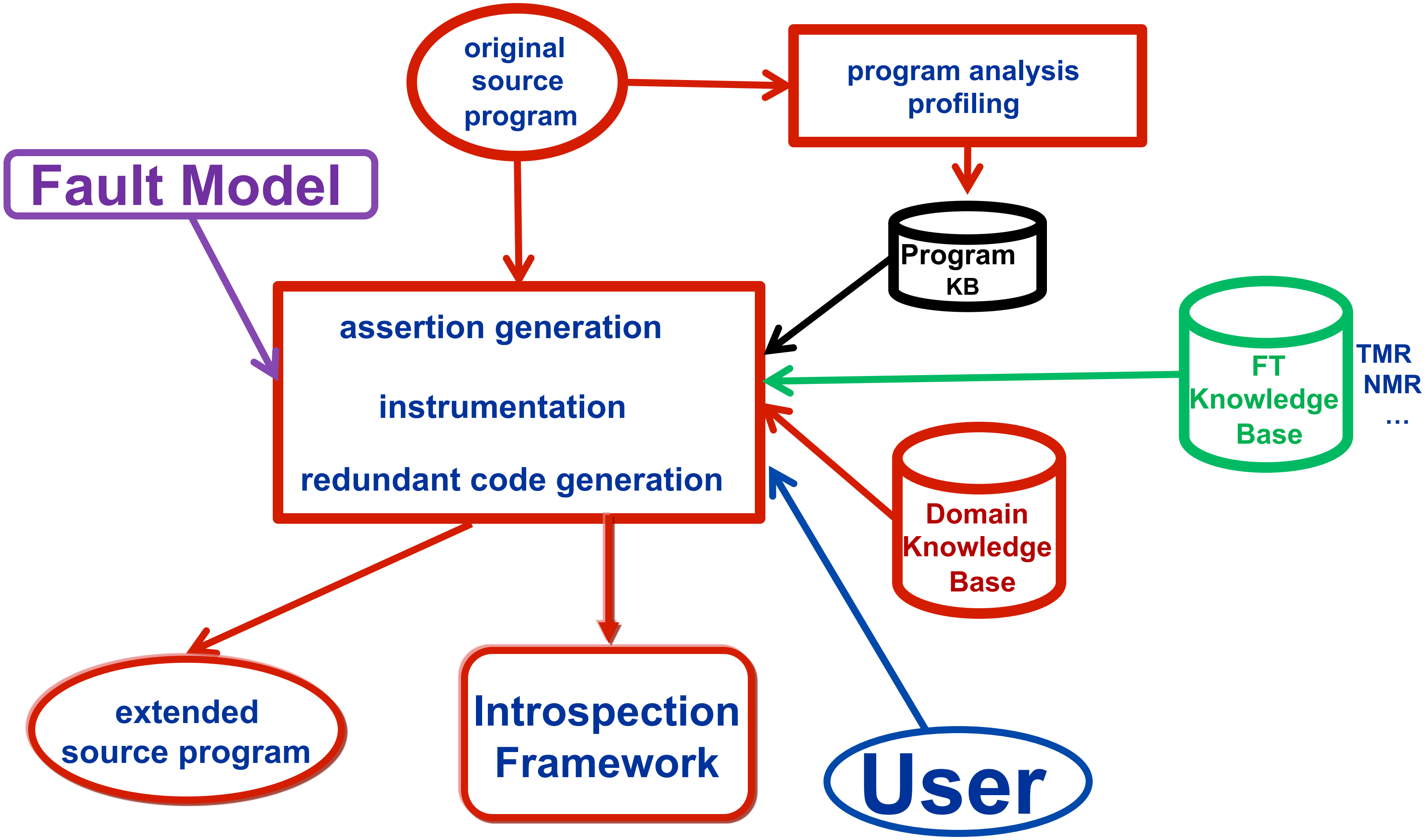
Compiler- and Tool-Supported Fault Tolerance



exploiting results of automatic program analysis

leveraging standard fault tolerance methods

exploiting domain and application knowledge

Static and Dynamic Analysis

- Static analysis and profiling determine properties of dynamic program behavior *before* actual execution
- Analysis of Sequential Threads
  - *control & data flow analysis: solving flow problems over a program graph*
  - *dependence analysis: determining read/write relationships*
  - *slicing: determining the set of statements that affect a variable's value*
- Analysis of Parallel Constructs
  - *data parallel loops: analysis of "independence" property*
  - *locality and communication analysis*
  - *race condition analysis*
  - *safety and liveness analysis*
  - *deadlock analysis*
- Dynamic Analysis
  - *program control and data flow, dynamic dependences*
  - *performance, energy, and behavior analysis*

Concluding Remarks

- Extreme-scale systems will need to deal with errors in a flexible and adaptive way
- Introspection
  - *provides a generic framework for dynamic monitoring and analysis of program execution, together with a recovery scheme*
  - *can support fault tolerance, performance tuning, power management*
- Analysis of program properties provides a basis for automatic generation of application-adaptive fault-tolerant code
- Integration of conventional V&V technology with introspection can provide a comprehensive approach to fault tolerance