Monitoring and Optimization of I/O performance with SIOX

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1 Introduction
2 Flexible Architecture
3 Intelligent Handling
4 Status and Outlook
5 Summary
SIOX will
- collect and analyse
  - activity patterns and
  - performance metrics

in order to
- assess system performance
- locate and diagnose problem
- learn optimizations
Example Cause-and-Effect Chain

```
fh = open("File.txt");
write(fh, "Text 1");
write(fh, "Text 2");
fh = open("File.txt");
write(fh, "Text 1");
write(fh, "Text 2");
```

Access Data (Open)
Access Data (Write 1)
Access Data (Write 2)
Bundesministerium für Bildung und Forschung

- Funded by the BMBF
  Grant No.: 01 IH 11008 B
- Start: Juli 1st, 2011
- Duration: 36 Months
Increasing SIOX’s Capabilities

The project proposal targets instrumentation of selected applications, MPI-IO, POSIX and GPFS.

We designed a flexible modular architecture and API. This allows us to integrate arbitrary:

- Libraries
- File systems
- Hardware information and statistics

An individual instantiation of modules is also possible:

- Decide which modules are configured:
  - For each layer, process, compute and server nodes
- Each module has an XML configuration
Industry Collaboration

- We collaborate to develop industry-relevant software
  - Collaborating companies: Xyratex, Netapp
- We aim to deliver components to the Exascale10 (EIOW) middleware
  - Monitoring, machine learning, automatic optimization
- SIOX is licensed under LGPL3
Flexible Architecture

Faces of SIOX (1): General System Architecture

- Data gathered is stored via the *monitoring path*.
- Components receive the knowledge gleaned via the *knowledge path*. 
Flexible Architecture

Faces of SIOX (2): Configuration for Online Mode

No pattern recording, optimization without machine learning

![Diagram of SIOX architecture]

1) sioxlib
   monitor data and apply optimizations

2) SIOX Daemon
   correlates component-wide and compresses

5) SIOX Knowledge Base
   holds analyses and optimizations

Compute node
Apply static best-practices with low overhead

- **sioxlib**
  - monitor data and apply optimizations

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Flexible Architecture

Faces of SIOX (3): Configuration for Static Knowledge
Overview of Concepts and Mechanisms

- User-level monitoring API
  - “Wrapper” to ease instrumentation of software layers
- Relation of activities
  - Implicit linking of process-internal activities
  - Explicit linking to remote activities
  - Explicit links are created during the ETL into the warehouse
- Analysis of observed activities and statistics by plug-ins
  - Synchronous and/or asynchronous
  - Activities can be handled stateful (within a process) or stateless
  - May use (static) system information/knowledge
- Incorporation of system knowledge
  - One database entry per node, file system, storage device
  - Plugins may create their own node/fs/device specific entries
  - Detect hardware changes (upon startup)
- Local and global “reasoning” to assess system state
Flexible Architecture

Semi-Automatic Instrumentation of Software-Layers

Workflow

1. Save relevant function prototypes in a header file
2. Annotate functions in the header
3. Tool parses header and creates either
   - a shared library for LD_PRELOAD
   - a library to use with ld --wrap

Instrumentation can be done incrementally
Flexible Architecture

Example Header for POSIX

```c
// @component "POSIX"

// @register_metric fileName "File Name"
        \rightarrow SIOX_STORAGE_STRING

///// END GLOBAL SECTION /~~~~~~~~~~~~~~/

// @activity
// @activity_attribute fileName pathname
// @horizontal_map_put_int ret
// @error 'ret < 0' errno
int open(const char *pathname, int flags, mode_t mode);

// @activity
// @activity_attribute bytesToWrite count
// @activity_link_int fd
// @error 'ret < 0' errno
ssize_t write(int fd, const void *buf, size_t count);
```
Putting the Knowledge to Good Use

SIOX will exploit the knowledge gleaned to

- control available I/O optimizations

Internally, we will use it to

- adapt own level of activity to the host system’s state
- reduce the amount of data logged
- focus and guide its acquisition of new data (active learning)
Putting the Knowledge to Good Use

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Why can’t we capture all events?
The Data Deluge – A Numerical Example

Assume program writes a 1 GB file to a parallel file system...

- ...of 100 I/O servers managing 5,000 storage devices
- ⇒ 200 KB per device to write...
- ...writing 4 KB per block on device
- ⇒ 250,000 blocks to write...
- ...logging 20 B per block written
- ⇒ 5 MB logging data
- ⇒ 0.5% logging overhead.
The HPC Cluster *Blizzard* at DKRZ reads and writes...

- ...10 GB/s, 24/7, 365 days a year
- ⇒ 50 MB/s to log for SIOX
- ⇒ 1.6 PB/a...
- ...at a very conservative estimate!
Intelligent Handling

Intelligent Components

Each layer and daemon may use:

- Plug-ins to **detect exceptional behavior** and steer logging
- Plug-ins to **suggest possible optimizations**

```
(1) sioxlib
monitor data
and apply
optimizations

(2) SIOX
Daemon
correlates component-wide
and compresses

(3) SIOX
Transaction System
collects and correlates
across system boundaries

(4) SIOX
Data Warehouse
cleanses, compresses
and archives

(5) SIOX
Knowledge Base
holds analyses
and optimizations
```

Monitoring Data

```
Compute node

Application
or Library

ADPI
ADPI
...
ADPI

and

SOPI
SOPI
...
SOPI

Monitoring Path

3) SIOX
Transaction System

collects and correlates
across system boundaries

extract,
transforms,
and loads
processes
(off-line)

4) SIOX
Data Warehouse
cleanses, compresses
and archives

5) SIOX
Knowledge Base
holds analyses
and optimizations
```

```
Component

Anomaly Detection

[ADPI, ADPI, ...]

Self-Optimization

[SOPI, SOPI, ...]

Activity History

[A BACAADAE...]

System Statistics

```

xyz: 3.573393

def: 4263.885635

mol: 42.000000

...
To harness the data gathered, SIOX uses *Knowledge Packages*.

A Knowledge Package... consists of
- a Machine Learning Plug-In
and corresponding plugins
  - Anomaly Detection Plug-In
  - Self-Optimization Plug-In
Knowledge Package may use private *Action Tables* in the Knowledge Base.

The MLPI will create (and possibly update) the action table, which may also be done manually.
A more complex Action Table: Injecting non-functional calls

<table>
<thead>
<tr>
<th>Pattern</th>
<th>Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>SequentialRead() SequentialRead() SequentialRead()</td>
<td>seq &amp; willneed(size)</td>
</tr>
<tr>
<td>Open(ext = &quot;nc&quot;)</td>
<td>willneed(0, 20 KiB)</td>
</tr>
<tr>
<td>Open(ext = &quot;dat&quot;)</td>
<td>noReuse &amp; random</td>
</tr>
<tr>
<td>RandomWrite(size &lt; 4K){5x}</td>
<td>noReuse &amp; random</td>
</tr>
</tbody>
</table>

A plug-in may use a state machine to track monitored activities
The SIOX Daemon

A physical node’s daemon holds:

- Recent node-local system statistics, updated regularly
- A module with plug-ins to provide node-local system statistics
- A rule-based reasoner classifying system-state and bottlenecks
- A module with plug-ins to control SIOX’s behavior
Reasoning

- Node-local reasoner decides when and how long to log
- System-state, detected bottlenecks and reasons are communicated
  - E.g. “Server overloaded”, “Bad I/O pattern“
  - Refined knowledge is transferred to a global reasoner
  - Overview is communicated to all daemons
- Each reasoner maintains statistics for later investigation
- Feedback to user upon application termination
SIOX manages data within a single process
- Full instrumentation for POSIX
- Partial instrumentations for NetCDF and HDF5
- Application behavior can be recorded in files
- Ontology and system information is stored in files
- Trace-reader parses all files
Towards a Prototype for SC’13
Summary

- SIOX aims to capture and optimize I/O
  - on all layers and filesystems
- Intelligent filtering reduces log size
- Integrated reasoning tries to localize causes and bottlenecks
- We are building a flexible and open system
Finally: SIOX and You

Think we missed a problem?
Think you could solve one?
Like to see SIOX on your favourite file system?

We cordially invite you to become involved at

http://www.HPC-IO.org
A simple Action Table: Adjusting a system parameter

### Action Table for an SOPI Write-behind Plug-in

<table>
<thead>
<tr>
<th>Pattern</th>
<th>Buffer Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open()</td>
<td>4 MiB</td>
</tr>
<tr>
<td>Write(size &lt; 2 KiB){5x}</td>
<td>1 MiB</td>
</tr>
<tr>
<td>Write(size &lt; 4 MiB) Write(size &lt; 4 MiB)</td>
<td>20 MiB</td>
</tr>
<tr>
<td>Write(size ≥ 100 MiB)</td>
<td>direct-write</td>
</tr>
</tbody>
</table>
Self-Optimization Plug-Ins

What SOPIs can do:

- Take any action available via any interface accessible, e.g.:
  - Adjust system parameters (cache size, MPU size,...)
  - Inject non-functional calls (fadvise(), MPI hints,...)
  - Inject "housekeeping" calls (flush(), refresh page,...)
  - Adjust parameters of functional calls (access mode, optional caching,...)
  - Select between alternative modules to employ (MPICH2 vs. OpenMPI, shmem vs. TCP,...)

SOPIs are controlled via *Action Tables* in the Knowledge Base.
Machine Learning Plug-Ins (MLPIs)

- Run off-line, on-demand
- Analyse data archived in the Data Warehouse with machine learning algorithms or heuristics
- Refine their findings into instructions for their ADPI and/or SOPI
- Store these in a plug-in-specific "action table" in the Knowledge Base
- Action tables may also be built manually (usually to implement common heuristics)
Scalability through Hierarchical Data Transport

Application A

Node a

Node b

Node c

T1 T2
Da

T3 T4
Db

T5 T6
Dc

Concentrator C1

Concentrator C2

Application B

Node d

Node e

T1 T2 T3
Dd

T2 T3
De

Concentrator C3

Application C

Node f

T1 T2 T3 T4 T5
Df

Knowledge Base
Logging
- every Activity
- on every Level
- all of the time
will cause prohibitive overhead.

The SIOX solution:
- Log to local window, discard the uneventful
- Focus on anomalies (good & bad)
- Learn from logs to improve filters
Instrumentation and the Activity Multiplexer

Activity Sequence

Instrumented Component

Higher Level Component

Call( Parameters )

activity_start()

activity_attribute()

Call( Parameters )

Actual processing of Call() will take place here!

Result

activity_stop()

activity_report()

activity_end()

Result

Log( Activity )

Higher Level Component

Component (instrumented)

Component (original)

sioxlib

Activity Multiplexer
Activity Multiplexer Normal Behavior

Click to access the PNG of the design
Activity Multiplexer Throttling (Overflow) Behavior

**Problem:**
Queue already filled to capacity, Notifier processing but overwhelmed! Push() is rejected, Activity lost; Queue enters *overflow mode*, rejecting any further Push() calls.
Anomaly Detection Plug-Ins

What ADPIs can do:

- Detect anomalies (exceptional system behaviour)
- Adjust log-levels
- Report recent activity history for analysis
- Mark recent activity sequence for future "watchlist": ⇒ Timely adjustments to log-levels before anomaly recurs
- Make every byte logged count!

ADPIs are controlled via Action Tables in the Knowledge Base.
ADPI Example 1

A simple rule-based and stateless plug-in detecting exceptional performance

Mathematical model and Action Table

\[ f_{Utilization}(\text{Component}, \text{Activity}) = \frac{t_{possible}(\text{Component}, \text{Activity})}{\text{Time(Activity)}} \]

\[ t_{possible} = \frac{\text{Size(Activity)}}{\text{SequentialTransferRate(Component)}} + \text{Latency(Component)} \]

<table>
<thead>
<tr>
<th>Result</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_{Utilization} &lt; 0.10 )</td>
<td>Report( &quot;Exceptionally low&quot; )</td>
</tr>
<tr>
<td>( 0.10 &lt; f_{Utilization} &lt; 0.95 )</td>
<td>No Action</td>
</tr>
<tr>
<td>( 0.95 &lt; f_{Utilization} )</td>
<td>Report( &quot;Exceptionally high&quot; )</td>
</tr>
</tbody>
</table>

“Component” can be a software layer, a compute node, or a file system.
ADPI Example 2

A very simple Action Table implementing a “watchlist”

Action table to detect a write cache filling up

<table>
<thead>
<tr>
<th>Pattern</th>
<th>Buffer Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Write( fast )</td>
<td>Report( &quot;Cache full&quot; )</td>
</tr>
<tr>
<td>Write( slow )</td>
<td></td>
</tr>
</tbody>
</table>

Number of Activities

cached
uncached

write()
Prototype (2)

- Application behavior can be recorded in files
- Activities and their metrics are read from files
- Replayer to mimic program behavior
- Machine learning restricted to parameters in heuristics