

Konfigurierbare Systemsoftware (KSS)

VL 4 – Aspect-Aware Development: The CiAO Approach

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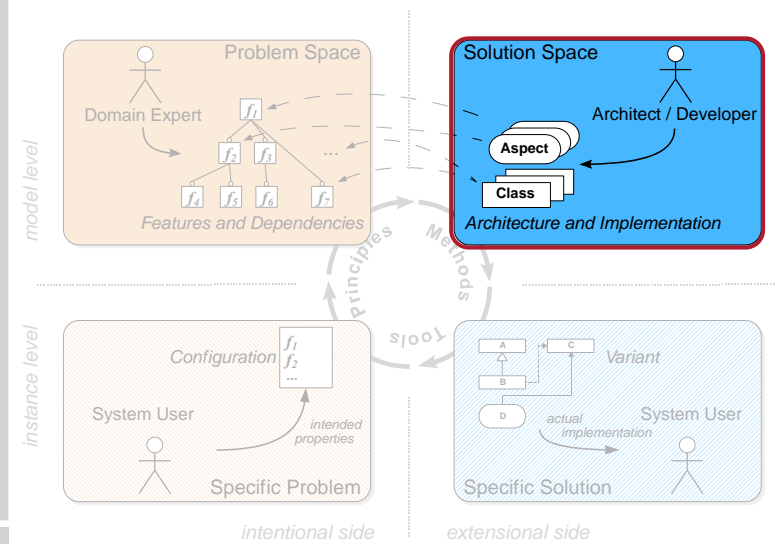
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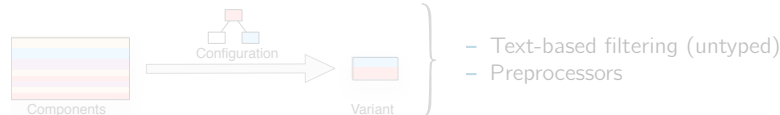
About this Lecture



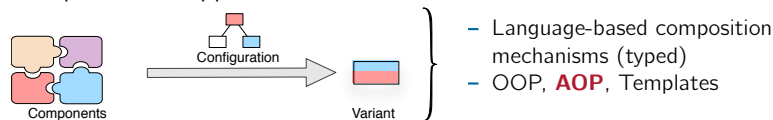
Implementation Techniques: Classification

↔ 3-3

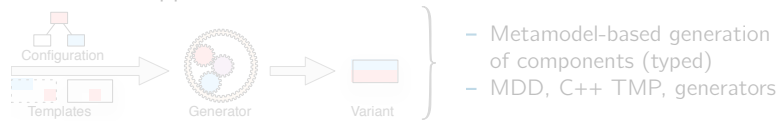
Decompositional Approaches



Compositional Approaches



Generative Approaches



Implementation Techniques: Goals

↔ 2-35

General

- 1 Separation of concerns (SoC)
- 2 Resource thriftiness

How to achieve these with AOP?

Operational

- 3 Granularity Components should be fine-grained. Each artifact should either be mandatory or dedicated to a single feature only.
- 4 Economy The use of memory/run-time expensive language features should be avoided as far as possible. Decide and bind as much as possible at generation time.
- 5 Pluggability Changing the set of optional features should not require modifications in any other part of the implementation. Feature implements should be able to "integrate themselves".
- 6 Extensibility The same should hold for new optional features, which may be available in a future version of the product line.



Agenda

- 4.1 AOP Mechanisms Under the Hood
- 4.2 Study: i4Weathermon AOP
- 4.3 CiAO
- 4.4 CiAO Results
- 4.5 Summary
- 4.6 References

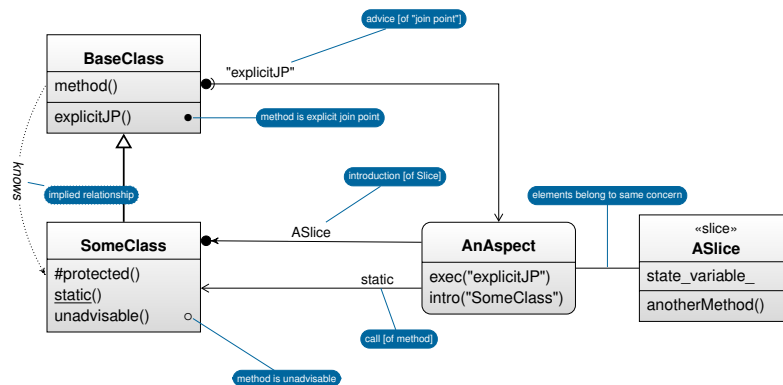


Agenda

- 4.1 AOP Mechanisms Under the Hood
 - Diagram Notation
 - Obliviousness & Quantification
 - AOP Mechanisms: Summary
- 4.2 Study: i4Weathermon AOP
- 4.3 CiAO
- 4.4 CiAO Results
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- 4.6 References



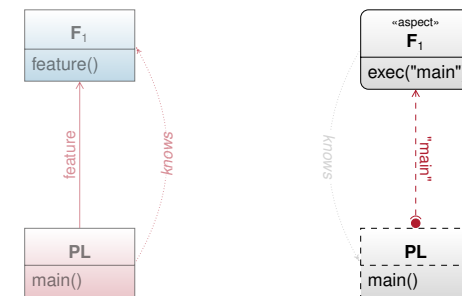
Notation



AOP Mechanisms Demystified: "Obliviousness"

Scenario:

Optional feature component F_1 shall be integrated into SPL component PL



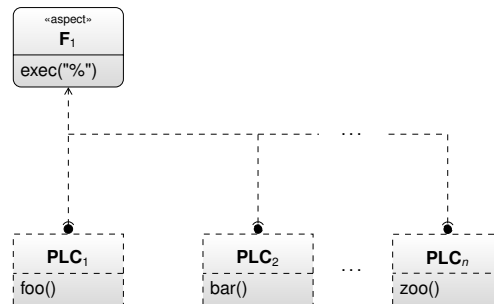
- With OOP:
 - PL has to call F_1 \rightsquigarrow PL has to know F_1
 - control flows can only be established in the direction of knowledge
- With AOP:
 - F_1 can give advice to PL \rightsquigarrow F_1 has to may know PL
 - control flow is established opposite to the direction of knowledge
 - binding is inherently loose \rightsquigarrow silently missed, if PL does not exist



AOP Mechanisms Demystified: "Quantification"

Scenario:

(Nonfunctional) feature component F_1 shall be integrated into (optional) SPL components $PLC_{1..n}$



- With AOP:
 - binding is **inherently loose** \leadsto may **quantify** over n join points
 - possible by declarative pointcut concept (here: wildcard in match expression)



Agenda

- 4.1 AOP Mechanisms Under the Hood
- 4.2 Study: i4Weathermon AOP
 - Flashback: i4Weathermon
 - i4WeatherMon with AOP
 - i4WeatherMon with AOP: Results
- 4.3 CiAO
- 4.4 CiAO Results
- 4.5 Summary
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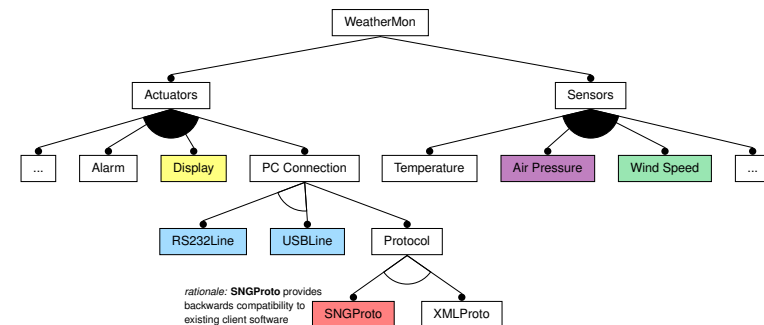
AOP Mechanisms Demystified: Summary

- **Advice** **inverses** the direction in which control-flow relationships are established: $C \text{ calls } A \implies A \text{ advises } C$
 - Aspects integrate themselves into the surrounding program
 - \leadsto "I make you call me"
 - Surrounding program can be kept oblivious of the aspects
 - \leadsto advice-based binding as a means to integrate (optional) features
- **Pointcuts** provide for an implicit **quantification** of this integration
 - Applies to $0 \dots M \dots n$ join points, depending on the pointcut expression
 - \leadsto Aspects can be kept oblivious of the surrounding program
 - Thereby, advice-based binding is inherently loose
 - \leadsto advice-based binding as a means to integrate interacting features



i4WeatherMon: Feature Model

\leftrightarrow 2-30

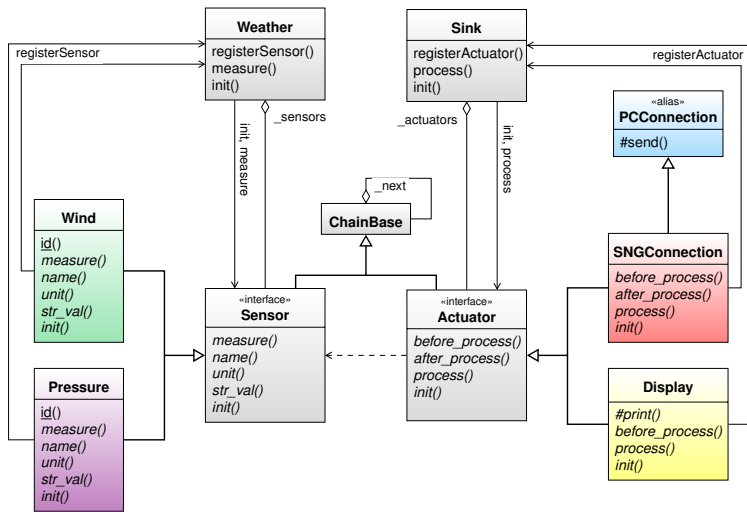


- How to achieve *Granularity, Economy, Pluggability, Extensibility*?
 - Configuration-dependent sensor and actuator sets
 - initialization, integration, interaction of optional feature code
 - Generic and nongeneric actuators
 - interacting optional feature code

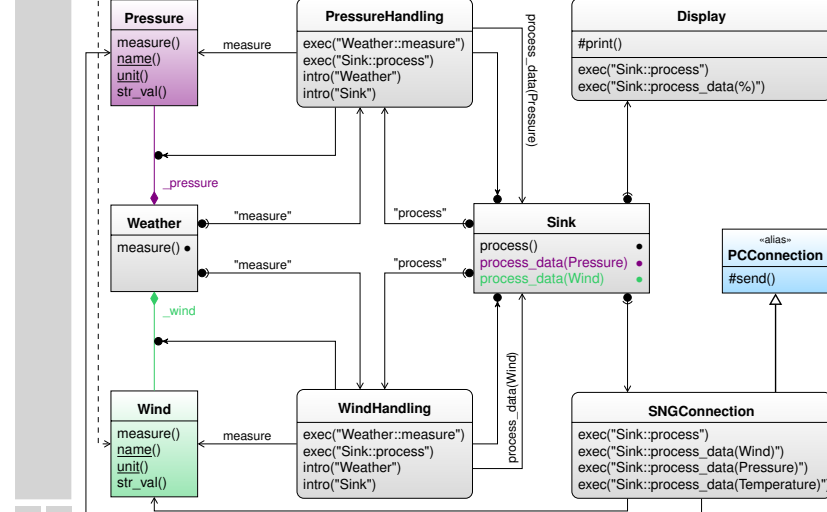


I4WeatherMon: OOP Solution Space

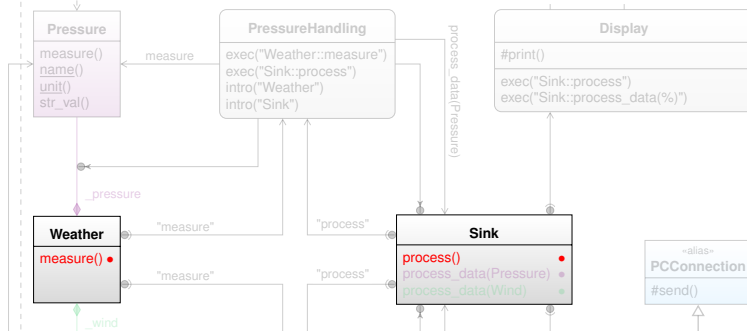
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I4WeatherMon: AOP Solution Space



I4WeatherMon: AOP Solution Space

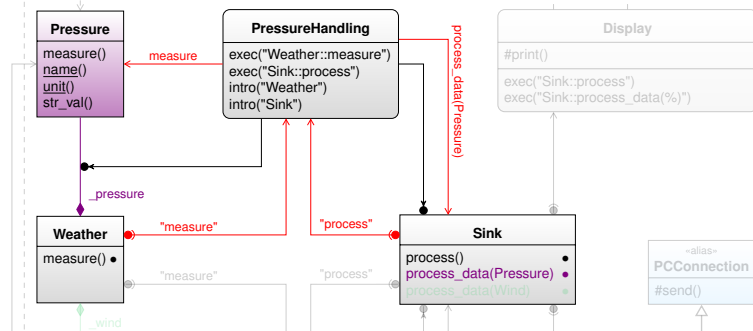


Basic structure

Weather and Sink are (almost) empty classes.

- Provide a **lexical scope** for sensor / actuator introductions
- Provide **explicit join points** (empty methods `measure()` / `process()`) that are invoked by the main loop, when measuring / processing should take place
- ~ All further functionality is provided by the aspects!

I4WeatherMon: AOP Solution Space



Sensor integration

A *Sensor* is implemented as a class with an accompanying Handling aspect

- Slices the sensor singleton instance into `Weather`
- Gives advice to `Weather::measure()` to invoke `Sensor::measure()`
- Slices an **explicit join point** `process_data(Sensor)` into `Sink`
- Gives advice to `Sink::process()` to invoke `process_data(Sensor)`

I4WeatherMon: AOP Generic Actuator Integration

```

aspect SNGConnection : protected PCConnection {
    UInt8 _p, _w, _t1, _t2;    // weather record
    ...
    // let this aspect take a higher precedence than <Sensor>Handling
    advice process () : order ("SNGConnection", "%Handling");
    advice execution("void Sink::process(const Weather&)")
        : before () { ... /* init record */ }
    advice execution("void Sink::process(const Weather&)")
        : after () { ... /* transmit record */ }

    // collect wind, pressure, temperature data by giving specific advice
    advice execution("void Sink::process_data(...)") && args (wind)
        : before (const Wind &wind) {
        _w = wind._w;
    }
    advice execution("void Sink::process_data(...)") && args (pressure)
        : before (const Pressure &pressure) {
        _p = pressure._p - 850;
    }
    advice execution("void Sink::process_data(...)") && args (temp)
        : before (const Temperature &temp) {
        _t1 = (UInt8)temp._t1;
        _t2 = temp._t2;
    }
};
    
```



I4WeatherMon (AOP): Evaluation

General

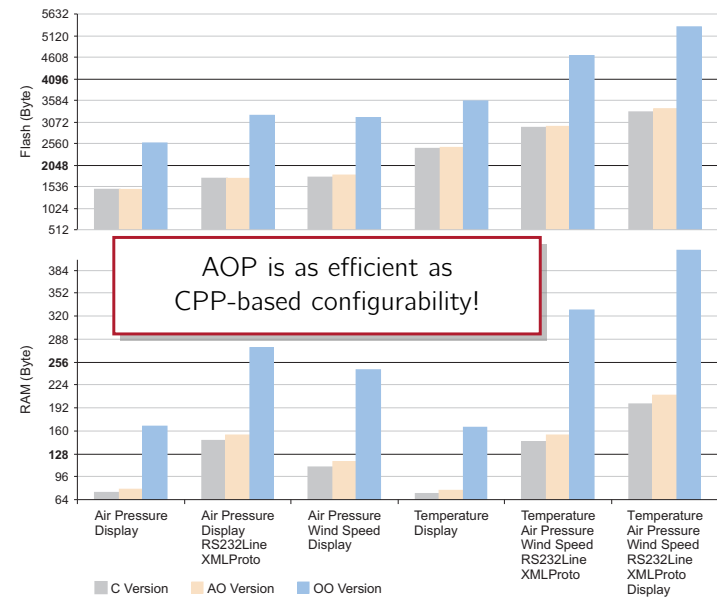
- ① Separation of concerns (SoC) ✓
- ② Resource thriftiness ✓

Operational

- ③ Granularity ✓
 - Every component implements functionality of a single feature only.
- ④ Economy ✓
 - All control-flow bindings are established at compile time.
- ⑤ Pluggability ✓
 - Sensors and actuators integrate themselves by aspects.
- ⑥ Extensibility ✓
 - "Plug & Play" of sensor and actuator implementations.



I4WeatherMon: CPP vs. AOP – Footprint



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- 4.1 AOP Mechanisms Under the Hood
- 4.2 Study: i4Weathermon AOP
- 4.3 CiAO
 - Motivation and Goals
 - Design Approach
 - Examples: Aspects in Action
 - Explicit Join Points
 - Further Examples
- 4.4 CiAO Results
- 4.5 Summary
- 4.6 References



CiAO: Motivation and Goals

“ Throughout the entire operating-system design cycle, we must be careful to **separate policy decisions** from implementation details (**mechanisms**). This separation allows maximum flexibility if policy decisions are to be changed later. ”

Silberschatz, Gagne, and Galvin 2005: *Operating System Concepts* [8, p. 72]

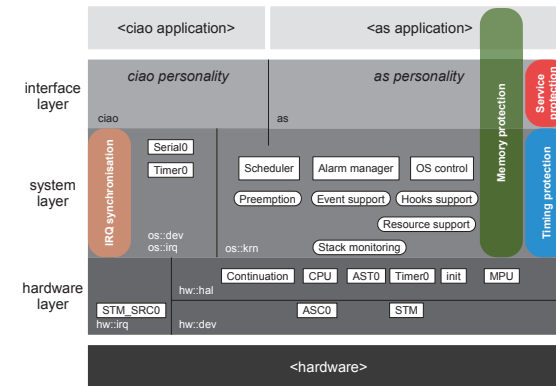
- **Primary goal:** architectural configurability
 - configurability of even fundamental policies
 - synchronization, protection, interaction
- **Secondary goal:** < the standards >
 - efficiency, configurability in general, portability
- **Approach:** aspect-aware operating system design
 - strict decoupling of policies and mechanisms in the implementation
 - using aspects as the primary composition technique



CiAO → CiAO is Aspect-Oriented

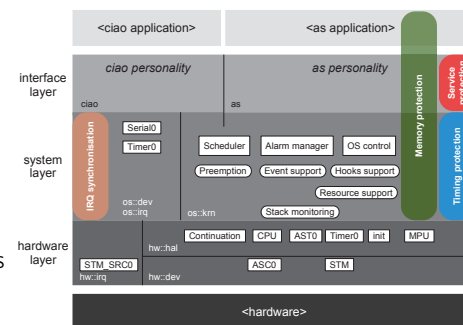
[3-5]

- A product line of aspect-oriented operating systems
 - Implements OSEK VDX / AUTOSAR OS [1, 7]
 - Fine-grained configurability of all system policies and abstractions
 - Developed from scratch with AOP



CiAO: General Structure

- **Layered Architecture**
 - Interface layer (as/ciao)
 - System layer (os)
 - Hardware layer (hw)
- **Layers → C++ namespaces**
 - Potential join points for cross-layer transitions
 - Further refined by sublayers (os::krn, hw::irq)
 - Layers as a means of aspect-aware development
 - ~> “visible transitions”



```
// yields all hardware invocations from the system layer
pointcut OStoHW() = call("% hw::...::%(...)")
&& within("% os::...::%(...)");
```



Methodology: Principles of Aspect-Aware Development

Design Principles

→

Development Idioms

- | | | |
|-------------------------------|----|----------------------|
| 1. loose coupling | by | advice-based binding |
| 2. visible transitions | by | explicit join points |
| 3. minimal extensions | by | extension slices |



Methodology: Principles of Aspect-Aware Development

The principle of **loose coupling**. Make sure that aspects can hook into all facets of the static and dynamic integration of system components. The *binding* of components, but also their *instantiation* (e.g. placement in a certain memory region) and the time and order of their *initialization* should all be established (or at least be influenceable) by aspects.

The principle of **visible transitions**. Make sure that aspects can hook into all control flows that run through the system. All control-flow transitions into, out of, and within the system should be influenceable by aspects. For this they have to be represented on the join-point level as statically evaluable, unambiguous join points.

The principle of **minimal extensions**. Make sure that aspects can extend all features provided by the system on a fine granularity. System components and system abstractions should be fine-grained, sparse, and extensible by aspects.



Methodology: Roles of Aspects and Classes

What to model as a *class* and what as an *aspect*?

- **< Thing >** is a class if – and only if – it is a **distinguishable, instantiable** concept of CiAO:
 - A **system component**, instantiated internally on behalf of CiAO
 - The Scheduler, the Alarm Manager, the OS control facility, ...
 - Hold and manage kernel state, singletons by definition
 - A **system abstraction**, instantiated as objects on behalf of the user
 - Task, Event, Resource, ...
 - In AUTOSAR OS: instantiated at compile time
 - Both are **sparse** ~ provide a **minimal implementation** only
- Otherwise **< thing >** is an aspect!

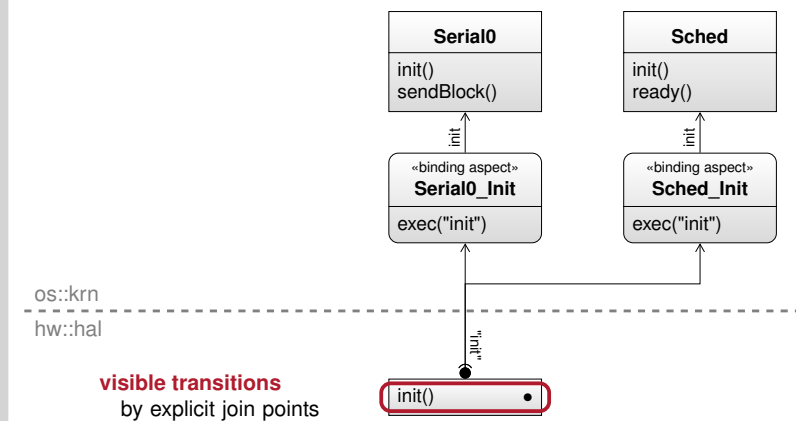


Methodology: Roles of Aspects and Classes (Cont'd)

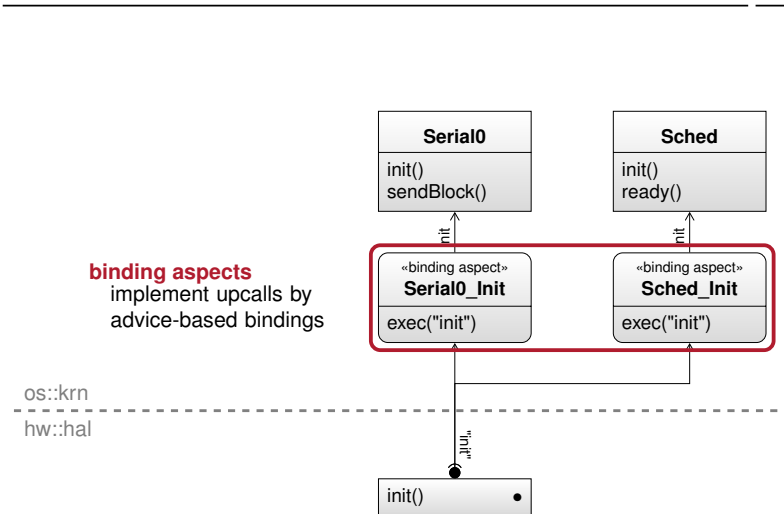
- Three idiomatic aspect roles
 - **Extension aspects:** extend some system component or system abstraction by additional functionality.
 - **Policy aspects:** “glue” otherwise unrelated system abstractions or components together to implement some CiAO kernel policy.
 - **Uppcall aspects:** bind behavior defined by higher layers to events produced in lower layers of the system.



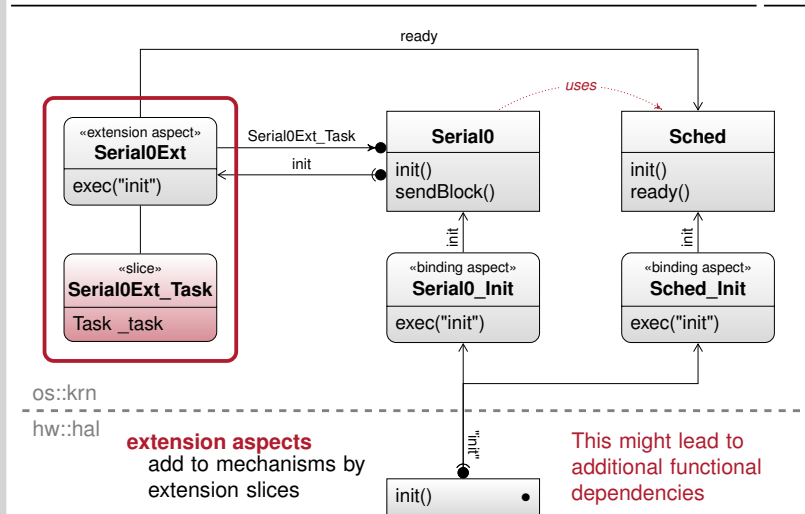
Example: Mechanism Integration



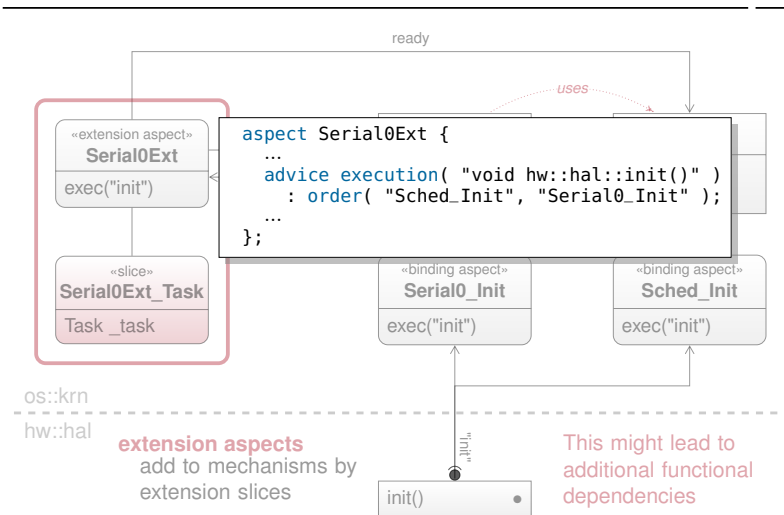
Example: Mechanism Integration



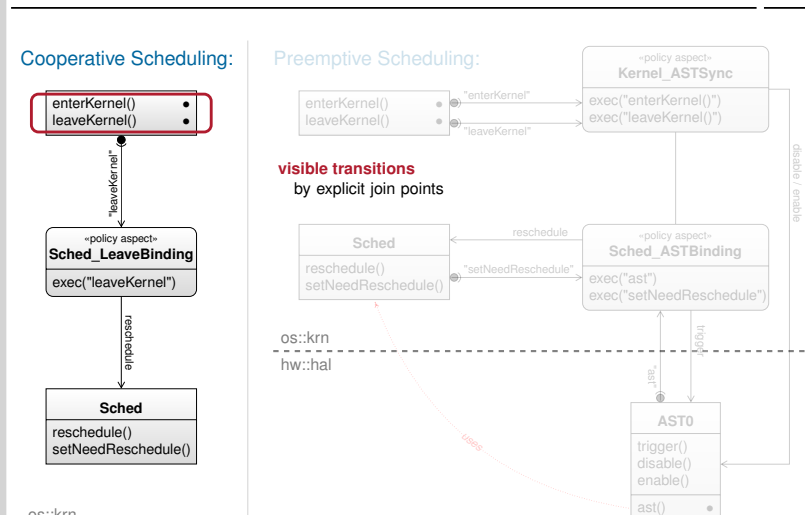
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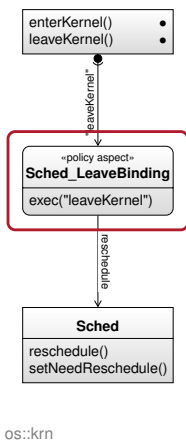


Example: Policy Integration

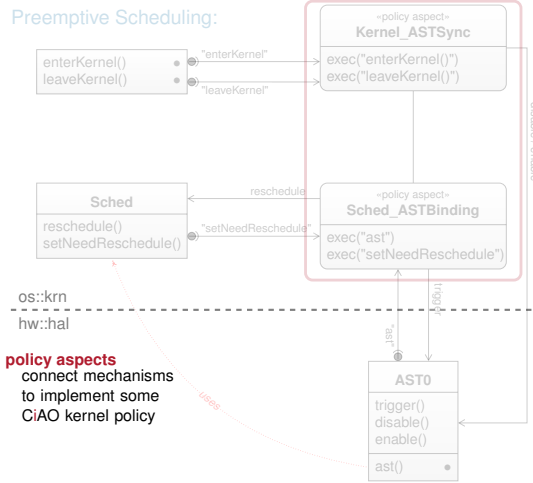


Example: Policy Integration

Cooperative Scheduling:



Preemptive Scheduling:

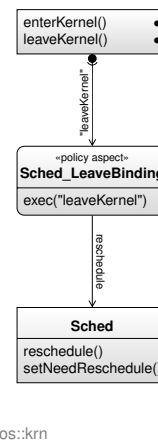


policy aspects connect mechanisms to implement some CIAO kernel policy

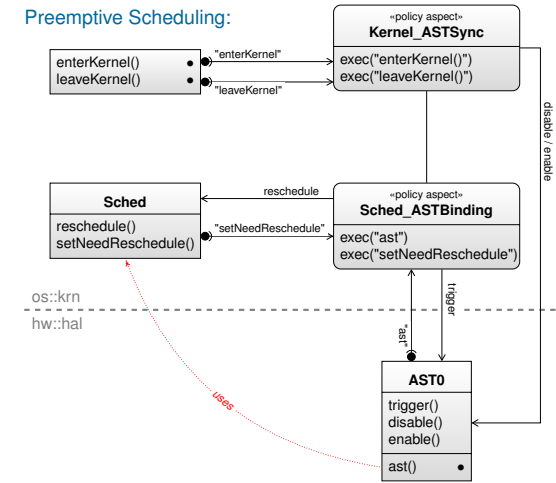


Example: Policy Integration

Cooperative Scheduling:



Preemptive Scheduling:



Methodology: Explicit Join Points

- Advice-based binding → availability of the “right” join points
 - for all semantically important transitions in the system
 - statically evaluable
- Fine-grained component structure ~ many implicit join points, but
 - amount and precise semantics often implementation dependent
 - aspects have to “know” ~ no obliviousness
- Important transitions not available for technical reasons as JPs
 - target code may be fragile (e.g., context switch) ~ must not be advised
 - target code may be written in assembly ~ transitions not visible as JPs



Methodology: Explicit Join Points (Cont'd)

- Solution: explicit join points
 - empty inline methods for the sole purpose that aspects can bind to them
 - explicitly triggered by components or other aspects
 ~ well defined semantics
- Upcall join points (U) represent system-internal events that are to be processed on a higher layer
 - exceptions, such as signals or interrupts
 - internal events, such as system initialization or entering of the idle state
- Transition join points (T) represent semantically important control-flow transitions inside the kernel
 - level transitions: *user* → *kernel*, *user* → *interrupt*
 - context transitions: *threadA* → *threadB*

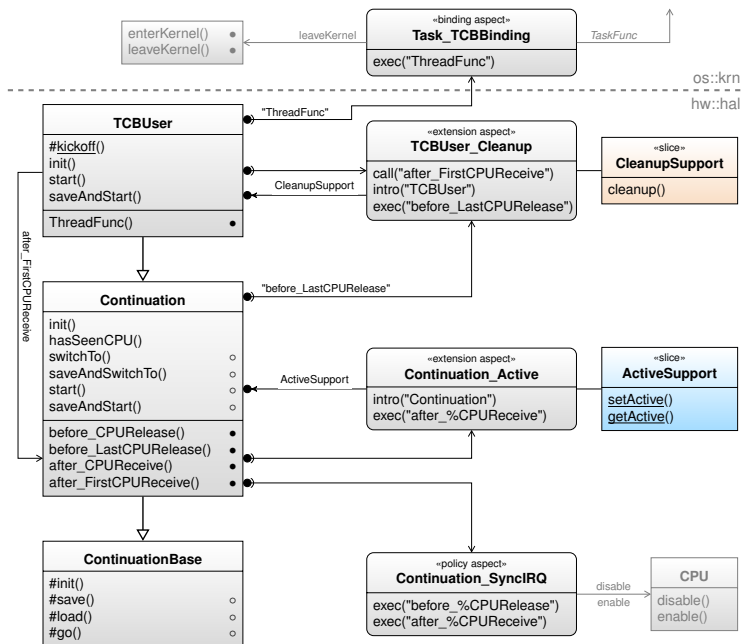


Explicit Join Points in CiAO (Excerpt) [5]

type	representing function or method	description
os:krm	U internalErrorHook()	Explicit join points for the support and binding of OSEK OS and AUTOSAR OS user-level hook functions, as specified in [36, p. 39] and [4, p. 46]. Triggered in case of an <i>error</i> , a <i>protection</i> violation, before (<i>pre</i>) and after (<i>post</i>) at high-level task switch, and at operating-system startup and shutdown time.
	U internalProtectionHook(StatusType error)	
	U internalPreTaskHook()	
	U internalPostTaskHook()	
	U internalStartupHook()	
	U internalShutdownHook()	
T	enterKernel()	Triggered when a control flow enters (respectively leaves) the kernel domain.
	leaveKernel()	
...		
hw:hal	U ThreadFunc()	Entry point of a new thread (continuation).
	T before_CPURelease(Continuation*& to)	Triggered immediately before the running continuation is deactivated or terminated; to is going to become the next running continuation.
	T before_LastCPURelease(Continuation*& to)	
	T after_CPUReceive()	Triggered immediately after the (new) running continuation got reactivated or started.
T after_FirstCPUReceive()		
U	AST<#>::ast()	Entry point of the respective AST.
	U init()	Triggered during system startup after memory busses and stack have been initialized.
	...	
	hw:irq	U <IRQ_NAME>::handler()
...		

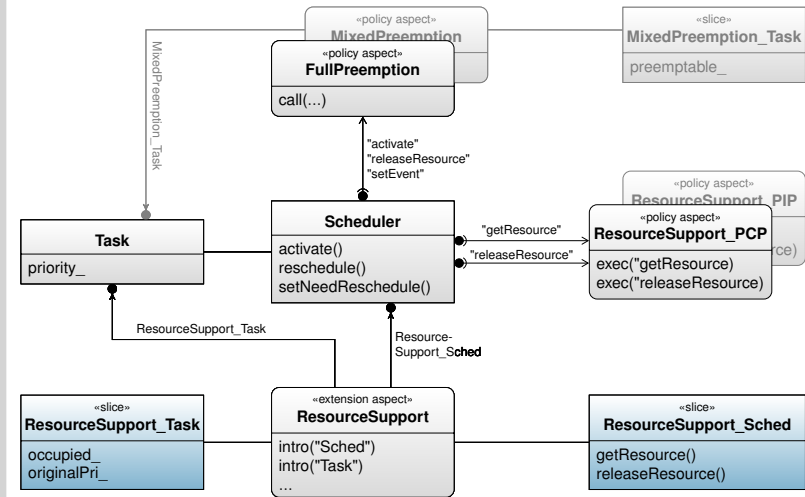


Continuation: CiAO's Thread Abstraction [5]



Example: Optional Feature Interaction [4]

[4]



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AUTOSAR-OS Features Implemented in CiAO as Aspects (Excerpt)

concern	extension policy upcall	advice	join points	extension of	advice-based binding to
ISR cat. 1 support	1	$m + 2 + m$	$2 + m$	API, OS control	m ISR bindings
ISR cat. 2 support	1	$n + 5 + n$	$5 + n$	API, OS control, scheduler	n ISR bindings
ISR abortion support	1	2	$1 + m + n$	scheduler	$m + n$ ISR functions
Resource support	1	1	3	5 scheduler, API, task	PCP policy implementation
Resource tracking	1	1	3	4 task, ISR	monitoring of Get/ReleaseResource
Event support	1	1	5	5 scheduler, API, task, alarm	trigger action JP
Alarm support	1	1	1	1 API	
OS application support	1	1	2	3 scheduler, task, ISR	
Full preemption	1	1	2	6	3 points of rescheduling
Mixed preemption					
Multiple activation					
Stack monitoring	1	2	2	3 task	CP-0 release JPs
Context check	1	1	1	s	s service calls
Disabled interrupts check	1	1	30	all services except interrupt services	
Enable w/o disable check	1	3	3	enable services	
Missing task end check	1	1	1	t	t task functions
Out of range check	1	1	4	alarm set and schedule table start services	
Invalid object check	1	1	25	services with an OS object parameter	
Error hook	1	2	30	scheduler	29 services
Protection hook	1	1	2	2 API	default policy implementation
Startup / shutdown hook	1	2	2	explicit hooks	
Pre-task / post-task hook	1	2	2	explicit hooks	

Plug & Play of optional features and policies!

Kernel Latency Comparison with "OSEK"

[4]

test scenario	CiAO		OSEK
	min	full	min
(a) voluntary task switch	160	178	218
(b) forced task switch	108	127	280
(c) preemptive task switch	192	219	274
(d) system startup	194	194	399
(e) resource acquisition	19	56	54
(f) resource release	14	52	41
(g) resource release with preemption	240	326	294
(h) category 2 ISR latency	47	47	47
(i) event blocking with task switch	141	172	224
(j) event setting with preemption	194	232	201
(k) comprehensive application	748	748	1216

Execution time [clock ticks] on TC1796@50 MHz
(ac++1.0pre3 with tricore-g++3.4.3 -O3 -fno-rtti -funit-at-a-time -ffunction-sections -Xlinker --gc-sections)

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CiAO outperforms the marked leader in 11 out of 12 cases by up to **260 percent**.

Execution time [clock ticks] on TC1796@50 MHz
(ac++1.0pre3 with tricore-g++3.4.3 -O3 -fno-rtti -funit-at-a-time -ffunction-sections -Xlinker --gc-sections)

Feature Granularity of CiAO (static memory demands per feature)

feature	with feature or instance	text	data	bss
<i>Base system (OS control and tasks)</i>				
per task		+ func	+ 20	+ 16 + stack
per application mode		0	+ 4	0
ISR cat. 1 support		0	0	0
per ISR		+ func	0	0
per disable-enable		+ 4	0	0
Resource support		+ 128	0	0
per resource		0	+ 4	0
per task		0	+ 8	0
per alarm		0	+ 12	0
Full preemption		0	0	0
per join point		+ 12	0	0
Mixed preemption		0	0	0
per join point		+ 44	0	0
per task		0	+ 4	0
Wrong context check		0	0	0
per void join point		0	0	0
per StatusType join point		+ 8	0	0
Interrupts disabled check		0	0	0
per join point		+ 64	0	0
Invalid parameters check		0	0	0
per join point		+ 36	0	0
Error hook		0	0	+ 4
per join point		+ 54	0	0
Startup hook or shutdown hook		0	0	0
Pre-task hook or post-task hook		0	0	0

CiAO achieves excellent granularity!

Discussion: Aspect-Aware Development

- By AAD CiAO achieves excellent properties [3–5]
 - configurability and granularity even for fundamental kernel policies
 - complete separation of concerns in the implementation
- The approach has also been applied to other system software
 - PUMA, the C/C++ transformation framework behind ac++ [9]
 - CiAO_{IP}, an aspect-oriented IP stack for embedded systems [2]
- Issues: comprehensibility & tool support
 - CiAO: aspect code/base code = 1/2.4
~ where the heck xyz is implemented?
 - calls for additional tool support
 - ac++ weaver implementation is stable, but not as mature as gcc
 - missing or confusing error messages
 - no support for weaving in template code
 - no C++0x support

	Base code		Aspect code	
	Files	LOC	Files	LOC
CiAO kernel only	423	21,086	333	5,923
CiAO COM	112	8,689	297	5,552
CiAO IP stack	45	5,038	96	3,230
CiAO overall	580	34,813	726	14,705

This is *research*,
after all :-)



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Summary

- Aspect-Aware Development exploits AOP mechanisms to achieve separation of concerns in configurable system software
 - Advice inverts the direction in which control-flow relationships are established: $C \text{ calls } A \implies A \text{ advises } C$
 - ~ advice-based binding as a means to integrate (optional) features
 - Pointcuts provide for an implicit quantification of this integration
 - ~ advice-based binding as a means to integrate interacting features
- CiAO applies these concepts from the very beginning
 - loose coupling by advice-based binding
 - visible transitions by explicit join points
 - minimal extensions by extension slices
- The results are compelling
 - configurability of even all fundamental system policies
 - excellent granularity and footprint



Referenzen

- [1] AUTOSAR. *Specification of Operating System (Version 2.0.1)*. Tech. rep. Automotive Open System Architecture GbR, June 2006.
- [2] Christoph Borchert, Daniel Lohmann, and Olaf Spinczyk. "CiAO/IP: A Highly Configurable Aspect-Oriented IP Stack". In: *Proceedings of the 10th International Conference on Mobile Systems, Applications, and Services (MobiSys '12)*. (Low Wood Bay, Lake District, UK). New York, NY, USA: ACM Press, June 2012, pp. 435–448. ISBN: 978-1-4503-1301-8. DOI: 10.1145/2307636.2307676.
- [3] Daniel Lohmann, Wanja Hofer, Wolfgang Schröder-Preikschat, et al. "Aspect-Aware Operating-System Development". In: *Proceedings of the 10th International Conference on Aspect-Oriented Software Development (AOSD '11)*. (Porto de Galinhas, Brazil). Ed. by Shigeru Chiba. New York, NY, USA: ACM Press, 2011, pp. 69–80. ISBN: 978-1-4503-0605-8. DOI: 10.1145/1960275.1960285.
- [4] Daniel Lohmann, Wanja Hofer, Wolfgang Schröder-Preikschat, et al. "CiAO: An Aspect-Oriented Operating-System Family for Resource-Constrained Embedded Systems". In: *Proceedings of the 2009 USENIX Annual Technical Conference*. Berkeley, CA, USA: USENIX Association, June 2009, pp. 215–228. ISBN: 978-1-931971-68-3. URL: http://www.usenix.org/event/usenix09/tech/full_papers/lohmann/lohmann.pdf.



- [5] Daniel Lohmann, Olaf Spinczyk, Wanja Hofer, et al. "The Aspect-Aware Design and Implementation of the CiAO Operating-System Family". In: *Transactions on AOSD IX*. Ed. by Gary T. Leavens and Shigeru Chiba. Lecture Notes in Computer Science 7271. Springer-Verlag, 2012, pp. 168–215. DOI: 10.1007/978-3-642-35551-6_5.
- [6] Daniel Lohmann, Olaf Spinczyk, and Wolfgang Schröder-Preikschat. "Lean and Efficient System Software Product Lines: Where Aspects Beat Objects". In: *Transactions on AOSD II*. Ed. by Awais Rashid and Mehmet Aksit. Lecture Notes in Computer Science 4242. Springer-Verlag, 2006, pp. 227–255. DOI: 10.1007/11922827_8.
- [7] OSEK/VDX Group. *Operating System Specification 2.2.3*. Tech. rep. <http://portal.osek-vdx.org/files/pdf/specs/os223.pdf>, visited 2014-09-29. OSEK/VDX Group, Feb. 2005.
- [8] Abraham Silberschatz, Greg Gagne, and Peter Bear Galvin. *Operating System Concepts*. Seventh. John Wiley & Sons, Inc., 2005. ISBN: 0-471-69466-5.
- [9] Matthias Urban, Daniel Lohmann, and Olaf Spinczyk. "The aspect-oriented design of the PUMA C/C++ parser framework". In: *Proceedings of the 9th International Conference on Aspect-Oriented Software Development (AOSD '10)*. (Rennes and Saint-Malo, France). New York, NY, USA: ACM Press, 2010, pp. 217–221. ISBN: 978-1-60558-958-9. DOI: 10.1145/1739230.1739256.

