Konfigurierbare Systemsoftware (KSS)

VL 4 – Aspect-Aware Development: The CiAO Approach

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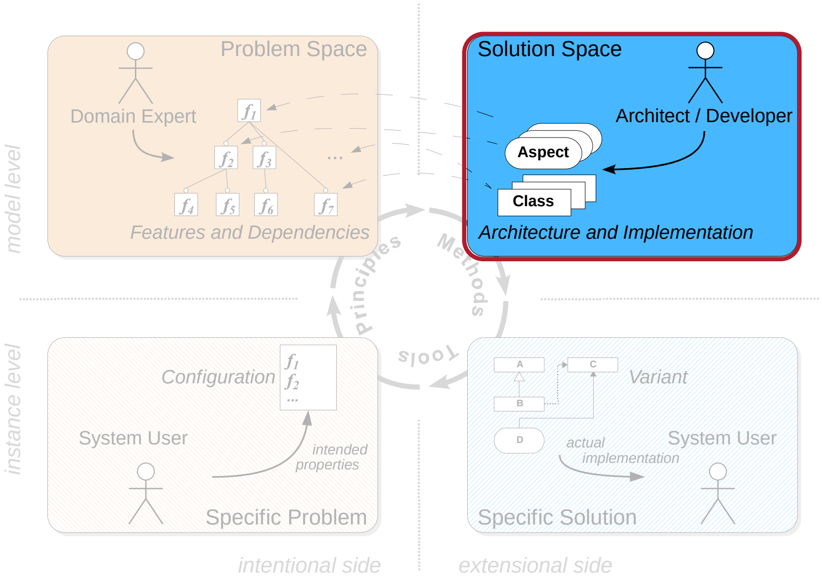
About this Lecture



Implementation Techniques: Classification

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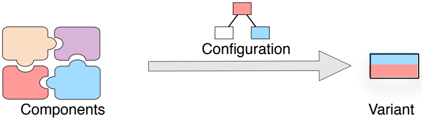
- Decompositional Approaches

  - Text-based filtering (untyped)
  - Preprocessors

- Compositional Approaches



  - Language-based composition mechanisms (typed)
  - OOP, **AOP**, Templates

- Generative Approaches

  - Metamodel-based generation of components (typed)
  - MDD, C++ TMP, generators

Implementation Techniques: Goals

↪ 2–35

General

❶ Separation of concerns (SoC)

❷ Resource thriftiness

How to achieve these with AOP?

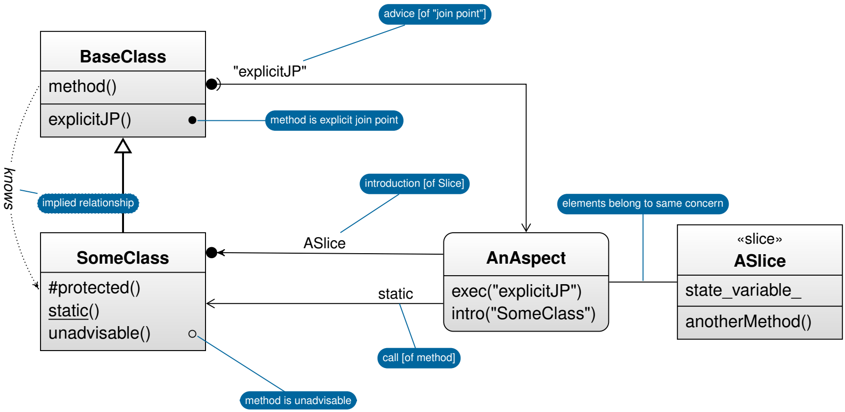
Operational

❸	Granularity	Components should be fine-grained. Each artifact should either be mandatory or dedicated to a single feature only.
❹	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.
❺	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".
❻	Extensibility	The same should hold for new optional features, which may be available in a future version of the product line.

Agenda

Agenda

Notation

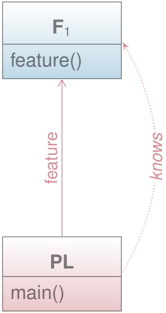


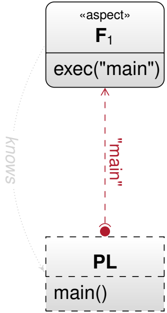
advice [of "join point"]
BaseClass
method()
explicitJP()
"explicitJP"
method is explicit join point
knows
implied relationship
introduction [of Slice]
elements belong to same concern
SomeClass
#protected()
static()
unadvisable()
ASlice
AnAspect
exec("explicitJP")
intro("SomeClass")
«slice»
ASlice
state_variable_
anotherMethod()
static
call [of method]
method is unadvisable

AOP Mechanisms Demystified: “Obliviousness”

Szenario:

Optional feature component $\mathbf{F}_1$ shall be integrated into SPL component **PL**

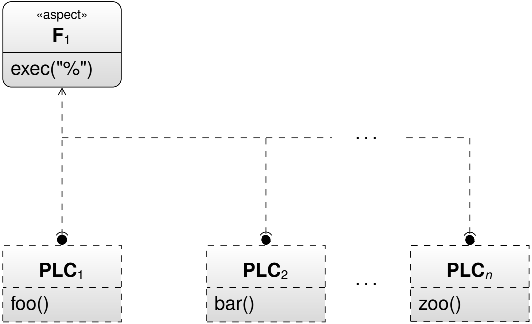




- With OOP:
  - **PL** has to call $\mathbf{F}_1$ $\rightsquigarrow$ **PL** has to **know** $\mathbf{F}_1$
  - control flows can only be established in the direction of knowledge
- With AOP:
  - $\mathbf{F}_1$ can give advice to **PL** $\rightsquigarrow$ $\mathbf{F}_1$ ~~has to~~ **may know** **PL**
  - 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"

Szenario:
(Nonfunctional) feature component $\mathbf{F}_1$ shall be integrated into (optional) SPL components $\mathbf{PLC}_{1\ldots n}$



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

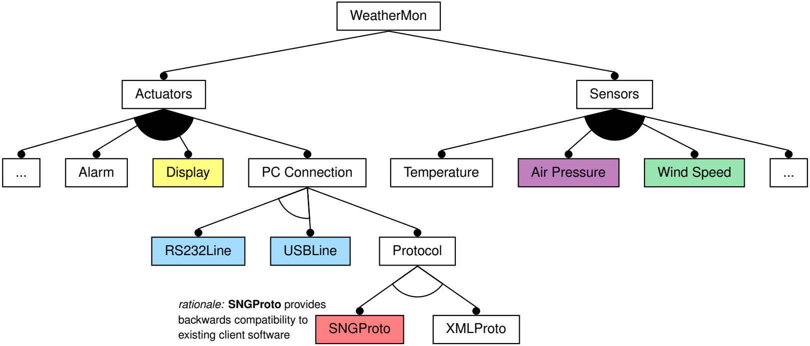
AOP Mechanisms Demystified: Summary

- **Advice** **inverses** the direction in which control-flow relationships are established: **C** *calls* **A** $\Longrightarrow$ **A** *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 **quantifiction** of this integration
  - Applies to $0 \ldots M \ldots n$ 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

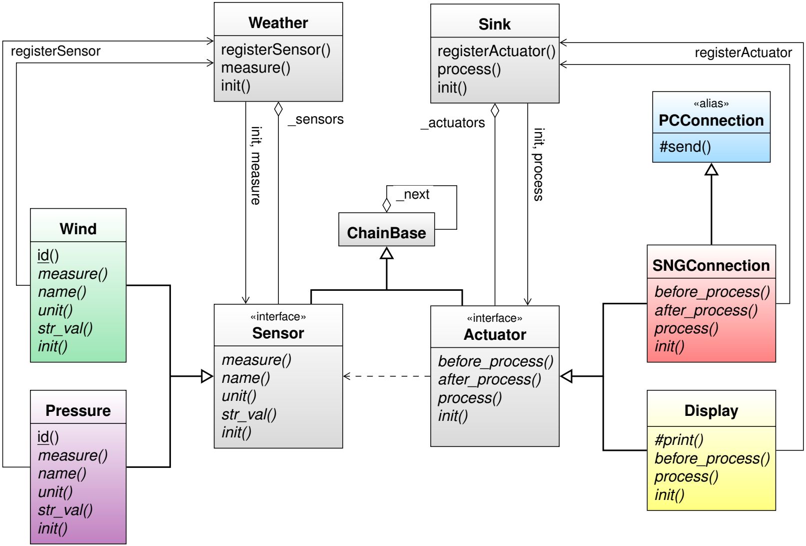
Agenda

I4WeatherMon: Feature Model

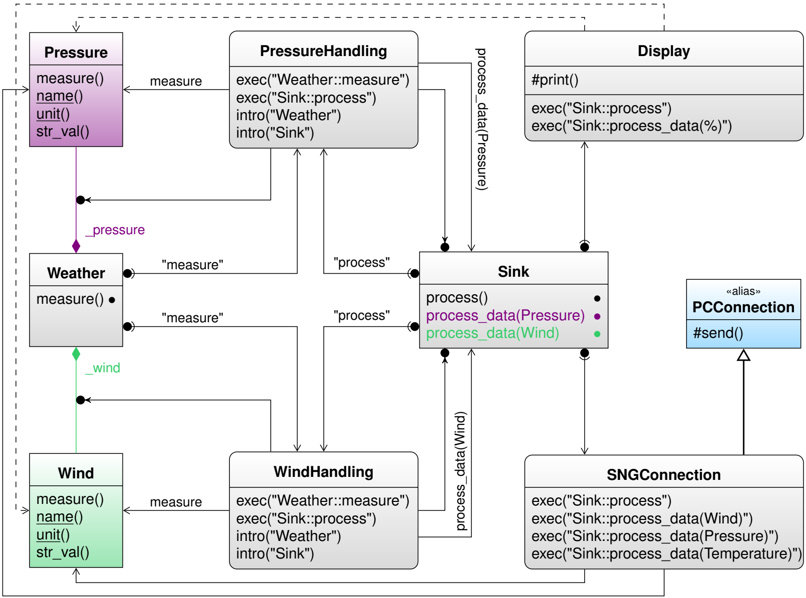


- How to achieve *Granularity*, *Economy*, *Pluggability*, *Extensibility*?
  - Configuration-dependent sensor and actuator sets
    - initialization, integration, interaction of optional feature code
  - Generic and nongeneric actuators
    - interacting optional feature code

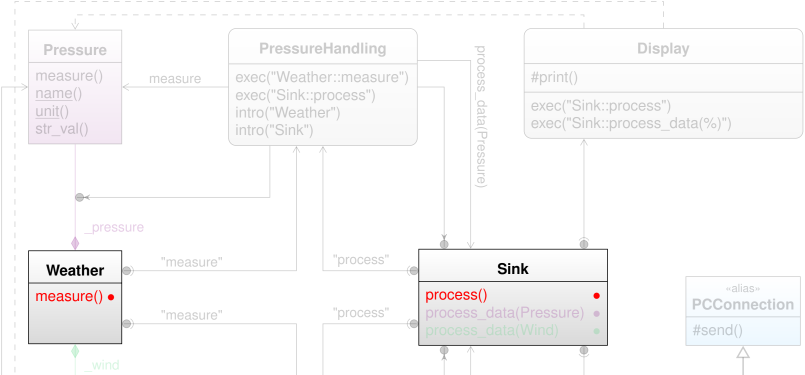
I4WeatherMon: **OOP** Solution Space



I4WeatherMon: **AOP** Solution Space



I4WeatherMon: **AOP** Solution Space



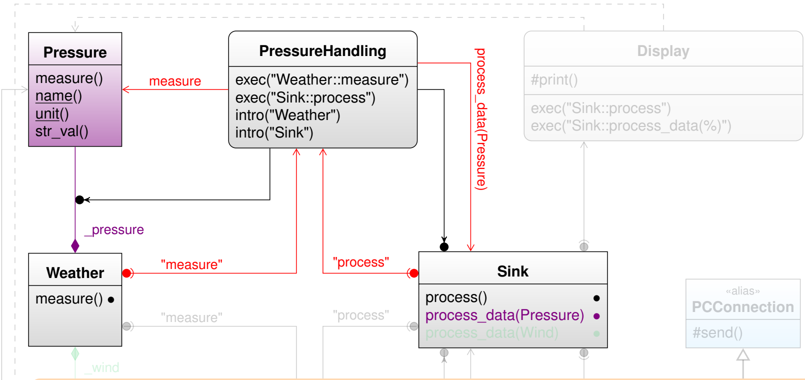
Basic structure

`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*`)`

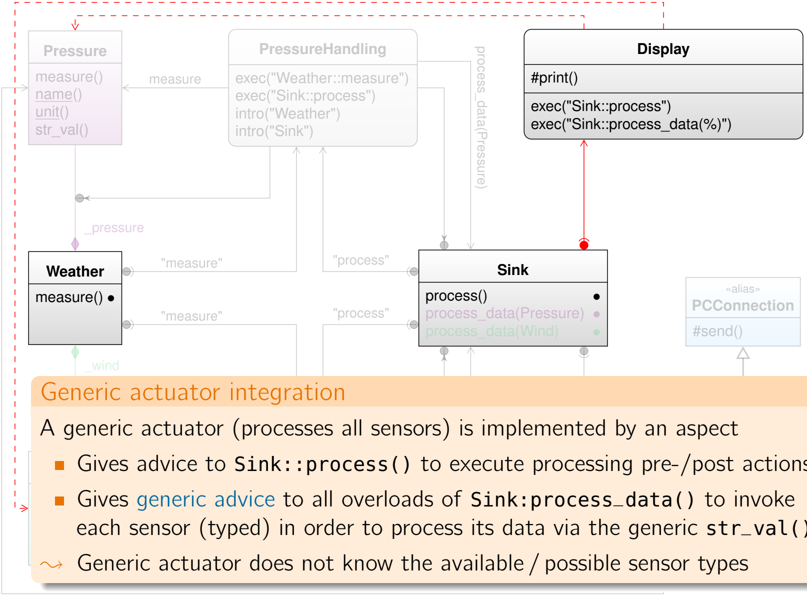
I4WeaterMon: AOP Sensor Integration

```
class Weather {
public:
  void measure() {} // empty implementation
};
```

```
class Sink {
public:
  void process() {} // empty implementation
};
```

```
aspect PressureHandling {
  // Weather integration
  advice "Weather" : slice struct{
    Pressure _pressure; // introduce sensor instance (singleton)
  };
  advice execution( "void Weather::measure()" ) : before() {
    theWeather._pressure.measure(); // invoke sensor's measure()
  }
  // Sink integration
  advice "Sink" : slice struct {
    // introduce sensor-specific explicit join point for actuator aspects
    void process_data( const Pressure & ) {}
  };
  advice execution( "void Sink::process()" ) : after() {
    theSink.process_data( theWeather._pressure ); // trigger it
  }
};
```

I4WeatherMon: **AOP** Solution Space



Generic actuator integration

A generic actuator (processes all sensors) is implemented by an aspect

- Gives advice to **`Sink::process()`** to execute processing pre-/post actions
- Gives generic advice to all overloads of **`Sink:process_data()`** to invoke each sensor (typed) in order to process its data via the generic **`str_val()`**

⇝ Generic actuator does not know the available / possible sensor types

I4WeaterMon: AOP Generic Actuator Integration

```
aspect Display {
  …
  // display each element of the weather data
  advice execution("void Sink::process_data(%)") : before () {
    typedef JoinPoint::template Arg<0>::ReferredType Data;
    char val[5];
    tjp->arg<0>()->str_val( val );
    print( Data::name(), val, Data::unit() );
  }
};
```

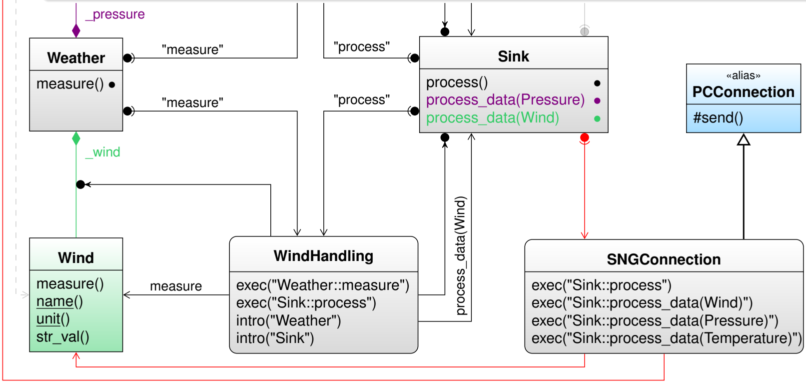
I4WeatherMon: **AOP** Solution Space

Nongeneric actuator integration

A nongeneric actuator (processes some sensors) is implemented by an aspect

- Gives advice to `Sink::process()` to execute processing pre-/post actions
- Gives advice to selected overloads of `Sink:process_data()` to invoke them in order to process each sensors data via a sensor-specific interface

⤳ Nongeneric actuator has to know specific sensor types



I4WeaterMon: 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;
  }
};
```

I4WeaterMon: CPP vs. AOP – Footprint

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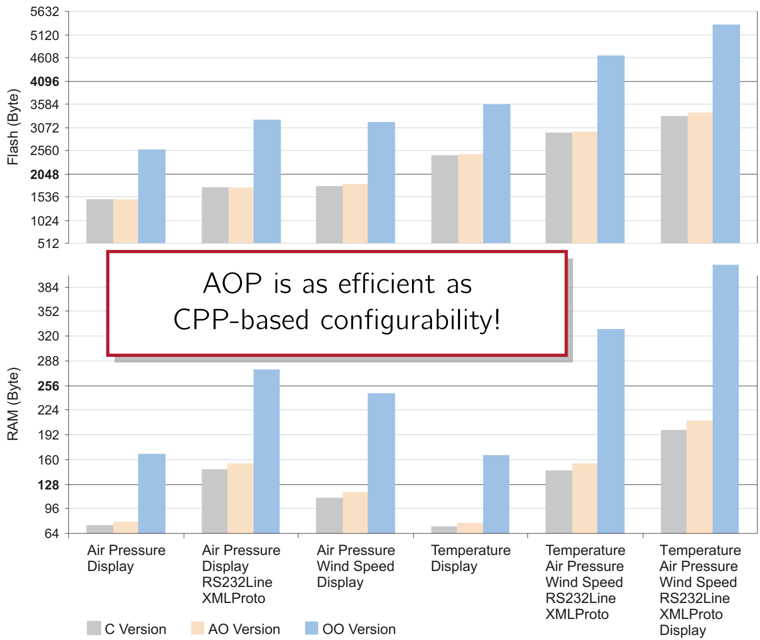


AOP is as efficient as CPP-based configurability!

I4WeaterMon (AOP): Evaluation

General

❶ Separation of concerns (SoC) ✔

❷ Resource thriftiness ✔

Operational

❸ Granularity ✔
- Every component implements functionality of a single feature only.

❹ Economy ✔
- All control-flow bindings are established at compile time.

❺ Pluggability ✔
- Sensors and actuators integrate themselves by aspects.

❻ Extensibility ✔
- "Plug & Play" of sensor and actuator implementations.

Agenda

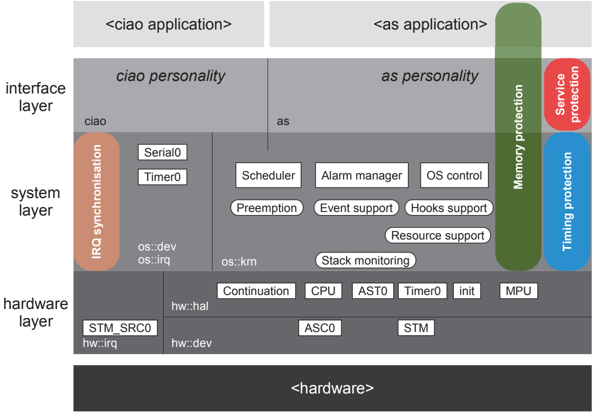
CiAO: Motivation and Goals

> *“ 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
    $\mapsto$ 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
    $\mapsto$ using aspects as the primary composition technique

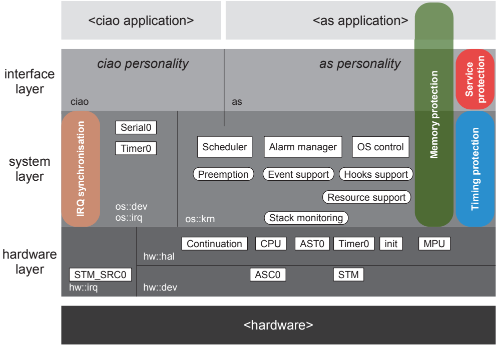
CiAO ↦ CiAO is Aspect-Oriented

- 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 $\mapsto$ 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
    $\leadsto$ *"visible transitions"*




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

Methodology: Principles of Aspect-Aware Development

Design Principles	$\mapsto$	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*?

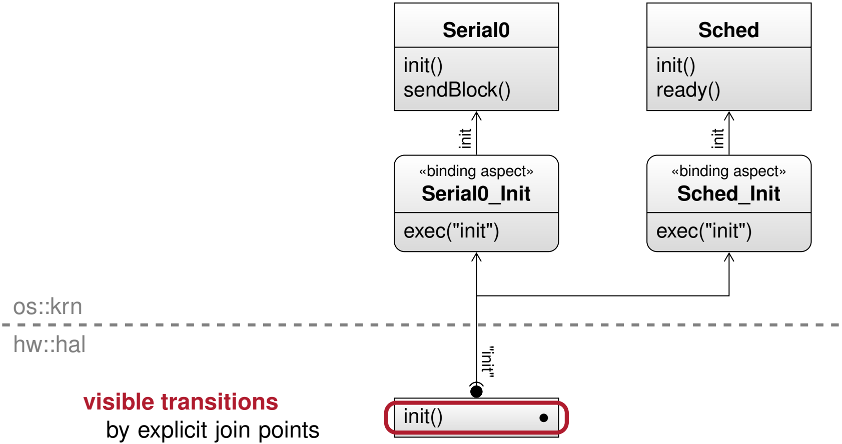
- < *Thing* > is a class if – and only if – it
  is a distinguishable, instantiable concept of CiAO:
  - A **system component**, instantiated internally on behalf of CiAO
    - The Scheduler, the Alarm Manager, the OS control facility, ...
    - Hold and manage kernel state, singletons by definition
  - 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.
  - **Upcall aspects:** bind behavior defined by higher layers to events produced in lower layers of the system.

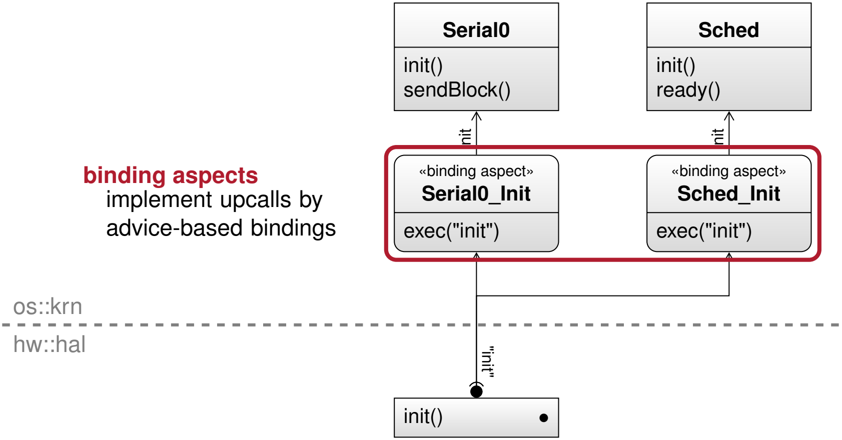
Example: Mechanism Integration



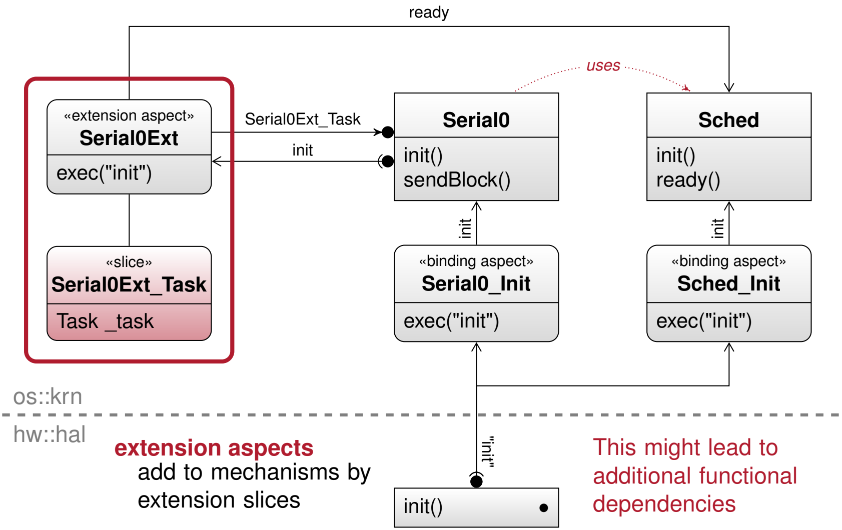
visible transitions
by explicit join points

Example: Mechanism Integration

binding aspects
implement upcalls by
advice-based bindings



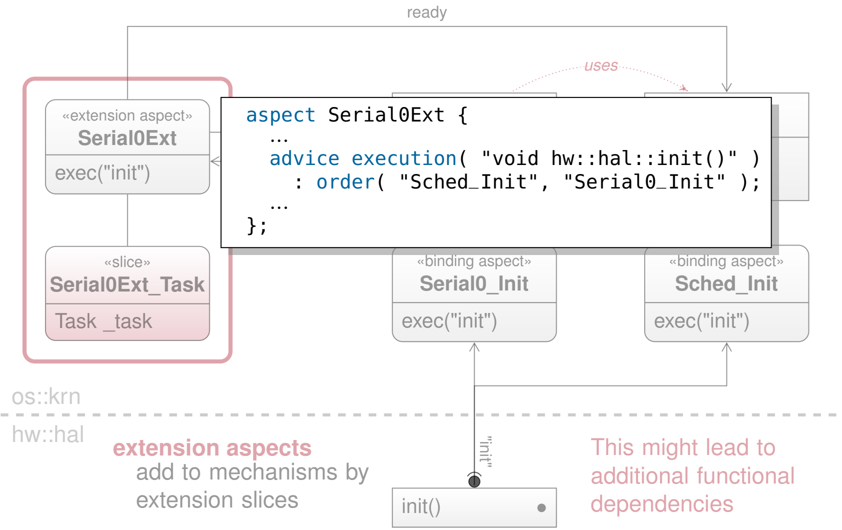
Example: Mechanism Integration



extension aspects
add to mechanisms by extension slices

This might lead to additional functional dependencies

Example: Mechanism Integration



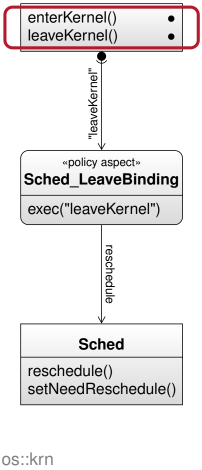

```
aspect Serial0Ext {
  …
  advice execution( "void hw::hal::init()" )
    : order( "Sched_Init", "Serial0_Init" );
  …
};
```

extension aspects
add to mechanisms by extension slices

This might lead to additional functional dependencies

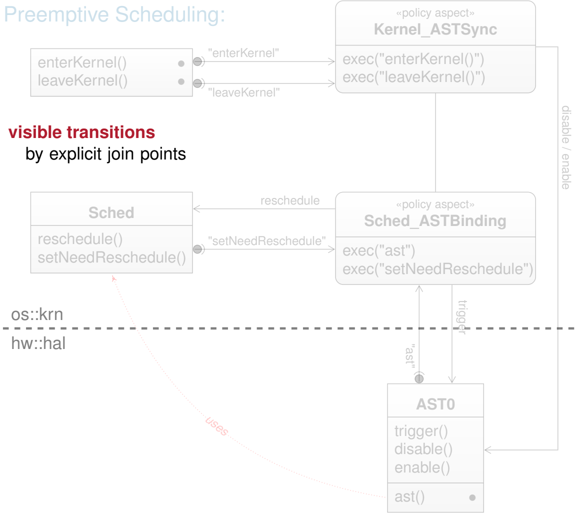
Example: Policy Integration

Cooperative Scheduling:



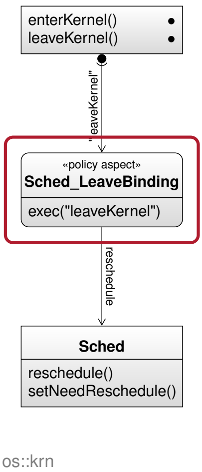
Preemptive Scheduling:

visible transitions
by explicit join points

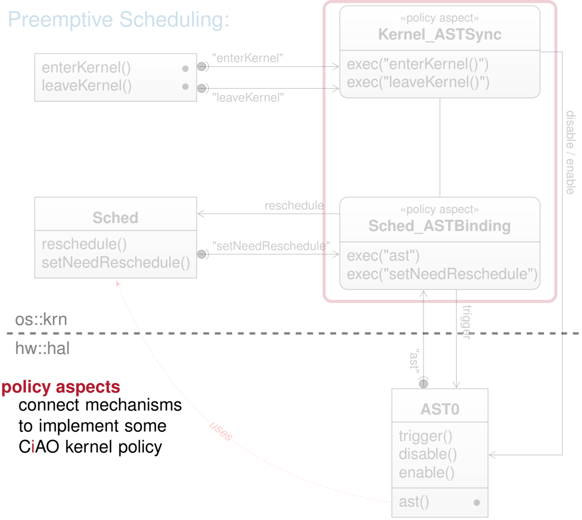


Example: Policy Integration

Cooperative Scheduling:



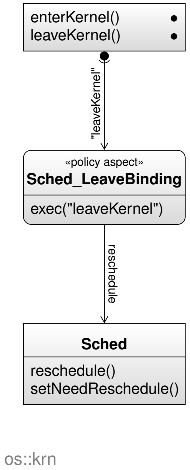
Preemptive Scheduling:



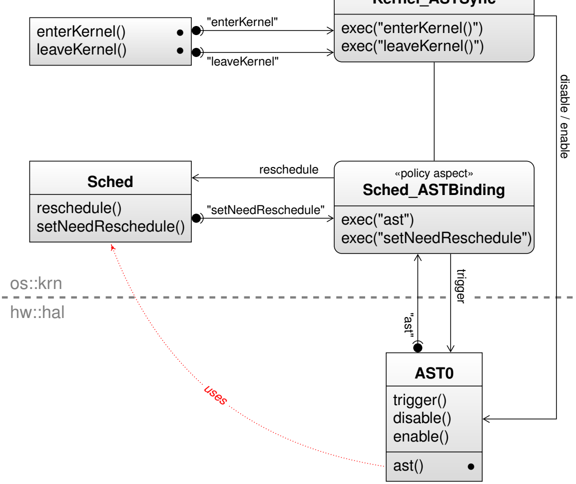
policy aspects connect mechanisms to implement some CiAO kernel policy

Example: Policy Integration

Cooperative Scheduling:



Preemptive Scheduling:



Methodology: Explicit Join Points

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

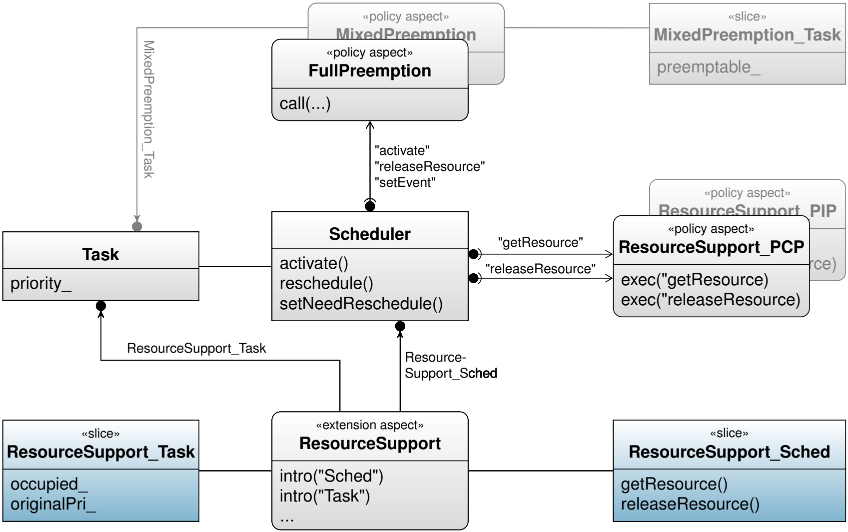
- Upcall join points (U) represent system-internal events that are to be processed on a higher layer
  - exceptions, such as signals or interrupts
  - internal events, such as system intitalization or entering of the idle state

- Transition join points (T) represent semantically important control-flow transitions inside the kernel
  - level transitions: *user* $\to$ *kernel*, *user* $\to$ *interrupt*
  - context transitions: *threadA* $\to$ *threadB*

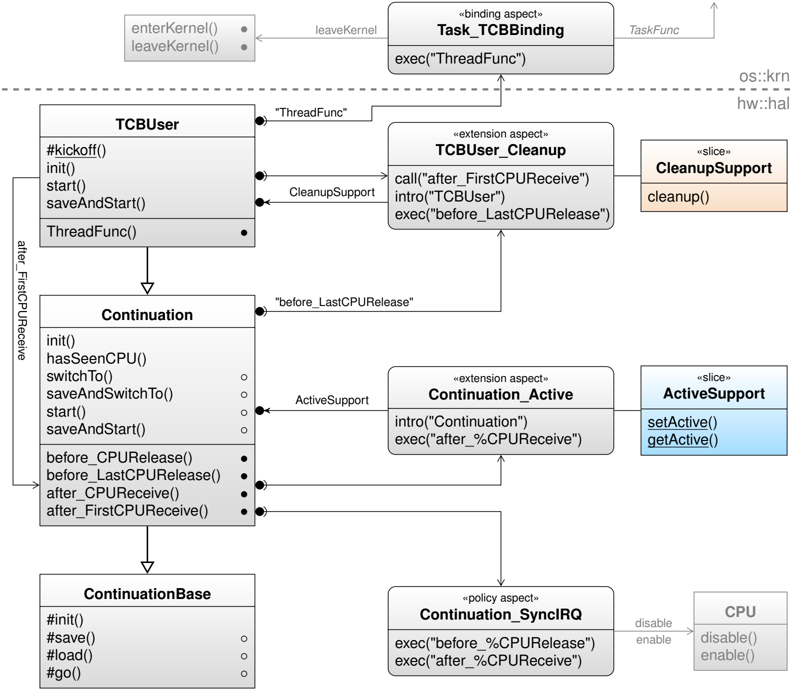
Explicit Join Points in CiAO (Excerpt) [5]

	type	representing function or method	description
os::krn	U	`interalErrorHook()`	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 *error*, a *protection* violation, before (*pre*) and after (*post*) 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.
	T	`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()`	Entry point of the respective interrupt handler. (Interrupts are still disabled.)
		...	

Example: Optional Feature Interaction [4]



Continuation: CiAO's Thread Abstraction [5]



Agenda

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		3	4	task, ISR	monitoring of Get/ReleaseResource
Event support	1			5	5	scheduler, API, task, alarm	trigger action JP
Alarm support	1			1	1	API	
OS application support	1			2	3	scheduler, task, ISR	
Full preemption		1		2	6		3 points of rescheduling
Mixed pree							
Multiple act							
Stack monitoring		1		2	3	task	CPU-release JPs
Context check		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	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 min	CiAO full	OSEK 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)

test scenario	CiAO min	CiAO full	OSEK min
(a) voluntary task switch	*160*	*178*	*218*
(b) forced task switch	*108*	*127*	*280*
(c) pr[illegible]	[illegible]	[illegible]	[illegible]
(d) sy[illegible]	[illegible]	[illegible]	[illegible]
(e) re[illegible]	[illegible]	[illegible]	[illegible]
(f) re[illegible]	[illegible]	[illegible]	[illegible]
(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*

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
Base system (OS control and tasks)				
	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*
				0
				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 $= 1/2.4$
    $\rightsquigarrow$ *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 :-)

Agenda

Summary

- Aspect-Aware Development exploits AOP mechanisms to achieve separation of concerns in configurable system software
  - Advice inverses the direction in which control-flow relationships are established: C *calls* A $\Longrightarrow$ A *advises* C
  - $\leadsto$ advice-based binding as a means to integrate (optional) features
  - Pointcuts provide for an implicit quantifiction of this integration
  - $\leadsto$ 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

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