Software Architecture
an informal introduction for CIS501

David Schmidt

Kansas State University

www.cis.ksu.edu/~schmidt

Outline

1. Components and connectors
2. Software architectures
3. Architectural description languages
4. Domain-specific design
5. Product lines
6. Middleware
7. Aspect-oriented programming
8. Closing remarks

1. Components and connectors

Programming has evolved (from the 1960s)

- Single programmer-projects have evolved into *development teams*
- Single-component applications are now *multi-component, distributed, and concurrent*
- One-of-a-kind-systems are replaced by *system families*, specialized to a problem *domain* and solution *framework*
- Built-from-scratch systems are replaced by systems composed from *Commerical-Off-The-Shelf (COTS) components* and components *reused* from previous projects

Motivation for software architecture

We use already architectural idioms for describing the structure of complex software systems:

- "Camelot is based on the *client-server model* and uses remote procedure calls both locally and remotely to provide communication among applications and servers." [Spector87]
- "The easiest way to make the canonical sequential compiler into a concurrent compiler is to *pipeline* the execution of the compiler phases over a number of processors." [Seshadri88]
- "The ARC network follows the *general network architecture* specified by the ISO in the Open Systems Interconnection Reference Model." [Paulk85]

Reference: David Garlan, *Architectures for Software Systems*, CMU, Spring 1998.

`http://www.cs.cmu.edu/afs/cs/project/tinker-arch/www/html/index.html`

Hardware architecture

There are standardized descriptions of computer hardware architectures:

- *RISC* (reduced instruction set computer)
- *pipelined architectures*
- *multi-processor architectures*

These descriptions are well understood and successful because

(i) there are a relatively small number of design components

(ii) large-scale design is achieved by replication of design elements

In contrast, software systems use a huge number of design components and scale upwards, not by replication of existing structure, but by adding more distinct design components.

Reference: D. E. Perry and A. L. Wolf. Foundations for the Study of Software Architectures. *ACM SIGSOFT Software Engineering Notes*, October 1992.

Network architecture

Again, there are standardized descriptions:

- *star* networks
- *ring* networks
- *manhattan street* (grid) networks

The architectures are described in terms of *nodes* and *connections*.
There are only a few standard topologies.

In contrast, software systems use a wide variety of topologies.

Classical architecture

The architecture of a building is described by

- *multiple views*: exterior, floor plans, plumbing/wiring, ...
- *architectural styles*: romanesque, gothic, ...
- *style and engineering*: how the choice of style influences the physical design of the building
- *style and materials*: how the choice of style influences the materials used to construct (implement) the building.

These concepts also appear in software systems: there are

(i) *views*: control-flow, data-flow, modular structure, behavioral requirements, ...

(ii) *styles*: pipe-and-filter, object-oriented, procedural, ...

(iii) *engineering*: modules, filters, messages, events, ...

(iv) *materials*: control structures, data structures, ...

A crucial motivating concept: *connectors*

The emergence of networks, client-server systems, and OO-based GUI applications led to the conclusion that

components can be *connected* in various ways

Mary Shaw stressed this point:

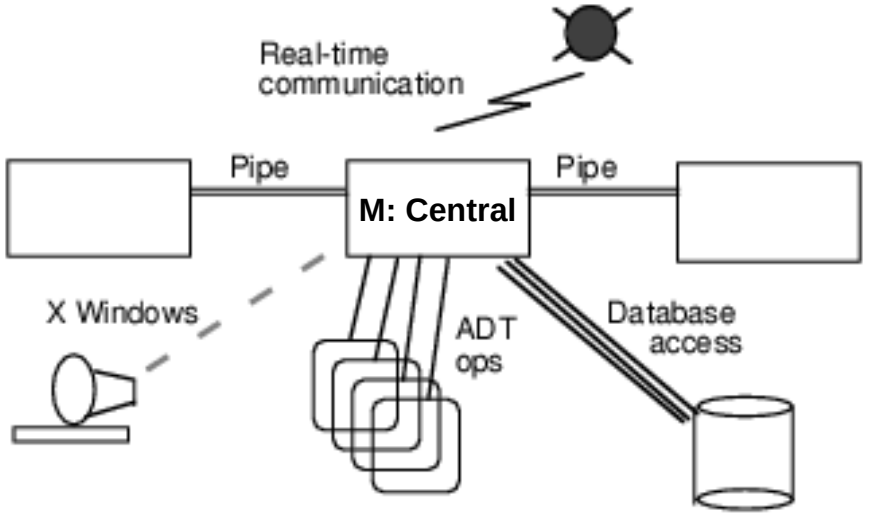


Figure 2: Revised architecture diagram with discrimination among connections

Reference: Mary Shaw, Procedure Calls are the Assembly Language of Software Interconnections: Connectors Deserve First-Class Status. Workshop on Studies of Software Design, 1993.

Shaw's observations

Connectors are forgotten because (it appears that) there are no codes for them.

But this is because the connectors must be coded in the same language as the components, which confuses the two forms.

Different forms of low-level connection (synchronous, asynchronous, peer-to-peer, event broadcast) are fundamentally different yet are all represented as procedure (system) calls in programming language.

Connectors can (and should?) be coded in languages different from the languages in which components are coded (e.g., unix pipes).

Shaw's philosophy

Components — compilation units (module, data structure, filter) — are specified by *interfaces*.

Connectors — "hookers-up" (RPC (Remote Procedure Call), event, pipe) — mediate communications between components and are specified by *protocols*.

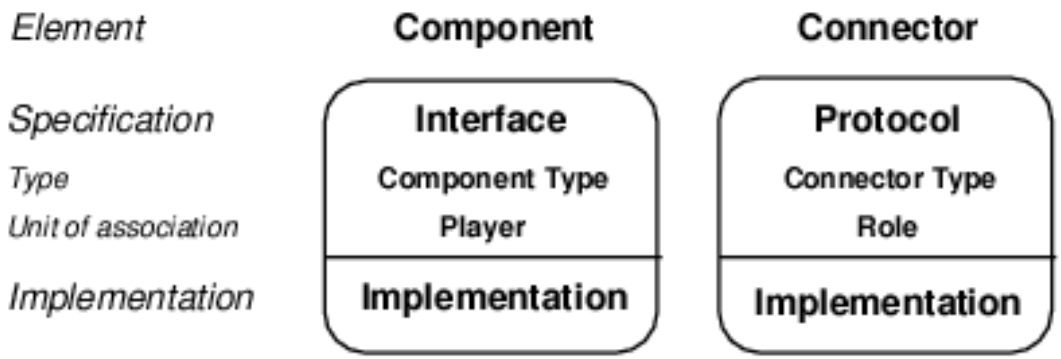


Figure 3: Gross structure of an architecture language

Example:

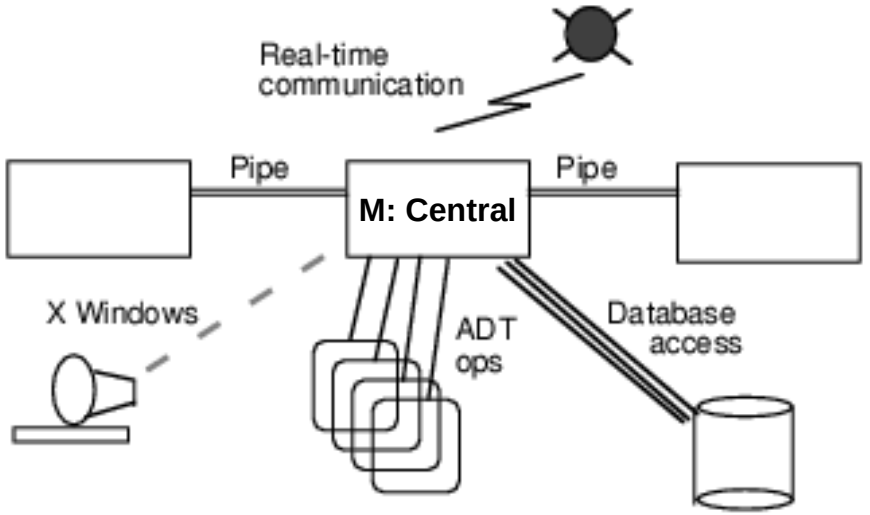


Figure 2: Revised architecture diagram with discrimination among connections

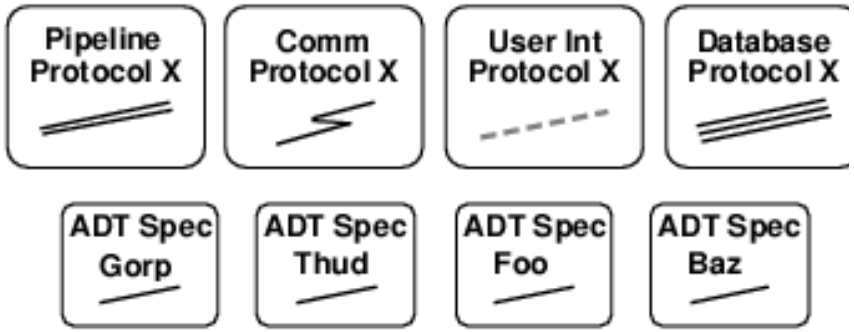


Figure 4: Constellation of protocol specifications required by exampl

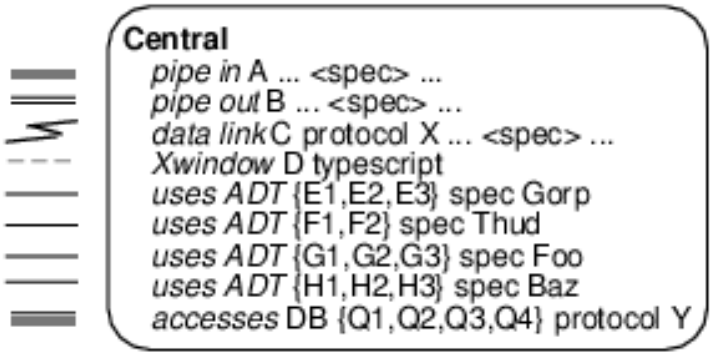


Figure 5: Interface specification of central component, referring to protocols

Interface **Central** is different from a Java-interface; it lists the “players” — `inA, outB, linkC, Gorp, Thud, ...` (connection points/ ports/ method invocations) — that use connectors.

2. Software Architecture

What is a software architecture? (Perry and Wolf)

A software architecture consists of

1. *elements*: processing elements ("functions"), connectors ("glue" — procedure calls, messages, events, shared storage cells), data elements (what "flows" between the processing elements)
2. *form*: properties (constraints on elements and system) and relationship (configuration, topology)
3. *rationale*: philosophy and pragmatics of the system: requirements, economics, reliability, performance

There can be "views" of the architecture from the perspective of the process elements, the data, or the connectors. The views might show static and dynamic structure.

Reference: D. E. Perry and A. L. Wolf. Foundations for the Study of Software Architectures. *ACM SIGSOFT Software Engineering Notes*, October 1992.

Architectural Styles (patterns)

1. *Data-flow systems:* batch sequential, pipes and filters
2. *Call-and-return systems:* main program and subroutines, hierarchical layers, object-oriented systems
3. *Virtual machines:* interpreters, rule-based systems
4. *Independent components:* communicating systems, event systems, distributed systems
5. *Repositories (data-centered systems):* databases, blackboards
6. and there are many others, including *hybrid* architectures

The *italicized* terms are the styles (e.g., *independent components*); the roman terms are architectures (e.g., communicating system). There are specific instances of the architectures (e.g., a client-server architecture is a distributed system). But these notions are not firm!

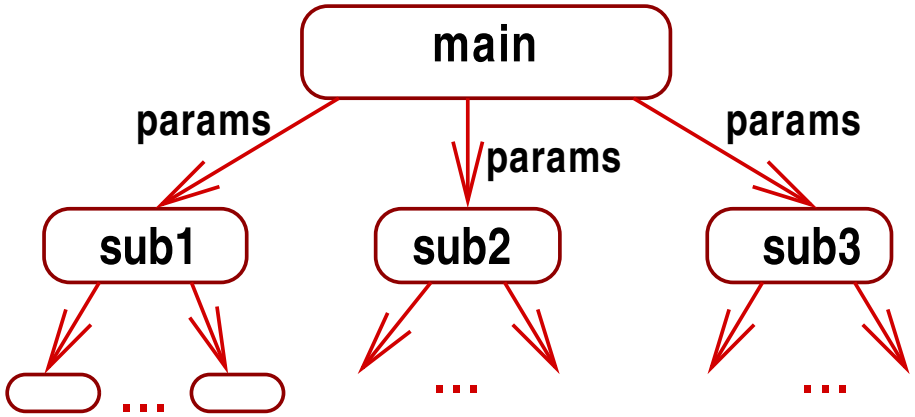
Data-flow systems: Batch-sequential and Pipe-and-filter

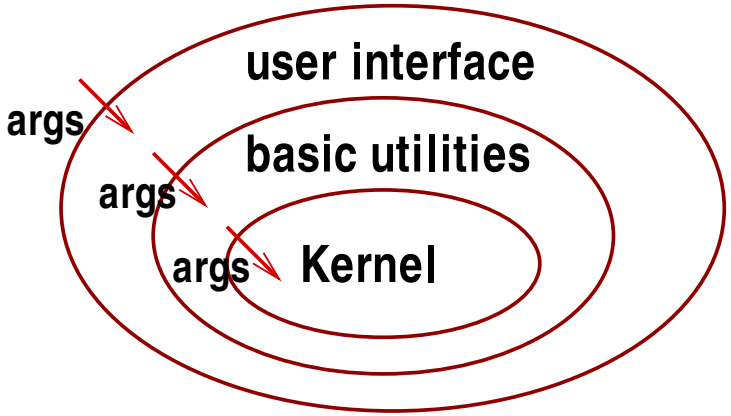
	Batch sequential	*Pipe and filter*
Components:	whole program	filter (function)
Connectors:	conventional input-output	pipe (data flow)
Constraints:	components execute to completion, consuming entire input, producing entire output	data arrives in increments to filters

Examples: Unix shells, signal processing, multi-pass compilers

Advantages: easy to unplug and replace filters; interactions between components easy to analyze. *Disadvantages:* interactivity with end-user severely limited; performs as quickly as slowest component.

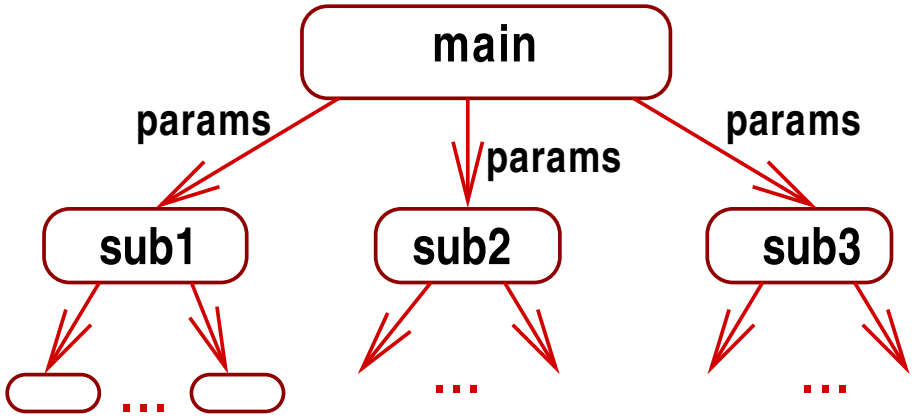
Call-and-return systems: subroutine and layered

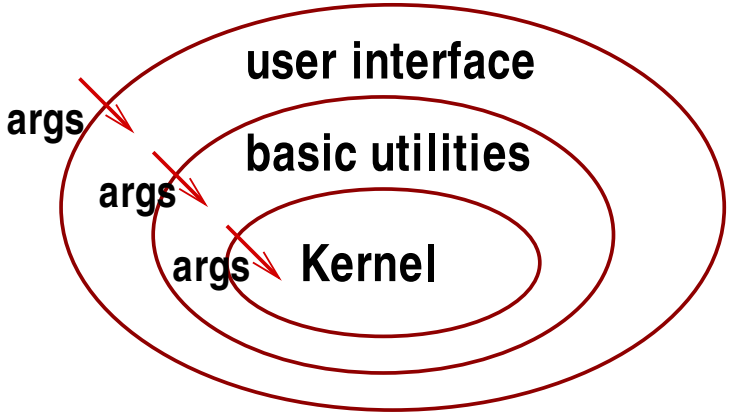




	Subroutine	*Layered*
Components:	subroutines (“servers”)	functions (“servers”)
Connectors:	parameter passing	protocols
Constraints:	hierarchical execution and encapsulation	functions within a layer invoke (API of) others at next lower layer

Examples: modular, object-oriented, N-tier systems (subroutine); communication protocols, operating systems (layered)

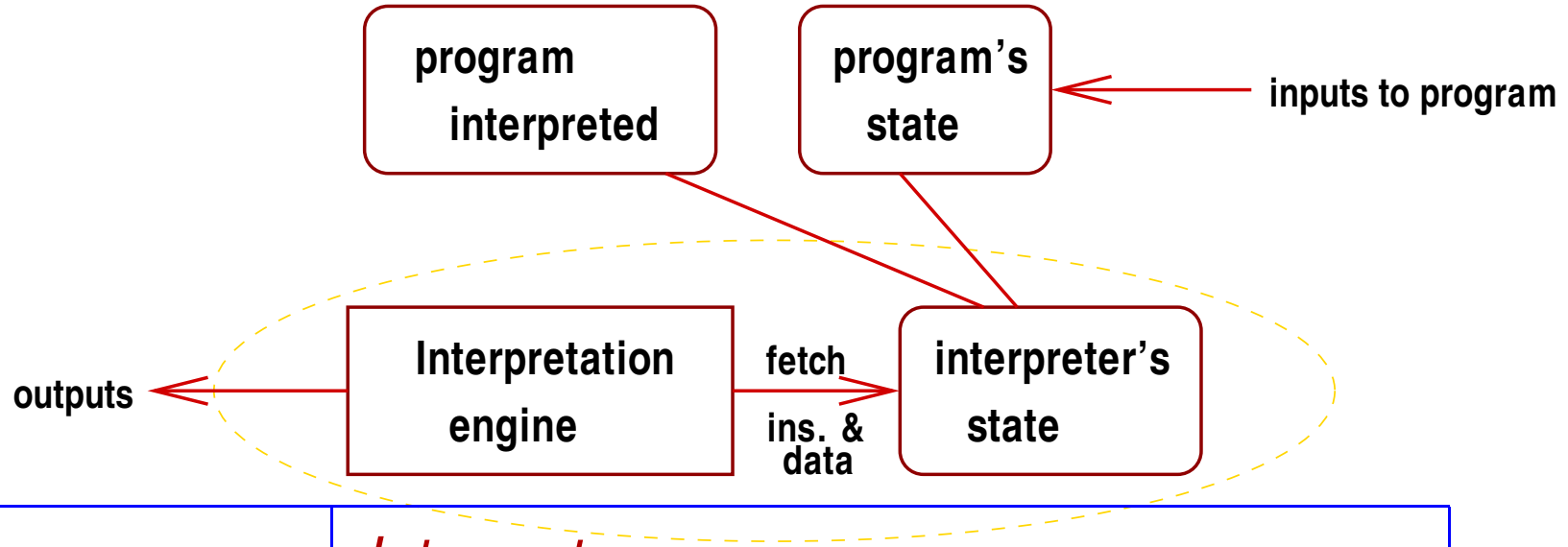




Advantages: hierarchical decomposition of solution; limits range of interactions between components, simplifying correctness reasoning; each layer defines a *virtual machine*; supports portability (by replacing lowest-level components).

Disadvantages: components must know the identities of other components to connect to them; side effects complicate correctness reasoning (e.g., `A` uses `C`, `B` uses and changes `C`, the result is an unexpected side effect from `A`'s perspective; components sensitive to performance at lower levels/layers.

Virtual machine: interpreter

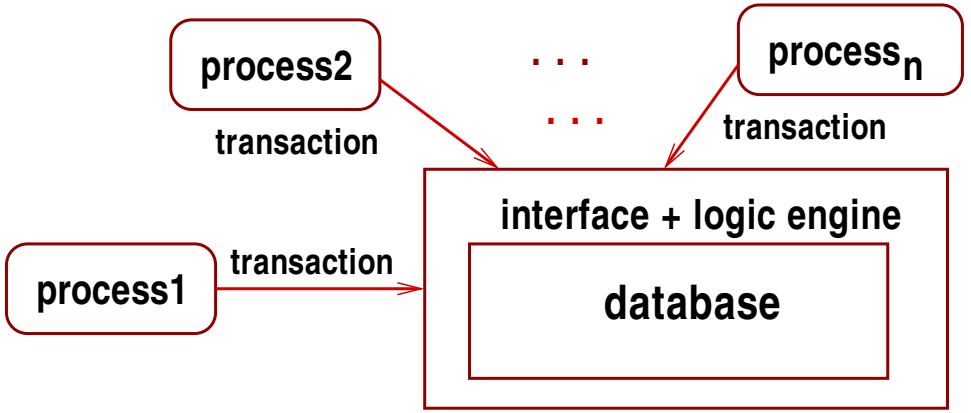


	Interpreter
Components:	"memories" and state-machine engine
Connectors:	fetch and store operations
Constraints:	engine's "execution cycle" controls the simulation of program's execution

Examples: high-level programming-language interpreters, byte-code machines, virtual machines

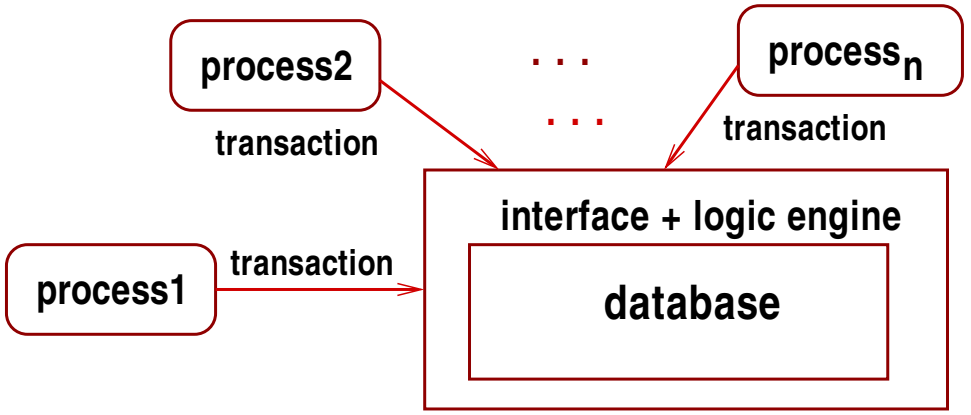
Advantages: rapid prototyping *Disadvantages:* inefficient.

Repositories: databases and blackboards



	Database	*Blackboard*
Components:	processes and database	knowledge sources and blackboard
Connectors:	queries and updates	notifications and updates
Constraints:	transactions (queries and updates) drive computation	knowledge sources respond when enabled by the state of the blackboard. Problem is solved by cooperative computation on blackboard.

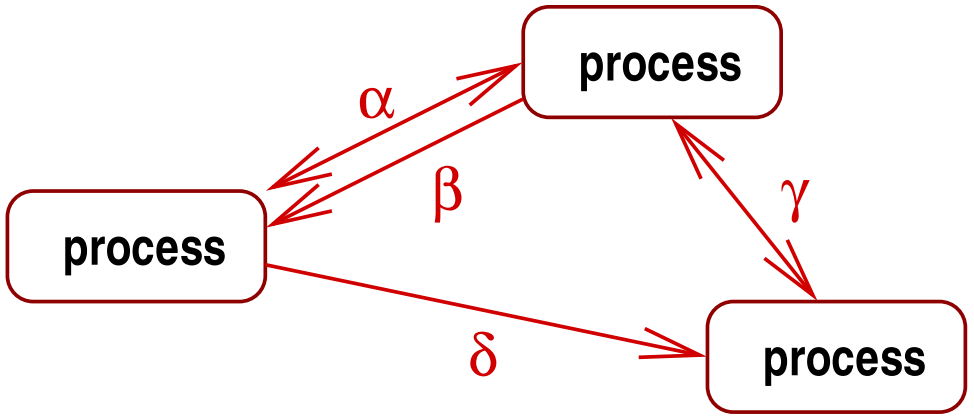
Examples: speech and pattern recognition (blackboard); syntax editors and compilers (parse tree and symbol table are repositories)



Advantages: easy to add new processes.

Disadvantages: alterations to repository affect all components.

Independent components: communicating processes

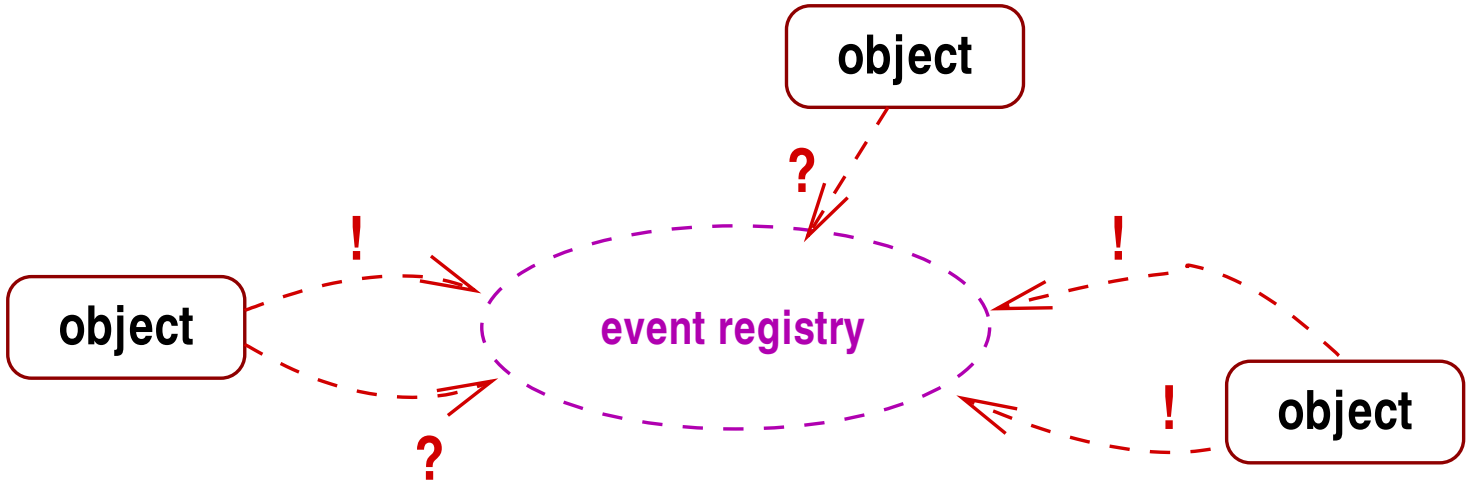


	Communicating processes
Components:	processes (“tasks”)
Connectors:	ports or buffers or RPC
Constraints:	processes execute in parallel and send messages (synchronously or asynchronously)

Example: client-server and peer-to-peer architectures

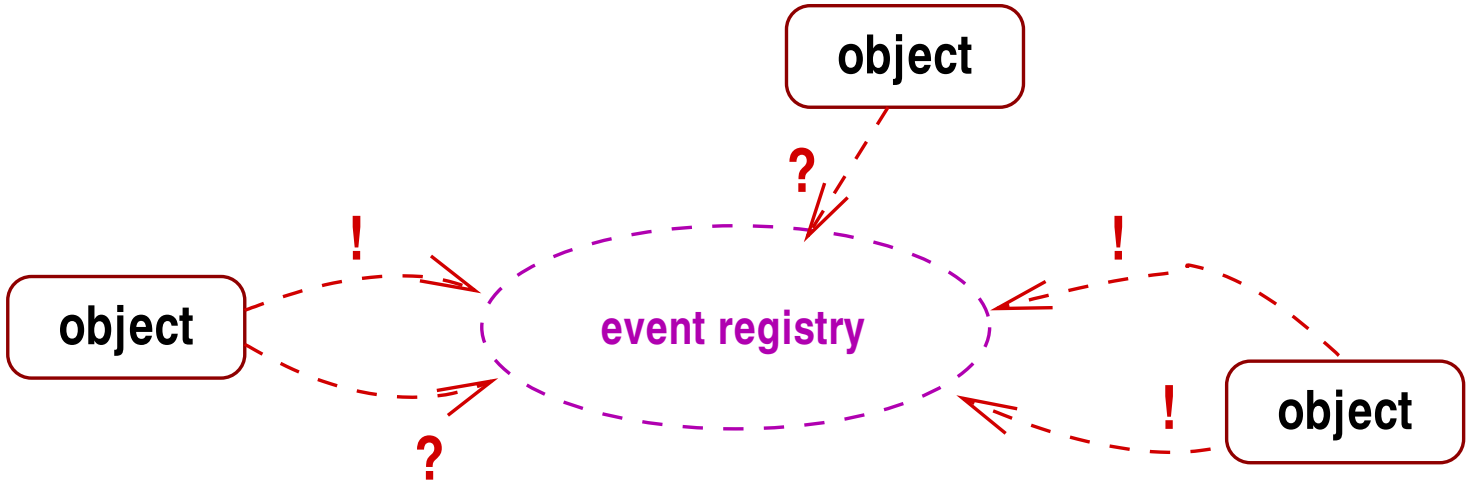
Advantages: easy to add and remove processes. *Disadvantages:* difficult to reason about control flow.

Independent components: event systems



	Event systems
Components:	objects or processes (“threads”)
Connectors:	event broadcast and notification (implicit invocation)
Constraints:	components “register” to receive event notification; components signal events, environment notifies registered “listeners”

Examples: GUI-based systems, debuggers, syntax-directed editors, database consistency checkers



Advantages: easy for new listeners to register and unregister dynamically; component reuse.

Disadvantages: difficult to reason about control flow and to formulate system-wide invariants of correct behavior.

Three architectures for a compiler (Garlan and Shaw)

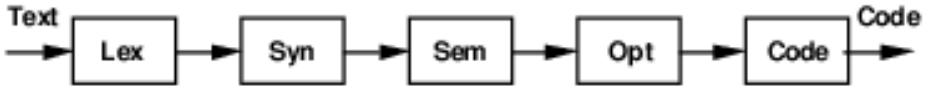


Figure 15: Traditional Compiler Model

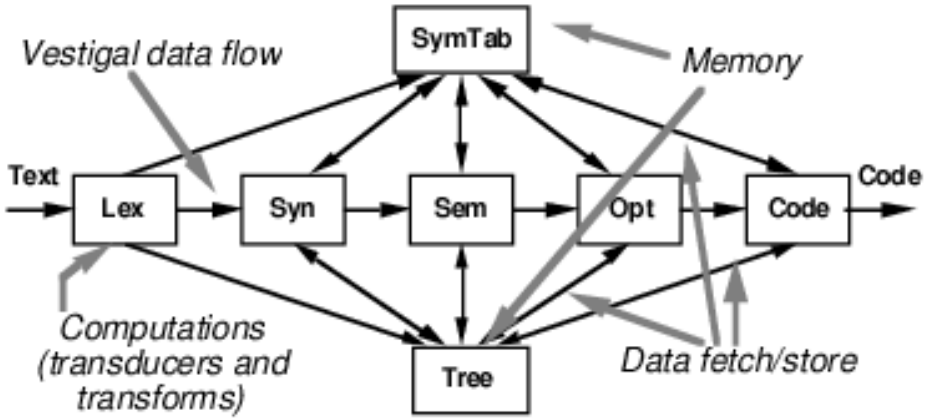


Figure 17: Modern Canonical Compiler

The symbol table and tree are "shared-data connectors"

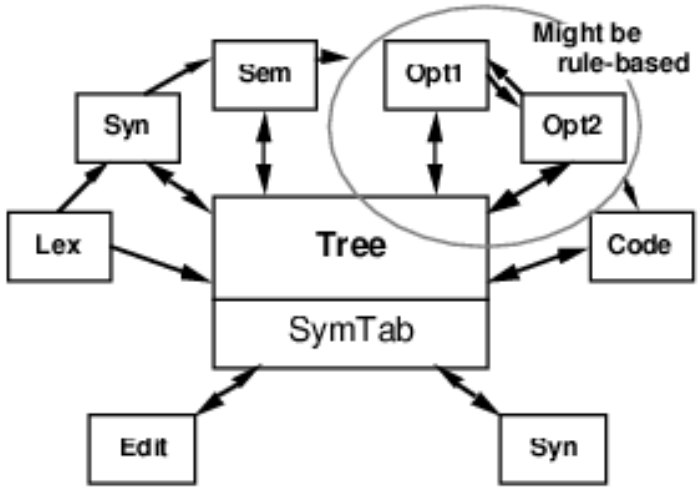


Figure 18: Canonical Compiler, Revisited

The blackboard triggers incremental checking and code generation

What do we gain from using a software architecture?

1. the architecture helps us *communicate* the system's design to the project's stakeholders (users, managers, implementors)
2. it helps us *analyze* design decisions
3. it helps us *reuse* concepts and components in future systems

4. Architecture Description Languages

A language for connectors: UniCon

Shaw developed a language, *UniCon* (*Universal Connector Language*), for describing connectors and components.

Components **are specified by** ***interfaces*****, which include**

(i) type;

(ii) attributes with values that specialize the type;

(iii) *players*, which are the component's connection points. Each player is itself typed.

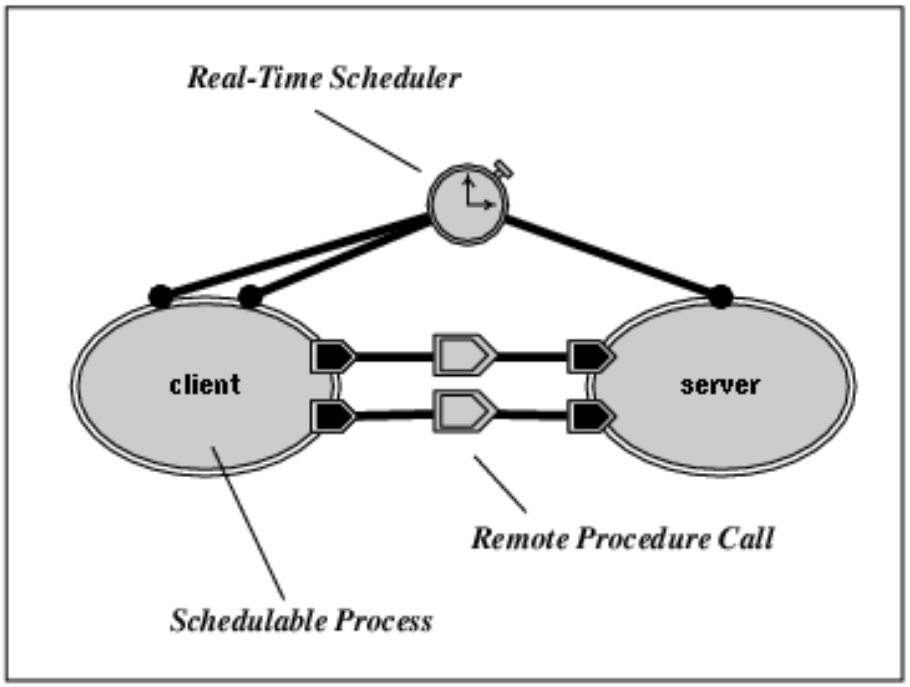
Connectors **are specified by** ***protocols*****; they have**

(i) type;

(ii) specific properties that specialize the type;

(iii) *roles* that the connector uses to mediate (make) communication between components.

Graphical depiction of an assembly of three components and four connectors:



A development tool helps the designer draw the configuration and map it to coding.

Reference: M. Shaw, R. DeLine, and G. Zelesnik, Abstractions and Implementations for Architectural Connections. In 3d Int. Conf. Configurable Distributed Systems, Annapolis, Maryland, May 1996.

```
component Real_Time_System
   interface is
      type General
   end interface

   implementation is
      uses client interface rtclient
         PRIORITY (10)
         ENTRYPOINT (client)
         end client

      uses server interface rtserver
         PRIORITY (9)
         RPCTYPEDEF (new_type; struct; 12)
         RPCTYPESIN ("unicon.h")
         end server

      establish RTM-realtime-sched with
         client.application1 as load
         client.application2 as load
         server.services as load
         ALGORITHM (rate_monotonic)
         PROCESSOR ("TESTBED.XX.EDU")
         TRACE (client.application1.
                        external_interrupt1;
            client.application1.work_block1;
            server.services.work_block1;
            client.application1.work_block2;
            server.services.work_block2;
            client.application1.work_block3)
         TRACE (client.application2.
                        external_interrupt2;
            client.application2.work_block1;
            server.services.work_block1;
            client.application2.work_block2;
            server.services.work_block2;
            client.application2.work_block3)
         end RTM-realtime-sched

      establish RTM-remote-proc-call with
         client.timeget as caller
         server.timeget as definer
         IDLTYPE(Mach)
         end RTM-remote-proc-call

      establish RTM-remote-proc-call with
         client.timeshow as caller
         server.timeshow as definer
         IDLTYPE(Mach)
         end RTM-remote-proc-call
   end implementation
end Real_Time_System
```

```
component RTClient
   interface is
      type SchedProcess
      PROCESSOR ("TESTBED.XX.EDU")
      TRIGGERDEF (external_interrupt1; 1.0)
      TRIGGERDEF (external_interrupt2; 0.5)
      SEGMENTDEF (work_block1; 0.02)
      SEGMENTDEF (work_block2; 0.03)
      SEGMENTDEF (work_block3; 0.05)
      player application1 is RTLoad
         TRIGGER (external_interrupt1)
         SEGMENTSET (work_block1,
            work_block2, work_block3)
         end application1
      player application2 is RTLoad
         TRIGGER (external_interrupt2)
         SEGMENTSET (work_block1,
            work_block2, work_block3)
         end application2
      player timeget is RPCCall
         SIGNATURE ("new_type *"; "void")
         end timeget
      player timeshow is RPCCall
         SIGNATURE ("void"; "void")
         end timeshow
   end interface


connector RTM-realtime-sched
   protocol is
      type RTScheduler
      role load is load
   end protocol

   implementation is
      builtin
   end implementation
end RTM-realtime-sched


connector RTM-remote-proc-call
   protocol is
      type RemoteProcCall
      role definer is definer
      role caller is caller
   end protocol

   implementation is
      builtin
   end implementation
end RTM-remote-proc-call
```

uses statements instantiate the parts composed

connect statements state how players satisfy roles

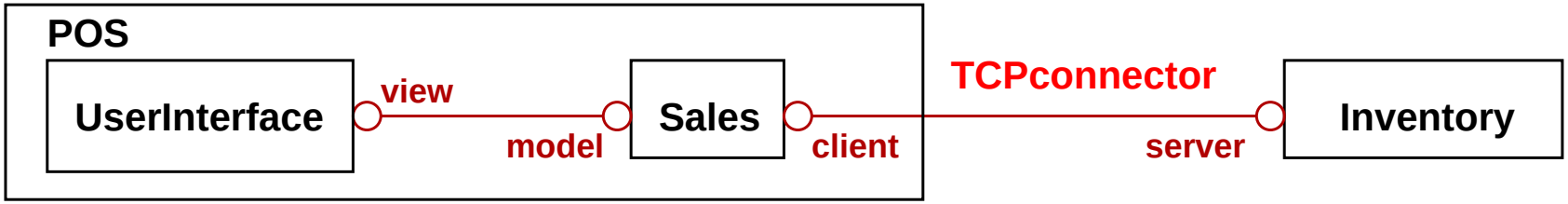
bind statements map the external interface to the internal configuration

Connectors described in UniCon:

- data-flow connectors (pipe)
- procedural connectors (procedure call, remote procedure call): pass control
- data-sharing connectors (data access): export and import data
- resource-contention connectors (RT scheduler): competition for resources
- aggregate connectors (PL bundler): compound connections

ArchJava: Java extended with Unicon features

- Each component (class) has its own interfaces (*ports*) that list which methods it `requires` and `provides`
- Connectors are coded as classes, too, and extend the basic classes, `Connector`, `Port`, `Method`, etc.
- The ArchJava run-time platform includes a run-time type checker that enforces correctness of run-time connections (e.g., RPC, TCP)
- There is an open-source implementation and Eclipse plug-in
- `www.archjava.org`




```
package pos;
…
public component class POS {
    …
    private final Sales sales = new Sales();
    private final UserInterface userInterface = new UserInterface();

    connect pattern Sales.model, UserInterface.view;
    connect pattern Sales.client, Inventory.server
        with TCPConnector {
        connect(Sales sender) throws Exception {
            return connect(sender.client, Inventory.server)
                    with new TCPConnector(connection, InetAddress.getByName(JDBC_SERVER_ADDRESS),
                                          JDBC_SERVER_PORT, JDBC_SERVER_NAME);
        }
    };

    public POS() {
        connect(sales.model, userInterface.view);
    }

    public void run() {
        sales.setData("Software Architecture in Practice, 2nd Edition");
    }

    public static void main (String[] args) {
        (new POS()).run();
    }
}
```


```
package pos;
…
public component class Sales {
    private String data;

    public port model {
        provides String getData();
        provides void setData(String data);
        requires void updated();
    }

    public port interface client {
        requires connect() throws Exception;
        requires String executeUpdate(String statement);
    }

    public String getData() {
        return data;
    }

    public void setData(String data) {
        try {
            this.data = (new client()).executeUpdate(data);
        } catch (Exception e) {
            e. printStackTrace();
        }
        model.updated();
    }
}
```


```
package pos;
…
public component class Inventory {
    public port interface server {
      provides String executeUpdate(String statement);
    }

    public String executeUpdate(String statement) {
      return statement + " (validated)";
    }

    public Inventory () {
      try {
          TCPConnector.registerObject(this, POS.JDBC_SERVER_PORT,
                                      POS.JDBC_SERVER_NAME);
      } catch (IOException e) {
          e.printStackTrace();
      }
    }

    public static void main(String[] args) {
      new Inventory();
    }
}
```

From K. M. Hansen, www.daimi.dk/~marius/teaching/ATiSA2005


```
public class TCPConnector extends Connector {
        // data members
        protected TCPEndpoint endpoint;
        // public interface
        public TCPConnector(InetAddress host, int prt, String objName) throws IOException {
                endpoint = new TCPEndpoint(this, host, prt, objName);
        }

        public Object invoke(Call call) throws Throwable {
                Method meth = call.getMethod();
                return endpoint.sendMethod(meth.getName(), meth.getParameterTypes(), call.getArguments());
        }

        public static void registerObject(Object o, int prt, String objName) throws IOException {
                TCPDaemon.createDaemon(prt).register(objName, o);
        }
        // interface used by TCPDaemon
        TCPConnector(TCPEndpoint endpoint, Object receiver, String portName) {
                super(new Object[] { receiver }, new String[] { portName });
                this.endpoint = endpoint;
                endpoint.setConnector(this);
        }
        Object invokeLocalMethod(String name, Type parameterTypes[], Object arguments[]) throws Throwable {
                // find method with parameters that match parameterTypes
                Method meth = findMethod(name, parameterTypes);
                return meth.invoke(arguments);
        }
```

A summary of some ADLs

ADL	ACME	Aesop	C2	Darwin	MetaH	Rapide	UniCon	Wright
Focus	Architectural interchange, predominantly at the structural level	Specification of architectures in specific styles	Architectures of highly-distributed, evolvable, and dynamic systems	Architectures of highly-distributed systems whose dynamism is guided by strict formal underpinnings	Architectures in the guidance, navigation, and control (GN&C) domain	Modeling and simulation of the dynamic behavior described by an architecture	Glue code generation for interconnecting existing components using common interaction protocols	Modeling and analysis (specifically, deadlock analysis) of the dynamic behavior of concurrent systems

From K. M. Hansen, `www.daimi.dk/~marius/teaching/ATiSA2005`

Features / *ADL*	Active Specification	Multiple Views	Analysis	Refinement	Implementation Generation	Dynamism
ACME	none	textual; "weblets" in ACME-Web; architecture views in terms of high-level (template), as well as basic constructs	parser	none	none	none
Aesop	syntax-directed editor for components; visualization classes invoke specialized external editors	textual and graphical; style-specific visualizations; component and connector types distinguished iconically	parser; style-specific compiler; type checker; cycle checker; checker for resource conflicts and scheduling feasibility	none	*build* tool constructs system glue code in C for pipe-and-filter style	none
C2	proactive "architecting" process in DRADEL; reactive, non-intrusive type checker; design critics and to-do lists in *Argo*	textual and graphical; view of development process	parser; style rule checker; type checker	generates application skeletons which can be completed by reusing OTS components	class framework enables generation of C/C++, Ada, and Java code; DRADEL generates application skeletons	*ArchStudio* allows unanticipated dynamic manipulation of architectures
Darwin	automated addition of ports to communicating components; propagation of changes across bound ports; dialogs to specify component properties;	textual, graphical, and hierarchical system view	parser; compiler; "what if" scenarios by instantiating parameters and dynamic components	compiler; primitive components are implemented in a traditional programming language	compiler generates C++ code	compilation and runtime support for *constrained* dynamic change of architectures (replication and conditional configuration)
MetaH	graphical editor requires error correction once architecture changes are *applied*; constrains the choice of component properties via menus	textual and graphical; component types distinguished iconically	parser; compiler; schedulability, reliability, and security analysis	compiler; primitive components are implemented in a traditional programming language	DSSA approach; compiler generates Ada code	none
Rapide	none	textual and graphical; visualization of execution behavior by animating simulations	parser; compiler; analysis via event filtering and animation; constraint checker to ensure valid mappings	compiler for executable sublanguage; tools to compile and verify event pattern maps during simulation	executable simulation construction in Rapide's executable sublanguage	compilation and runtime support for *constrained* dynamic change of architectures (conditional configuration)
UniCon	graphical editor prevents errors during design by invoking language checker	textual and graphical; component and connector types distinguished iconically	parser; compiler; schedulability analysis	compiler; primitive components are implemented in a traditional programming language	compiler generates C code	none
Wright	none	textual only; model checker provides a textual equivalent of CSP symbols	parser; model checker for type conformance of ports to roles; analysis of individual connectors for deadlock	none	none	none

So, what is an architectural description language?

It is a notation (linear or graphical) for specifying an architecture.

It should specify

- *structure*: components (interfaces), connectors (protocols), configuration (both static and dynamic structure)
- *behavior*: semantical properties of individual components and connectors, patterns of acceptable communication, global invariants,
- *design patterns*: global constraints that support correctness-reasoning techniques, design- and run-time tool support, and implementation.

But it is difficult to design a *general-purpose* architectural description language that is *elegant*, *expressive*, and *useful*.

5. Domain-specific design

Domain-specific design

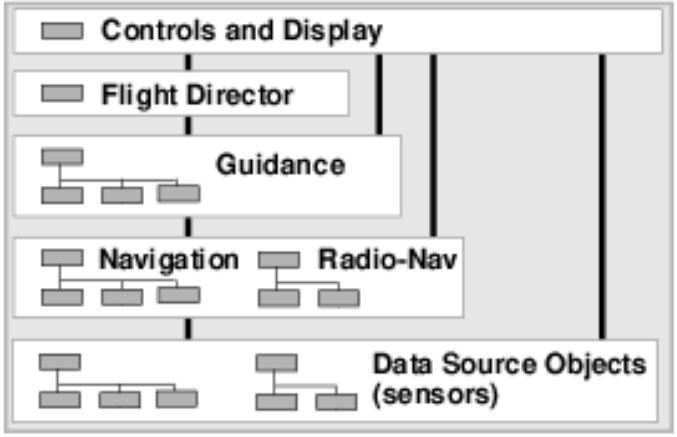
If the problem domain is a standard one (e.g., flight-control or telecommunications or banking), then there are precedents to follow.

A *Domain-Specific Software Architecture* has

- a *domain*: defines the problem area domain concepts and terminology; customer requirements; scenarios; configuration models (entity-relationship, data flow, etc.)
- *reference requirements*: *features* that restrict solutions to fit the domain. ("Features" are studied shortly.) Also: platform, language, user interface, security, performance
- a *reference architecture*
- a *supporting environment/infrastructure*: tools for modelling, design, implementation, evaluation; run-time platform
- a *process* or *methodology* to implement the reference architecture and evaluate it.

Avionics DSSA

- **A**vionics **D**omain **A**pplication **G**eneration **E**nvironment
- Layered reference architecture
  - subsystems decomposed into primitive components with standardized interfaces
  - over 40 different realms with over 350 distinct components
    - realm $\equiv$ { x : component | ($\forall$i,j)(x_i.interface = x_j.interface) }
- ADAGE reference architecture model:



  - reference architecture is defined by component realms and domain-specific composition constraints
  - even simple avionics systems often require over 50 distinct components stacked 15 layers deep

from Medvidovic's course, `http://sunset.usc.edu/classes/cs578_2002`

Domain-specific (modelling) language (DSL)

is a modelling language specialized to a specific problem domain, e.g., telecommunications, banking, transportation.

We use a DSL to describe a problem and its solution in concepts familiar to people who work in the domain.

It might define (entity-relationship) models, ontologies (class hierarchies), scenarios, architectures, and implementations.

Example: a DSL for sensor-alarm networks: *domains:* sites (building, floor, hallway, room), devices (alarm, movement detector, camera, badge), people (employee, guard, police, intruder). Domain elements have *features/attributes* and *operations*. *Actions* can be by initiated by *events* — "when a movement detector detects an intruder in a room, it generates a movement-event for a camera and sends a message to a guard...."

When a DSL can generate computer implementations, it is a *domain-specific programming language*.

Domain-specific programming language

In the Unix world, these are "little languages" or "mini-languages," designed to solve a specific class of problems. Examples are `awk`, `make`, `lex`, `yacc`, `ps`, and `Glade` (for GUI-building in X).

Other examples are Excel, HTML, XML, SQL, regular-expression notation and BNF. These are called *top-down* DSLs, because they are designed to implement domain concepts and nothing more. Non-programmers can use a top-down DSL to write solutions.

The *bottom-up* approach, called *embedded* or *in-language DSL*, starts with a dynamic-data-structure language, like Scheme or Perl or Python, and adds libraries (modules) of functions that encode domain-concepts-as-code, thus "building the language upwards towards the problem to be solved." Experienced programmers use bottom-up DSLs to program solutions.

Tradeoffs in using (top-down) DSLs

- ✔ non-programmers can discuss and use the DSL
- ✔ the DSL supports patterns of design, implementation, and optimization
- ✔ fast development
- ✘ staff must be trained to use the DSL
- ✘ interaction of DSL-generated software with other software components can be difficult
- ✘ there is high cost in developing and maintaining a DSL

Reference: J. Lawall and T. Mogensen. Course on Scripting Languages and DSLs, Univ. Copenhagen, 2006, `www.diku.dk/undervisning/2006f/213`

6. Software product lines

A software product line

is also called a *software system family* — a collection of software products that share an architecture and components, constructed by a product line. They are inspired by the products produced by industrial assembly lines, e.g., automobiles.

The CMU Software Engineering Institute definition:

A *product line* is a set of software intensive systems that
(i) share a common set of features,
(ii) satisfy the needs of a particular mission, and
(iii) are developed from a set of core assets in a prescribed way.

Key issues:

variability: Can we state precisely the products' variations (*features*) ?

guidance: Is there a precise recipe that guides feature selection and product assembly?

Reference: `www.softwareproductlines.com`

An example product line: Cummins Corporation

produces diesel engines for trucks and heavy machinery. An engine controller has 100K-200K lines-of-code. At level of 12 engine "builds," company switched to a product line approach:

1. defined engine controller domain
2. defined a reference architecture
3. built reusable components
4. required all teams to follow product line approach

Cummins now produces 20 basic "builds" — 1000 products total; development time dropped from 250 person/months to < 10. A new controller consists of 75% reused software.

Reference: S. Cohen. Product line practice state of the art report. CMU/SEI-2002-TN-017.

Features and feature diagrams

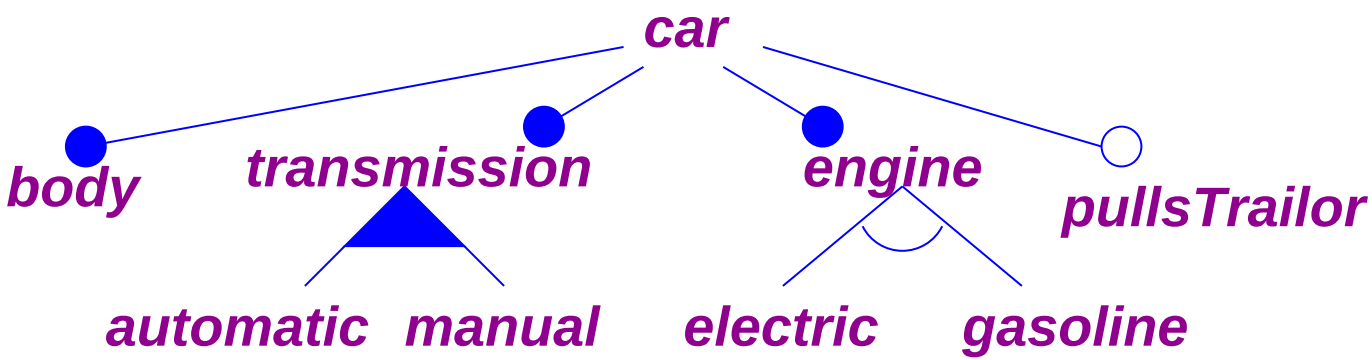
are a development tool for domain-specific architectures and product lines. They help define a domain's reference requirements and guide implementions of instances of the reference architecture.

A *feature* is merely a property of the domain. (Example: the features/options/choices of an automobile that you order from the factory.)

A *feature diagram* displays the features and guides a user in choosing features for the solution to a domain problem.

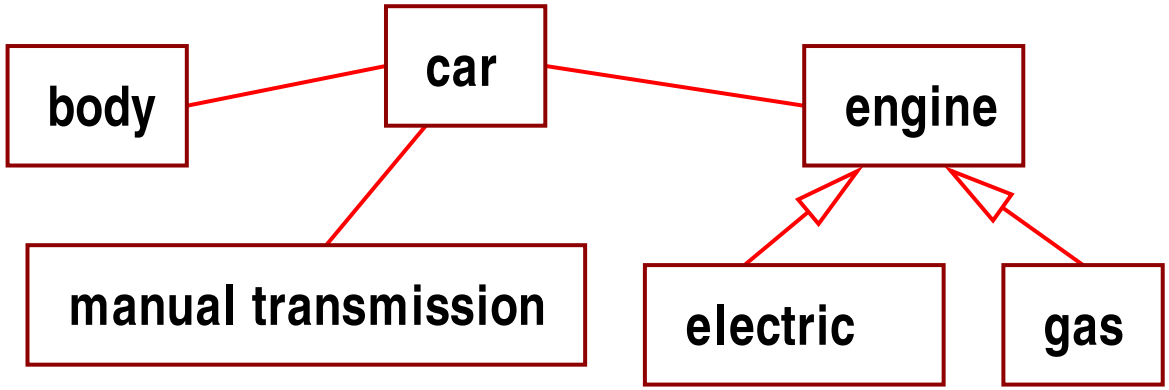
It is a form of decision tree with *and-or-xor* branching, and its hierarchy reflects dependencies of features as well as modification costs.

Feature diagram for assembling automobiles

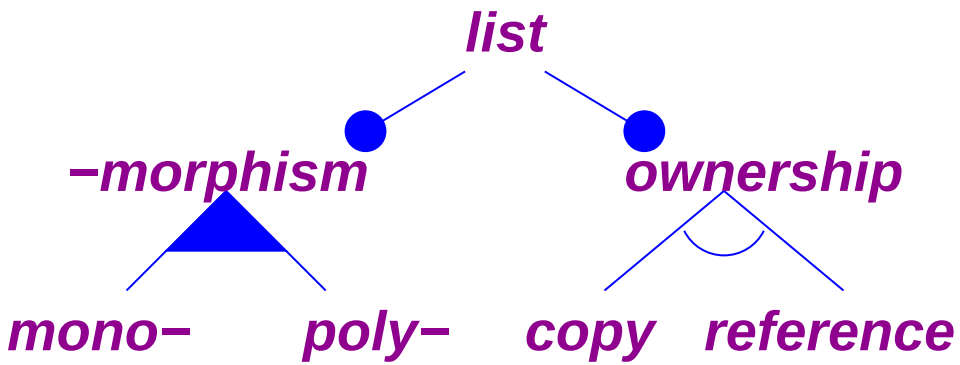


Filled circles label required features; unfilled circles label optional ones. Filled arcs label xor-choices; unfilled arcs label or-choices (where at least one choice is selected).

Here is one possible outcome of “executing” the feature diagram:



Feature diagrams work well for configuring generic data structures:



Compare the diagram to the typical class-library representation of a generic list structure.

An advantage of a feature-diagram construction of a list structure over a class-library construction is that the former can generate a smaller, more efficient list structure, customized to exactly the choices of the client.

Feature diagrams are useful for both *constraining* as well as *generating* an architecture: the feature requirements are displayed in a feature diagram, which guides the user to generating the desired instance of the reference architecture.

Feature diagrams are an attempt at making software assembly appear similar to assembly of mass-produced products like automobiles.

In particular, feature diagrams encourage the use of *standardized, parameterized, reusable software components*.

Feature diagrams might be implemented by a tool that selects components according to feature selection. Or, they might be implemented within the structure of a *domain-specific programming language* whose programs select and assemble features.

Reference: K. Czarnecki and U. Eisenecker. *Generative Programming.* Addison-Wesley 2000.

7. Middleware

Middleware: a popular form of domain-specific software architecture

Middleware lies between hardware and software in the design of independent-component (e.g., client-server) architectures. Middleware is also called a *distributed component platform.* It gives

- *standards* for writing the APIs (and code) for components (and connectors) so that they can connect, communicate, and be reused. The standards are independent of any particular programming language, allowing *heterogeneous* (different styles of) components to be used together.
- *prebuilt components, connectors, and interfaces,* along with a *development environment*, for assembling an architecture.

Middleware provides "smart" connectors that hide the details behind communication. The user writes components that conform to the middleware's standards/APIs.

CORBA: Common Object Request Broker Architecture

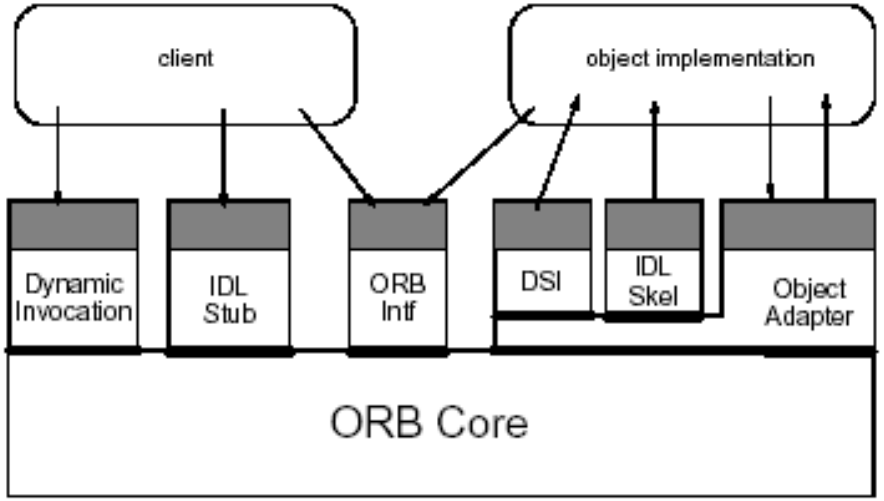
CORBA is middleware for building distributed, object-based, client-server architectures; developed by the Object Management Group (OMG).

Components communicate through a centralized service, the *Object Request Broker* (*ORB*).

An object can be a *client* or a *server* (or both).

To use the ORB, a server component must implement an API (interface) that lets it connect to an *object adapter*, which itself connects to the ORB. (Object adapters contain code for object registration with a global naming service, reference generation, and server activation).

Object adapters are available in Java, C++, Perl, etc.; components are written in these languages and communicate via procedure calls.



The physical locations of objects are hidden — references, held in a naming service, are used instead.

The implementations of objects are hidden.

The communications protocols (TCP/IP, RPC, ...) are hidden.

Only the interfaces are known.

Diagram is from: S. Vinoski. CORBA: Integrating Diverse Applications Within Distributed Heterogeneous Environments. *IEEE Communications*, Feb. 1997.

How connectors work

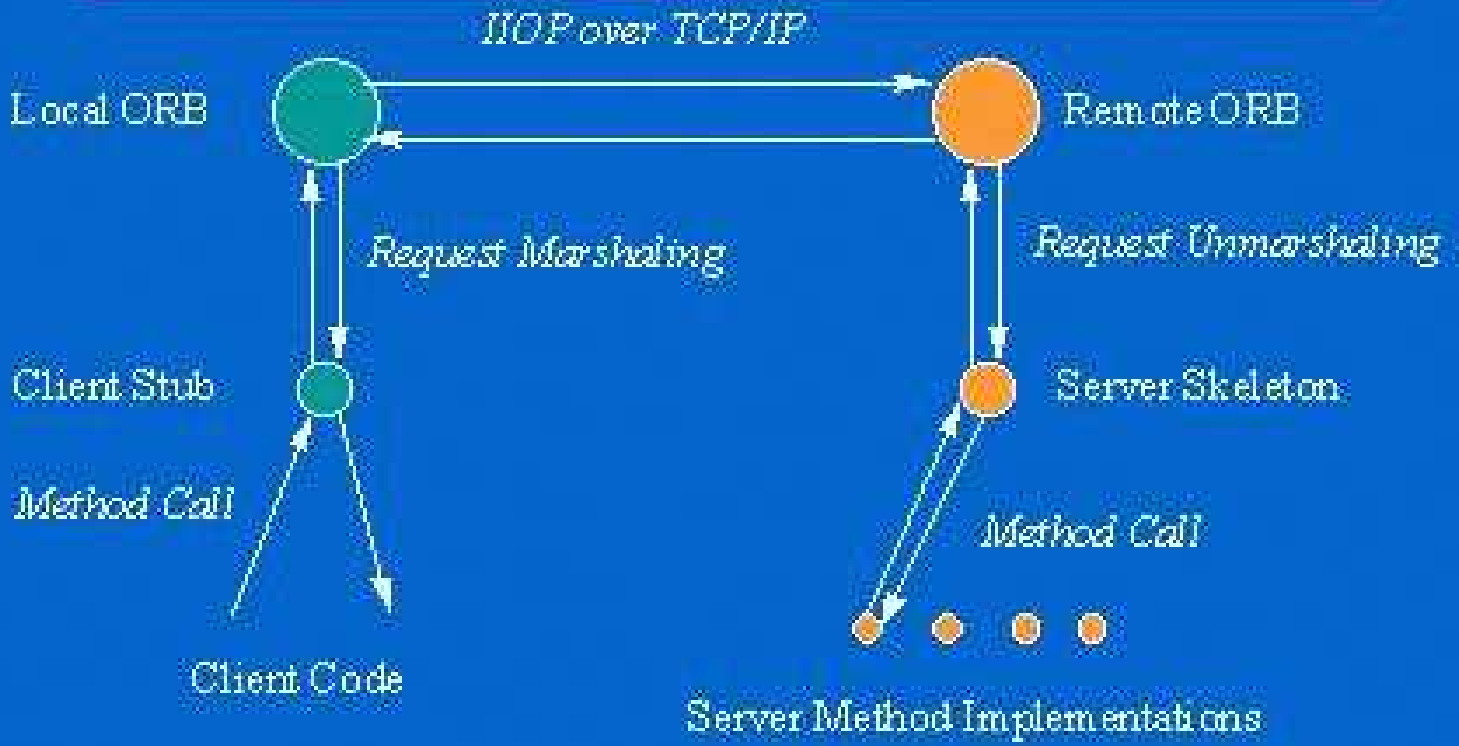
A client knows the API of the server it wishes to use.

The client uses the naming service to obtain a reference to a server; the reference is used to obtain a local copy of the server object, a "proxy," called a *stub*. To send a request, the client invokes a method of the stub. The stub encodes (*marshalls*) the request and forwards it to the ORB, which transmits it to the true server object.

The request is received by the server's *skeleton*, which decodes (*unmarshalls*) the request and invokes the appropriate method of the server.

The result is returned along the same "path."

Let's look at that one up close...



From the client's perspective, a send connection looks like a method invocation:

> Language mappings usually map operation invocation to the equivalent of a function call in the programming language. For example, given a `Factory` object reference in C++, the client code to issue a request looks like this:
>
> ```
> // C++
> Factory_var factory_objref;
>
> // Initialize factory_objref using Naming or
> // Trading Service (not shown), then issue request
> Object_var objref = factory_objref->create();
> ```
>
> This code makes the invocation of the `create` operation on the target object appear as a regular C++ member function call. However, what this call is really doing is invoking a stub. Because the stub essentially is a stand-in within the local process for the actual (possibly remote) target object, stubs are sometimes called *surrogates* or *proxies*. The stub works directly with the client ORB to *marshal* the request.

Reference: S. Vinoski. CORBA. *IEEE Communications*, Feb. 1997.

CORBA has become popular because it is a *standard* that is *supported* by many programming languages. Its architecture is useful because it allows *heterogenous components* that communicate by *implementing interfaces*: the ORB interfaces, the object-adapter interfaces, the stub and skeleton interfaces.

But CORBA has some disadvantages, too:

- the architecture is difficult to optimize
- there is no deadlock detection nor garbage collection (in the middleware)
- *all objects are treated as potentially remote*
- all object's references are stored in a global database

DCOM: Microsoft's Distributed Object Component Model (now in .NET)

has similar objectives and structure as CORBA but tries to address some of CORBA's deficiencies:

supports reference-counting garbage collection (uses "pinging" to detect inactive clients)

batches together multiple method calls (and pings) to minimize network "round trips"

exploits locality: thread-local and machine-local method calls are implemented more efficiently than RPCs. Uses a *virtual table* to standardize method call lookup and hide the differences between implementations

makes it easier to program proxy objects and implement dynamic load balancing

allows a component to learn dynamically the interface of another.

But it uses a different IDL and interfaces than CORBA's)-:

Figure 1 - COM Components in the same process

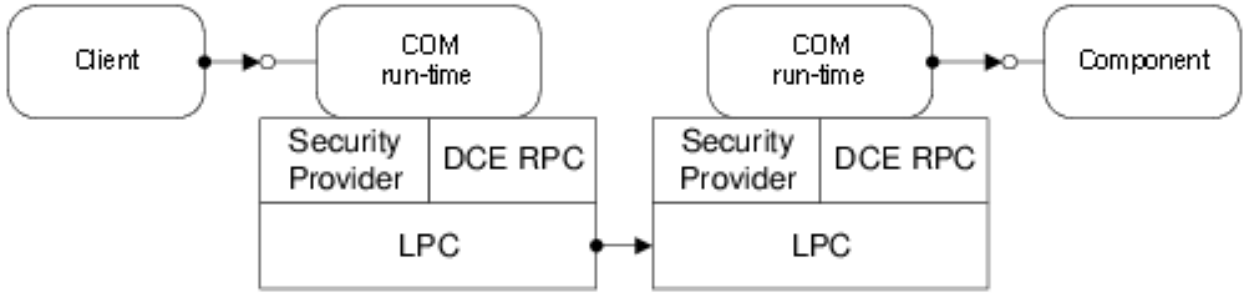


Figure 2 - COM Components in different processes

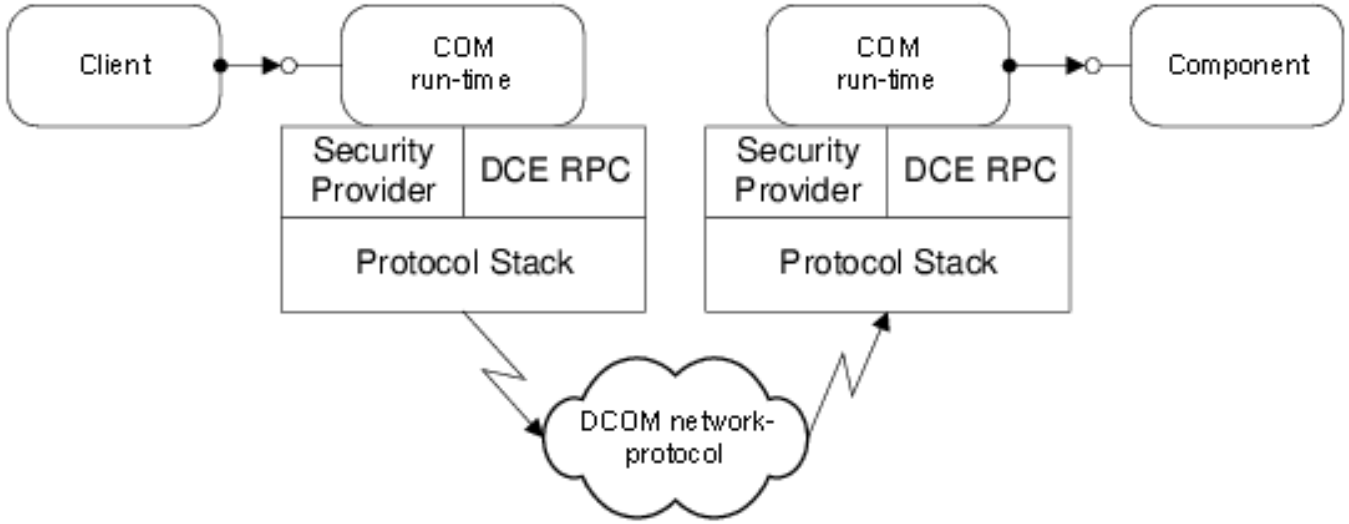


Figure 3 - DCOM: COM Components on different machines

Reference: DCOM Technical Overview. Microsoft Windows/NT white paper, 1996.

Java beans: middleware for Java

A Java *bean* is a reusable (Java-coded) component, that can be manipulated (its attributes set and its methods executed) both at *design-time* and *run-time*.

For this reason, a bean has a *design-time interface* and a separate *run-time interface* — this is the key architectural concept for beans.

The design-time interface almost always includes a GUI that is displayed by the builder tool.

The run-time interface lists properties (attributes), methods, and events that the bean possesses.

The interfaces are more general than usual: they include “properties” (attributes – local state), methods, and event broadcast-listening. The interfaces need not be written by the programmer; they can be extracted from the bean by a development tool.

A development tool (the *bean box*) uses a bean’s design-time

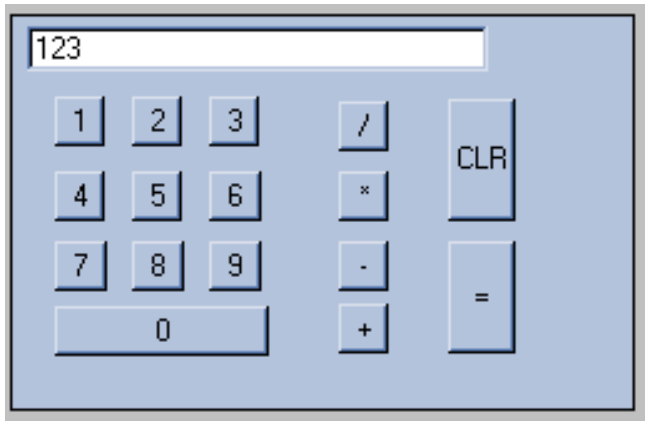
interface to help an application builder position a bean in the application, customize its appearance, and select its run-time behaviors (methods).

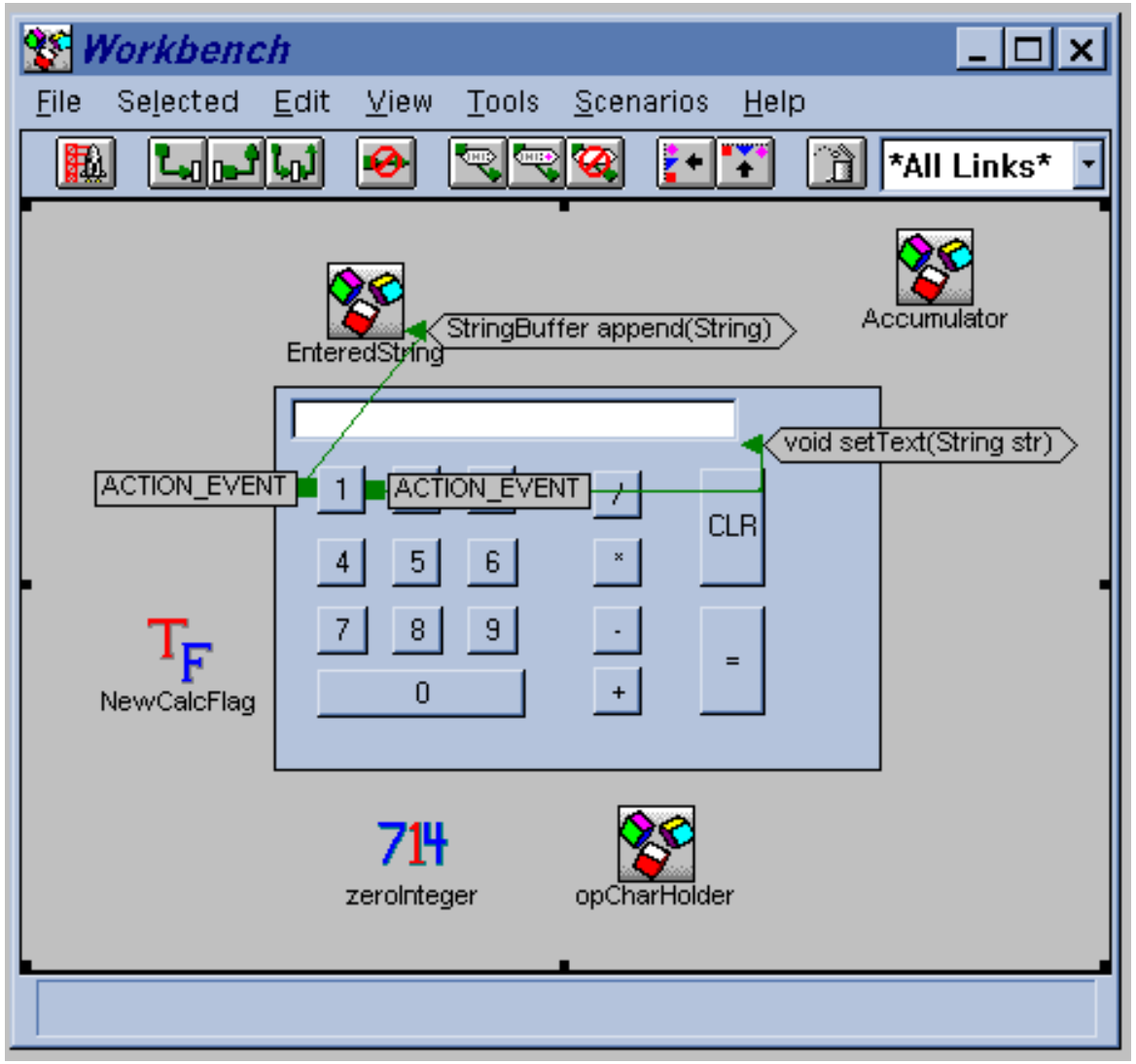
Java beans were originally tailored towards GUI-building applications — buttons, text fields, and sliders are obvious candidates for beans — but the concept also works for data structures and algorithms.

Examples:

- insert a sorting-algorithm-bean into a spreadsheet bean
- insert a spreadsheet bean into a table bean
- insert a table bean into a web-page bean

A calculator and its assembly via beans:





Examples are from `http://www.tcs.tifr.res.in/man/javaTutorial/beans`

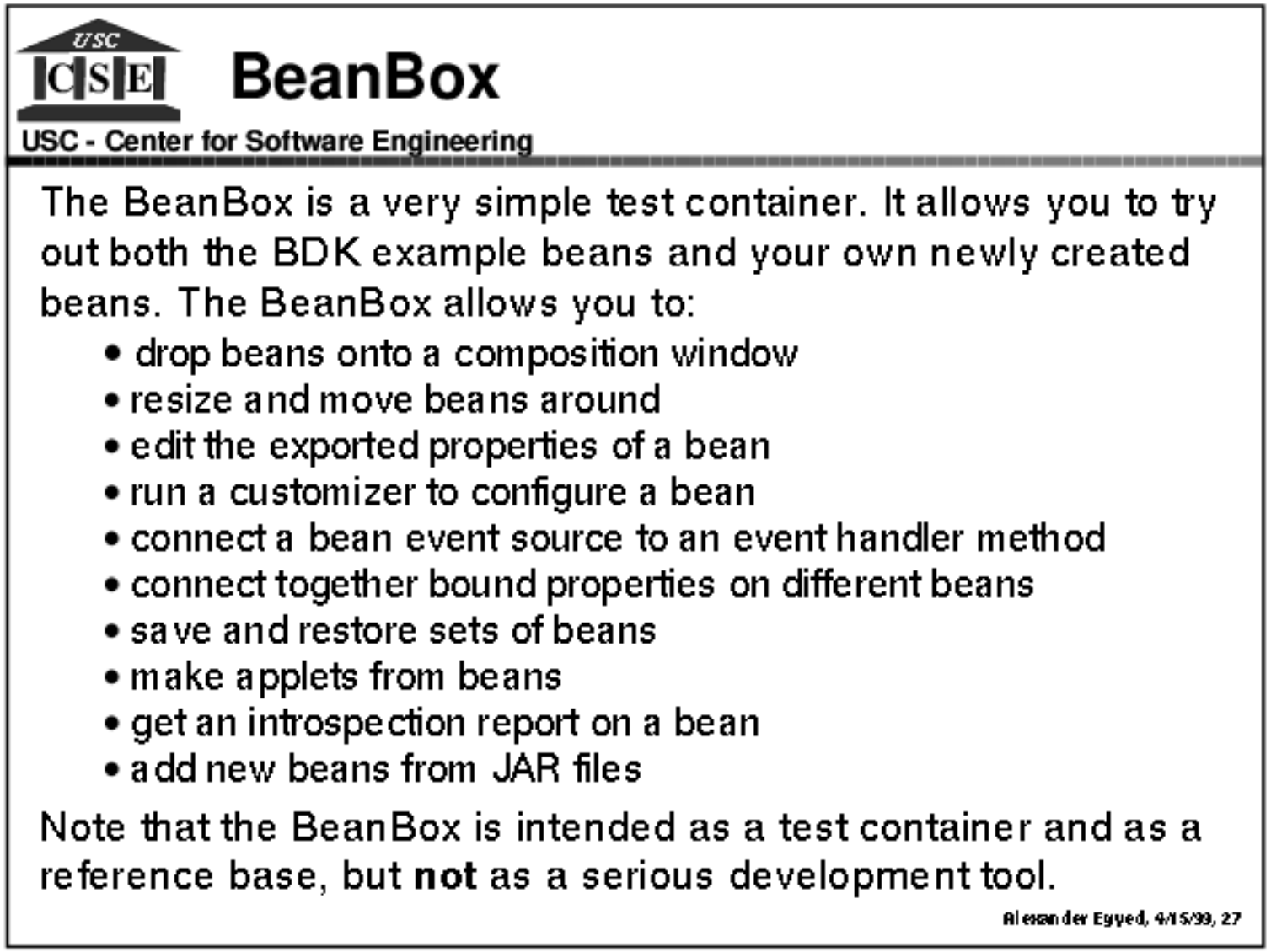
Java beans communicate by Java-style event broadcast; a bean can be an *event source* or an *event listener* or both.

Beans execute within a run-time environment, a form of middleware. The environment broadcasts and delivers events; it rests on top of the Java Virtual Machine.

Because it is complex to construct the design-time and run-time interfaces, beans have an *introspection* facility, based on a Java `interface Property`, which the development tool uses to extract the bean's interfaces.

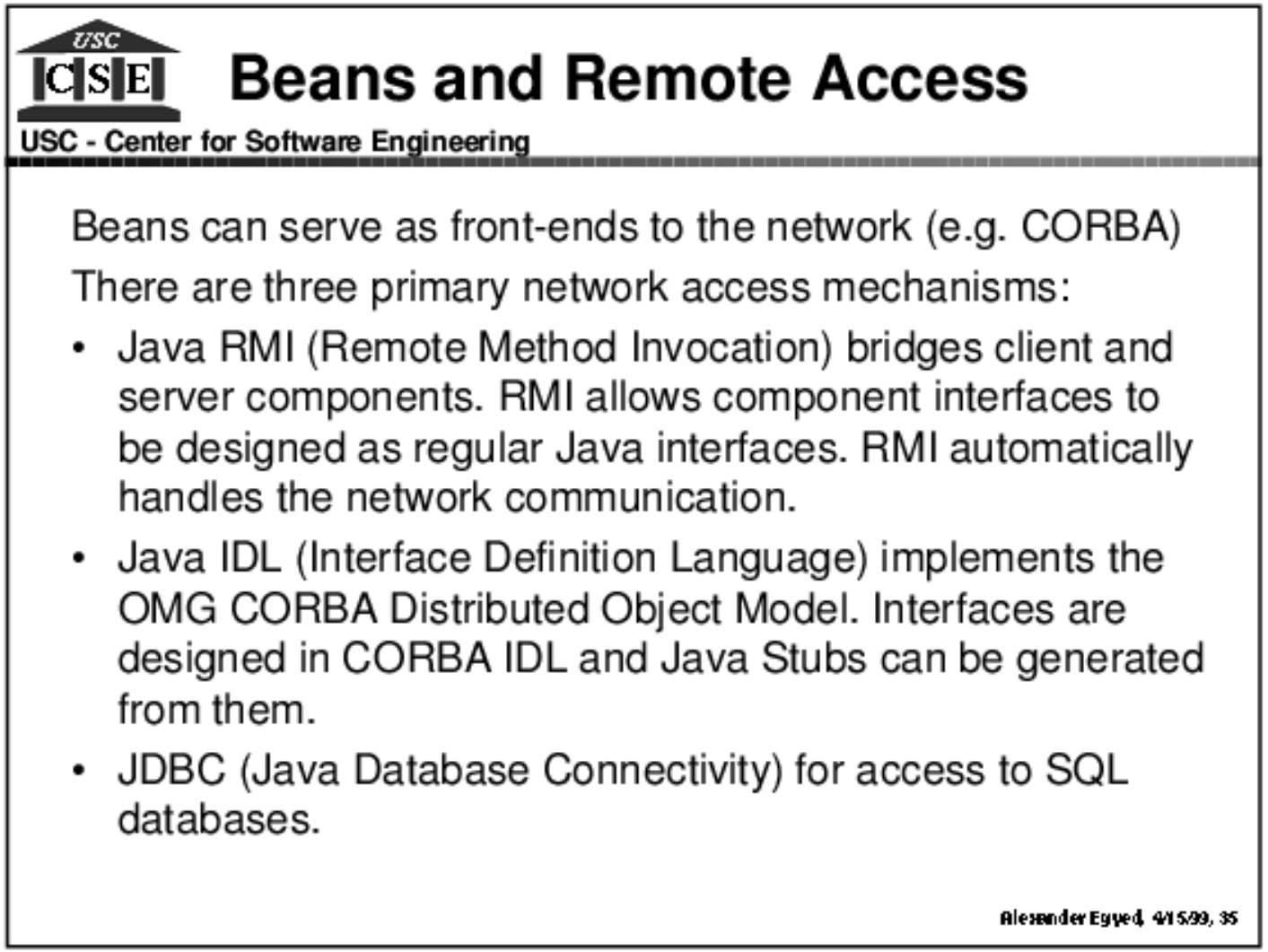
The extraction is done in a primitive way: the bean must use standard naming conventions for its attributes, methods, and events (e.g., `addListener, removeListener, get, set`). Better, the programmer can write a `class BeanInfo` whose methods surrender the property-method-event interfaces.

The Java Bean Box: a simple development tool

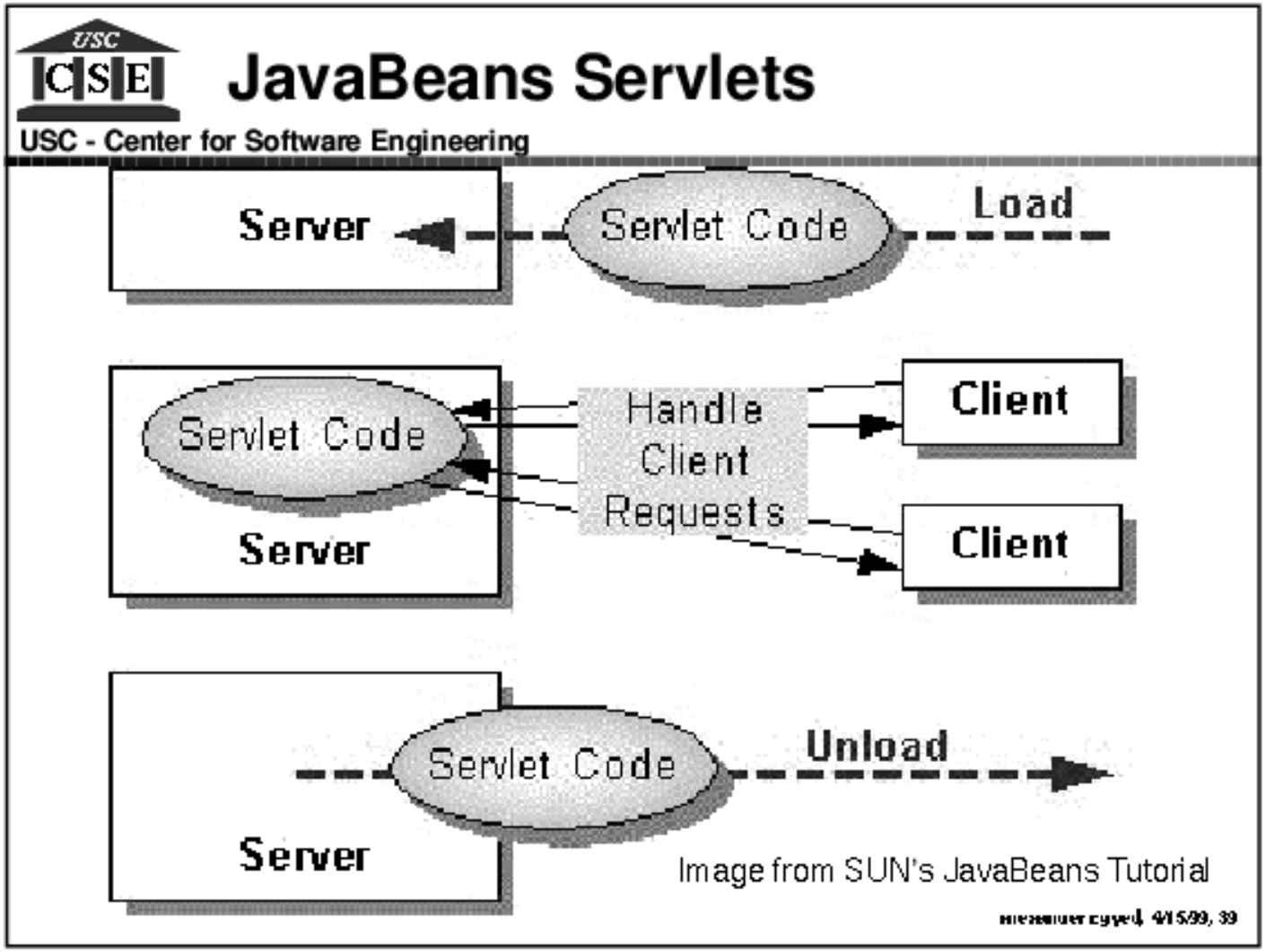


Slide is from `http://sunset.usc.edu/classes/cs578_2002`

Beans and remote access



Servlets: beans as proxies



Enterprise Java Beans (EJB) (now in J2EE)

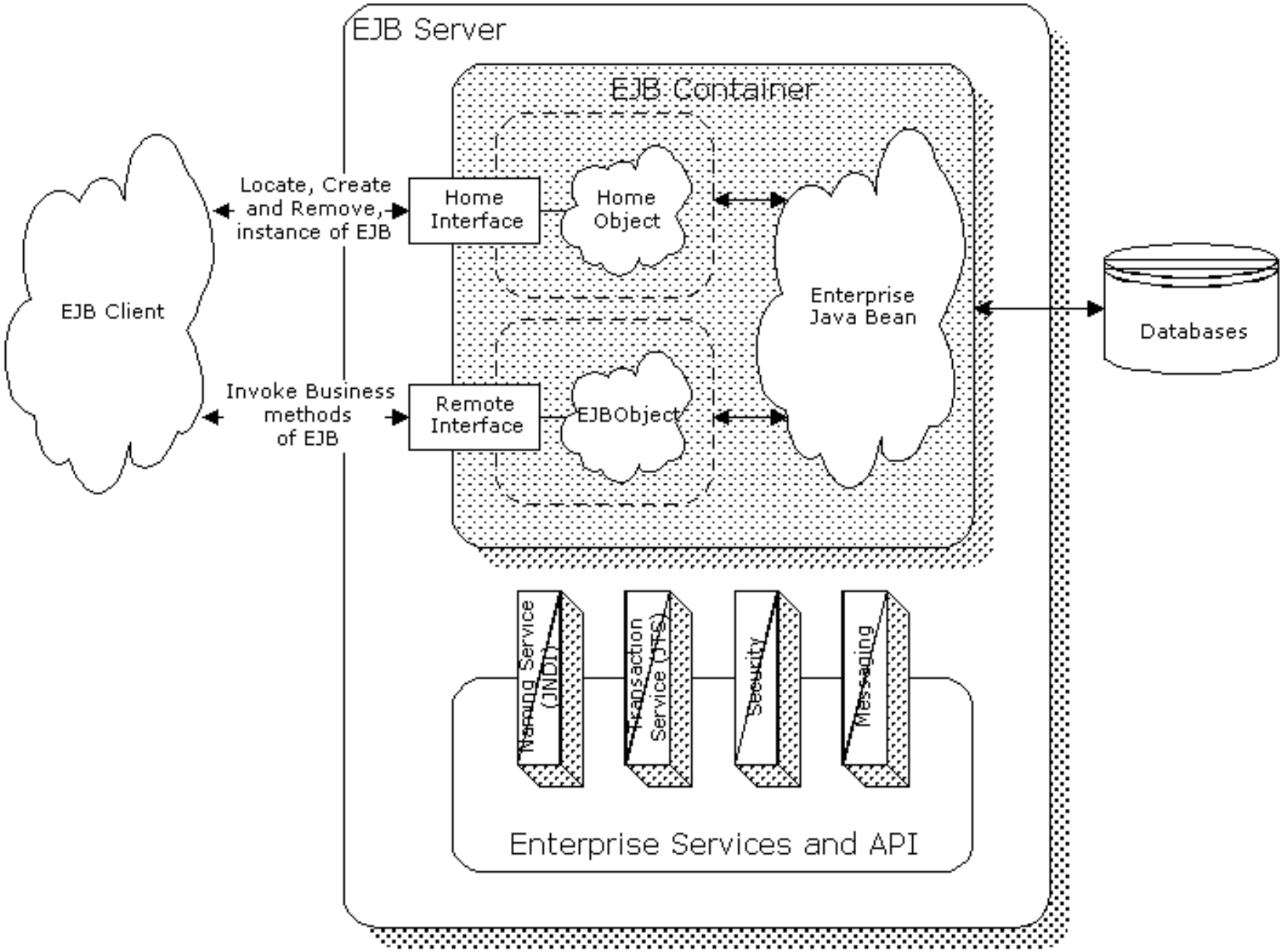
are a variant of Java beans (and not truly compatible with them), oriented to client-server applications.

An EJB is a servlet-like object that is remotely constructed by a client, using methods in the server's *home interface*. The EJB is placed in a *container* (an "adaptor" or "wrapper") that receives the client's transaction, decodes it, and gives it to the EJB. Such an EJB is called a *session bean.*

(An *entity bean* is an EJB that is shared by multiple clients; it has no internal state.)

The EJB implements methods in the *remote interface*, which are the method names invoked by the client to request transactions.

The client uses methods in the home interface to remove the session bean.


EJB Server
EJB Container
EJB Client
Locate, Create and Remove, instance of EJB
Home Interface
Home Object
Enterprise Java Bean
Databases
Invoke Business methods of EJB
Remote Interface
EJBObject
Naming Service (JNDI)
Transaction Service (JTS)
Security
Messaging
Enterprise Services and API

9. Aspect-oriented programming

Recall Kruchten's 4 *views* of software:

1. *logical*: behavioral and functional requirements
2. *process*: concurrency, coordination, and synchronization
3. *development*: organization of software modules
4. *physical*: deployment onto hardware

Each view tells us how to code part of the software.

Kiczales at Xerox PARC said that software contains *aspects*:

- functional behavior (what the software "does")
- synchronization and security control
- error handling
- persistency and memory management
- monitoring and logging

Each aspect tells us how to code part of the software.

But the aspect's codings "cross cut" the functional components and are "scattered" throughout the program.

Example: a synchronized stack in Java: functional code in *black*, synchronization code in *red*, error-handling in *blue*:

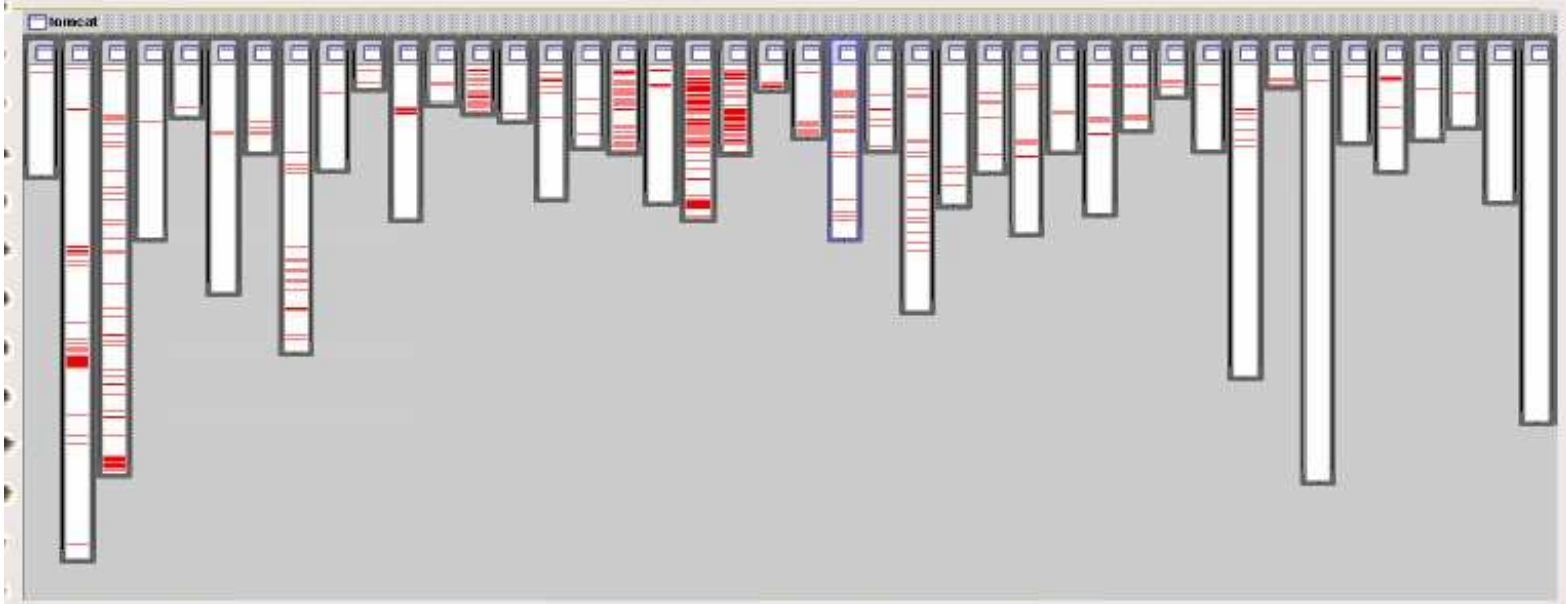
```
public class Stack
{ private int top;    private Object[] elements;

public Stack(int size) { elements = new Object[size]; top = 0; }

public synchronized void push(Object element) {
   while (top == elements.length) {
         try {  wait(); } catch (InterruptedException e) { ...  }
   }
   elements[top] = element; top++;
   if (top == 1) { notifyAll(); } // signal that stack is nonempty
}

public synchronized Object pop() {
   while (top == 0) {
      try {  wait(); } catch (InterruptedException e) { ...  }
   }
   top--; Object return_val = elements[top];
   if (top < elements.length) { notifyAll(); } // stack not full
   return return_val;
} }
```

The synchronized stack example is not so elegant:

- The various aspects are “tangled” (intertwined) in the code, and it is difficult to see which lines of code compute which aspect.
- One aspect is divided (“scattered”) across many components; if there is a change in the aspect, many components must be rewritten.
- It is difficult to study and code an aspect separately.

Example of scattering

[Kiczales 2001]



logging in org.apache.tomcat

- each bar shows one module
- red shows lines of code that handle logging
- not in just one place, not even in a small number of places

From M. Wand, invited talk, ICFP 2003: `www.ccs.neu.edu/home/wand`

How do we code and integrate an aspect?

Kiczales proposed that each aspect be coded separately and the aspects be *woven* together by a tool called a *weaver*. The weaver inserts code at connection points, called *join points*.

A standard join point is a method call; another is (the entry and exit points of) a method's definition. Join points can be field declarations or even references to variable names (e.g., for monitoring).

The aspects should be

- *noninvasive*: one aspect should not be written specially to allow it to be "woven into" by another
- *orthogonal*: one aspect does not interfere with the local, logical properties of another
- *minimal coupling*: aspects can be unconnected and reused

Normally, other aspects are woven into the functional aspect.

Lopes developed *COOL*: A language dedicated to synchronization aspects

// In a separate Java file, write the functional component:

```
public class Stack {
   private int top;    private Object[] elements;

   public Stack(int size) { elements = new Object[size]; top = 0; }

   public void push(Object element) { elements[top] = element; top++; }

   public Object pop() { top--; return elements[top]; }
}
```

// In a separate Cool file, state the synchronization policy:

```
coordinator Stack {
   selfex push, pop; // self exclusive methods
   mutex { push, pop }; // mutually exclusive methods
   condition full = false; condition empty = true;

   guard push:  requires !full;
      onexit { if (empty) empty = false; }

   guard pop:  requires !empty;
      onexit { if (full) full = false;
               if (top == 0) empty = true; }
}
```

When the two classes are woven, the result is the synchronized stack:

```
public class Stack
{ private int top;    private Object[] elements;
   private boolean empty;    private boolean full;

public Stack(int size)
   { elements = new Object[size]; top = 0;
   full = false; empty = true;  }

public synchronized void push(Object element) {
   while (full) {
         try {  wait(); } catch (InterruptedException e) { }
   }
   elements[top] = element; top++;
   if (empty) { empty = false; notifyAll(); }
}

public synchronized Object pop() {
   while (empty) {
      try {  wait(); } catch (InterruptedException e) { }
   }
   top--; Object return_val = elements[top];
   if (top == 0) empty = true;
   if (full) { full = false; notifyAll(); }
   return return_val;
} }
```

The COOL language looks somewhat like a language for *writing connectors*!

Indeed, when join points are method calls or method definitions, then weaving two aspects is weaving the connector code into the component code!

10. Final Remarks

TABLE 1. **Academic versus industrial view on software architecture**

Academia	Industry
• Architecture is explicitly defined.	• Mostly conceptual understanding of architecture. Minimal explicit definition, often through notations.
• Architecture consists of components and first-class connectors.	• No explicit first-class connectors (sometimes ad-hoc solutions for run-time binding and glue code for adaptation between assets).
• Architectural description languages (ADLs) explicitly describe architectures and are used to automatically generate applications.	• Programming languages (e.g., C++) and script languages (e.g., Make) used to describe the configuration of the complete system.

Reference: Jan Bosch. *Design and Use of Software Architectures*. Addison-Wesley, 2000.

TABLE 2. **Academic versus industrial view on reusable components**

Academia	Industry
• Reusable components are black-box entities.	• Components are large pieces of software (sometimes more than 80 KLOC) with a complex internal structure and no enforced encapsulation boundary, e.g., object-oriented frameworks.
• Components have narrow interface through a single point of access.	• The component interface is provided through entities, e.g., classes in the component. These interface entities have no explicit differences to non-interface entities.
• Components have few and explicitly defined variation points that are configured during instantiation.	• Variation is implemented through configuration and specialization or replacement of entities in the component. Sometimes multiple implementations (versions) of components exist to cover variation requirements
• Components implement standardized interfaces and can be traded on component markets.	• Components are primarily developed internally. Externally developed components go through considerable (source code) adaptation to match the product-line architecture requirements.
• Focus is on component functionality and on the formal verification of functionality.	• Functionality and quality attributes, e.g. performance, reliability, code size, reusability and maintainability, have equal importance.

Selected textbook references

F. Buschmann, et al. *Pattern-Oriented Software Architecture.* Wiley 1996.

P. Clements and L. Northrup. *Software Product Lines*. Addison-Wesley 2002.

P. Clements, et al. *Documenting Software Architectures: Views and Beyond*. Addison Wesley, 2002.

K. Czarnecki and U. Eisenecker. *Generative Programming.* Addison-Wesley 2000.

E. Gamma, et al. *Design Patterns: Elements of Reusable Object-Oriented Software*. Addison Wesley, 1994.

M. Shaw and D. Garlan. *Software Architecture.* Prentice Hall 1996.