A DCI Execution Model

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Abstract

Computers provide three essential services: Data transformation, data storage, and data communication. Transformation and storage have long been well entrenched in algorithmic and data languages. Unaccountably, communication is only seen as an I/O operation without explicit language support. At long last, this deficiency has now been remedied with the new Data - Context - Interaction (DCI) paradigm.

Alan Kay introduced the notion of *object orientation* in the early seventies. He regarded an object as a virtual computer and an object system as thousands of computers hooked together by a very fast network. The locus of DCI is in the *DCI Context* where we find the specification of object system behavior. The Context declares a network of communicating objects where the nodes are called *Roles* and the edges *Connectors*. The system behavior algorithm is composed from *RoleMethods*; methods that are associated with the Roles.

This article is about an execution model for DCI. An important aspect is the handling of DCI Contexts at runtime; where they are stored and how they are accessed. DCI in general and the DCI Context in particular make data communication a first class citizen of computer programming.

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1 Introduction

NOTE 1: Readers not familiar with hardware and assembly programming may find it useful to glance at the appendixes first.

Note 2: Readers familiar with the DCI paradigm may jump directly to
Section 2 (p. 4): *The Plain Old Java Object (POJO) Execution Model*

Computers can essentially provide three services: *Data transformation*, *data storage*, and *data communication*. Algorithmic languages such as FORTRAN and Algol are data transformation languages. Data languages such as SQL and NIAM support data storage and retrieval.

Communication has long been a first class citizen in the hardware world; the bus centered IBM PC came in 1981. The software world has been slow in following suit. Communication has remained an I/O operation outside the scope of all major programming languages.

The idea of communicating objects could have lifted communication to become a first class citizen of software. Alan Kay, who coined the term *object orientation*, regarded an object system as a network of communicating computers:

> *In computer terms, Smalltalk is a recursion on the notion of computer itself. Instead of dividing "computer stuff" into things each less strong than the whole--like data structures, procedures, and functions which are the usual paraphernalia of programming languages--each Smalltalk object is a recursion on the entire possibilities of the computer. Thus its semantics are a bit like having thousands and thousands of computers all hooked together by a very fast network.* [Kay-93]

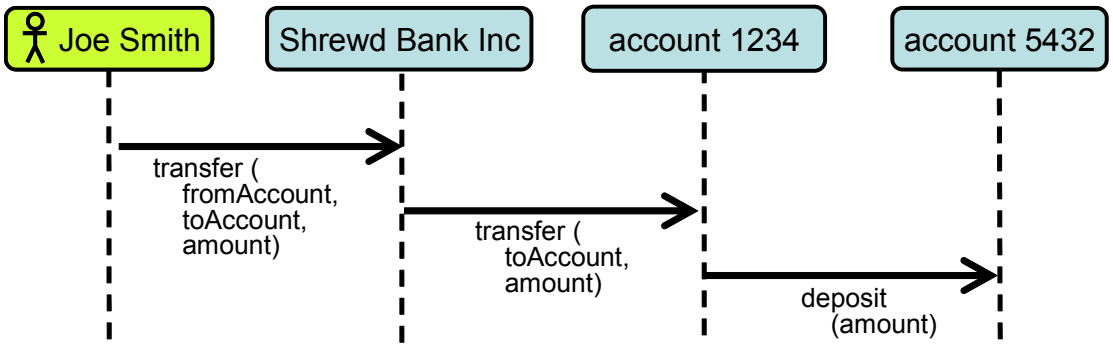
The Smalltalk programming language is a class-based language where a class specifies one of Kay's virtual computers. A class specifies what an instance will do with an incoming message; it says nothing about the message sender or the enclosing network of communicating objects. The roots of this deficiency can be found in a faulty assumption: If a class is programmed to make its instances "do the right thing"; these instances will behave appropriately when they are combined into systems of communicating objects. This assumption fails when "the right thing" depends on context so that a class cannot be properly understood when seen in isolation. Another problem with class-based programming is that it ignores the well known axiom that "the value of a system is greater than the sum of its parts". The added value is caused by a particular organization of the parts into a coherent structure, their context. The most important feature of an object system is communication, i.e., what happens in the space between its objects.

True object orientated systems can be described in some modeling languages such as OOram[OORAM-92] and UML[UML-09]. Since Kay's notion of an object is recursive; an object can be a member of an enclosing network as well as being the container of an inner network.

Class based programming languages cannot be used to specify a system of communicating objects since it can only describe one object (class) at the time. This fundamental deficiency is remedied in the *Data-Context-Interaction (DCI)* paradigm by going outside the limitations of the class concept. DCI advances true object orientation from modeling to programming.

Figure 1 illustrates how a simple example of a network of communicating objects accomplish a simple task. (Note that this is not an example of sensible programming, but an illustration of the DCI principle). Consider a person, Joe Smith, who wants to transfer some funds from one of his bank accounts to another. He goes to his bank and requests that it shall effectuate the transfer. Joe gives the transfer order to the bank, the bank instructs `Account 1234` to do the transfer, this account deducts the amount from its balance before it instructs `Account 5432` to deposit the amount. This way of looking at a computer application has two advantages: It is easy to understand for the bank customer and it can be a high level picture of the computer program.

Figure 1: A possible user's mental model of a bank transfer transaction.



DCI can be studied from different viewpoints. When DCI is seen from the end user, we find use cases and user mental models. When DCI is seen from the application programmer's point of view, we also see the DCI paradigm with its three perspectives of Data, Context, and Interaction. See for example the Wikipedia article *Data, Context, and Interaction*[DCI-Wiki] for a definition, *The DCI Architecture: A New Vision of Object-Oriented Programming* [ReeCop-09] for an overview, and *The Common Sense of Object Oriented Programming*[Ree-09] for details and commented examples.

We use the following terms in this article:

DATA	A representation of facts or ideas in a formalized manner capable of being communicated or manipulated by some process.[IFIP-66]
INFORMATION	In *automatic data processing* the meaning that a human assigns to *data* by means of the known conventions used in its representation.[IFIP-66]
COMPUTER	: one that computes; specifically : a programmable usually electronic device that can store, retrieve, and process data.[Webster]
COMPUTING	2: to use a computer.[Webster]
COMMUNICATION	Communication is a process whereby information is enclosed in a package and is channeled and imparted by a sender to a receiver via some medium. [Wikipeadia] *.Note: For <information> read <data> to conform to the above definitions.*
SYSTEM	A *system* is a part of the world *which we choose to regard as a whole*, separated from the rest of the world during some period of consideration, *a whole which we choose to consider as containing a collection of components*, each characterized by a selected set of associated data items and patterns, and by actions which may involve itself and other components.[Holbæk-Hanssen-75]

This article is written for the systems programmer who wants to create a DCI infrastructure. The purpose of the article is to gain an understanding of the realization of DCI in a computer. There are many possible ways of doing this, most of them require compromises caused by the nature of the available programming language and its runtime system. We here present a clean execution model that implementers can use as a point of departure.

For completeness, we have included older memory management systems and find that they are inadequate for object oriented program execution. Readers unfamiliar with computer architecture and assembly programming may find these appendixes helpful for understanding the main sections (section 2 and section 3).

2 The Plain Old Java Object (POJO) Execution Model

In POJO systems, memory is divided into two parts: A *heap* and a *stack*. The *heap* is a part of the memory that is reserved for objects. Objects represent system state.

Another part of the memory is reserved for the *stack*. The stack is LIFO list of activation records with one activation record for each method activation. (see Appendix 2 (p. 14): *Stack Based memory Management*).

2. 1 System state: What the system IS

When a class is instantiated, the new object is placed in an available part of the heap. The block of memory that represents the object includes a pointer to the object's class and a slot for each instance variable. Every object has a unique and immutable identity. The memory management system maintains a dictionary that binds object IDs to the location of the object on the heap. (Conceptually, that is. There are many different implementations.) An object stays on the heap until it is either deleted programatically or, more common these days, when it is no longer accessible and is removed automatically by a garbage collector. The memory management system is part of the runtime system, often called the *virtual machine (VM)*.

2. 2 System behavior: What the system DOES

System behavior is controlled[1] through the stack. The stack acts both as a computation stack and a call stack. In a procedure oriented computation, the activation record for a procedure call typically includes local variables, actual parameters. and the return address. POJO activation records can also include a link to the current method and a program counter within this method. A return address is not needed since the activation record contains all data needed to resume the method execution from the point where it was interrupted.

Individual object behavior is triggered when an object receives a message. The currently running method is interrupted and a new activation record is pushed onto the stack:

1) A method in the sender object creates a message. This message includes the sender object ID, the receiver object ID, the message name, and possible message arguments.

2) The VM adds an activation record on the top of the stack as illustrated in figure 2. (Control data are not shown here)

1.Controlled, because the POJO activation record contains the data needed by the Control Unit in a von Neumann architecture.[Wikipeadia] (See figure 7 (p. 12)

3) The VM follows the class pointer in the receiver object to find its message dictionary. Using the message name as a key, it looks up the corresponding method in the receiving object. The lookup is repeated along the superclass chain if necessary. (A `doesNotUnderstand`-exception is raised on failure).

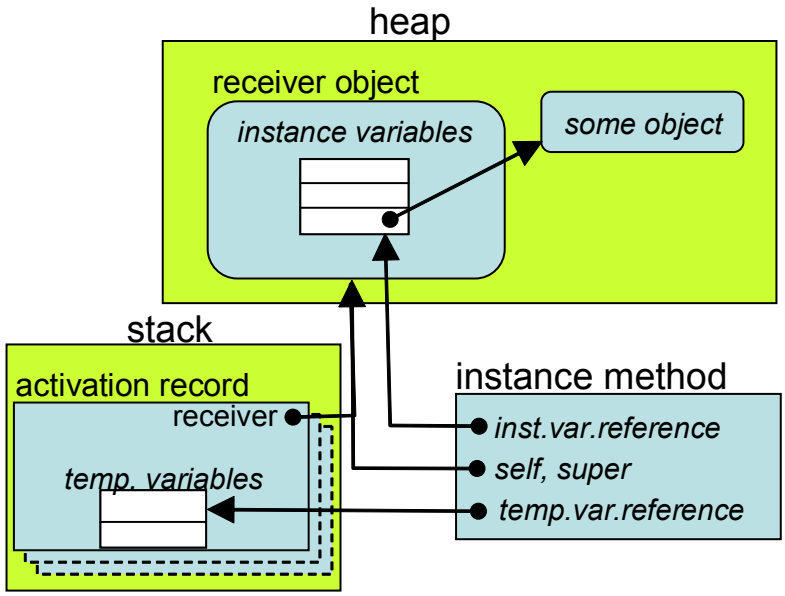
4) The activation record is initialized with a link to the current method and its program counter.

5) The execution of the calling method is suspended and the execution of the selected method is triggered. A method may change the object's state. It can also send messages and the process is repeated from point *1)* above.

6) The activation record is removed from the stack upon method completion. The execution of the calling method is continued from where it was suspended.

Figure 2 illustrates the runtime memory location of variables that are visible from a binary POJO instance method during its execution. There is an activation record for the current method. The stack grows and shrinks on top of this record as the method is executed. The activation record includes a link to the receiver object and slots for the method's temporary variables (actual arguments and local variables).

Figure 2: Runtime POJO memory link structure.



The method source code namespace includes identifiers for the temporary variables, the instance variables of the receiver object, and other variables[1]. The compiler transforms the source code into a binary method as a sequence of instructions (*byte codes*) to the VM. Some instructions move values between the top of the stack and various memory locations, some request message sends. and some do other operations.

3 The DCI Execution Model

The DCI execution model builds on the POJO model. The handling of system state is as described in section 2. 1 above. The system behavior is as described in section 2. 2 with the addition of a new kind of variable: the Role. We will see how this gives rise to an extended runtime model and a corresponding change to the code that is input to the compiler.

1.Static, global and other special variables are also visible; they are not discussed in this article.

3. 1 Programmer's view of DCI

A programmer needs to make many decisions in order to fill the message sequence chart shown in figure 1 (p. 3) with details. The programmer decides to base his thinking on the notion of a *system* defined on page 3. Let's assume he *chooses* to regard the bank part of the fund transfer transaction as a *system*. He *chooses* to let this system consist of two interconnected *Roles*: A `FromAccount` and a `ToAccount`. He has finally *chooses* to let the system as a whole be represented by a `BankTransferContext`; the transfer takes place within this Context.

The user mental model in figure 1 is now refined to become the application programmer's mental model shown in figure 3:

1) The chosen system is represented by a *Context*: The `BankTransferContext`.

2) An object in the system's environment provides a trigger message; this message is called a *system operation* (or *use case*, or *habit*).

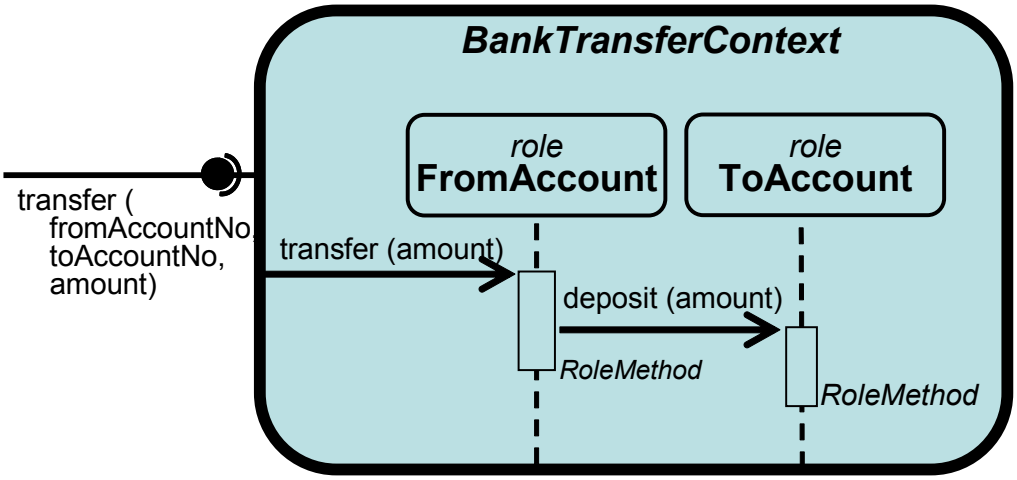
3) The system's *Data* objects (the accounts) are represented by the Roles they play in this Context: `FromAccount`, `ToAccount`. The Context binds these Roles to the appropriate Data objects; here by looking up the account numbers to find the account objects.

4) The vertical timeline below each Role symbol is augmented with a rectangle that represents the method that will be executed. The method is a *RoleMethod*; it is common to all objects that can play the Role. (Polymorphism is suspended for RoleMethods). Taken together, the RoleMethods specify the *Interaction or Algorithm* that is executed when the system performs a system operation.

5) RoleMethods executed within the Context do not need the account objects as arguments because the Roles that represent them are visible in the Context

6) The *Data* objects are the account objects that play the Roles. (See in figure 4).

Figure 3: Application programmer's DCI based mental model of the Interaction.

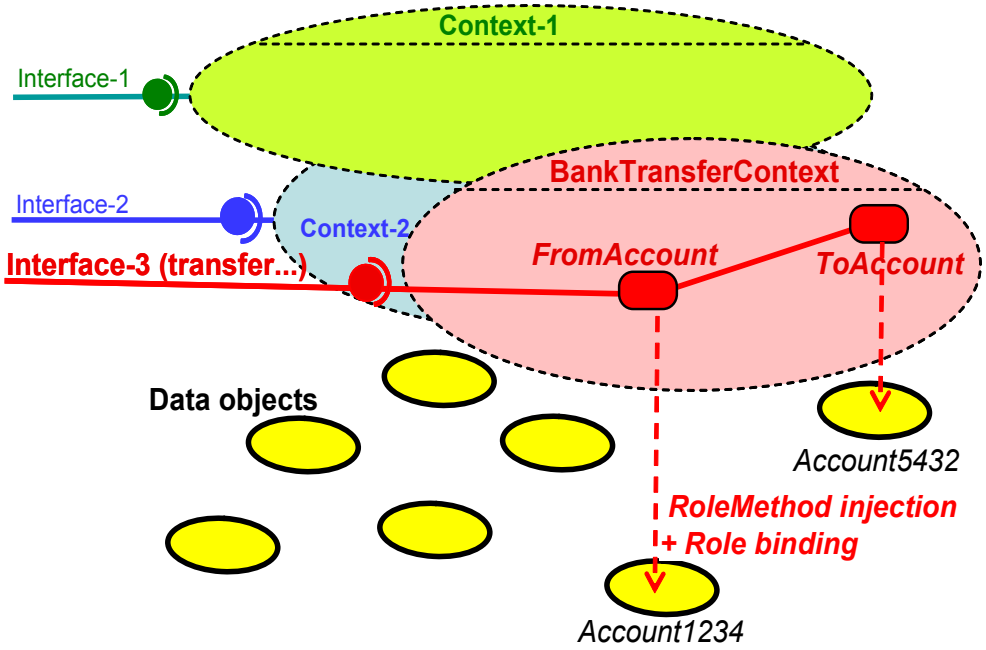


In one of his many clarifying posts on the object-composition@googlegroups.com list, Rickard Öberg wrote:

> *with DCI, the application facade that used to look something like this:*
> *facade.method(id1,id2,id3,param1,param2)*
> *is now replaced by:*
> *context<id1,id2,id3>.interaction(param1,param2)*

A bank offers many different services to their clients, the transfer of funds being one of them. Figure 4 shows how different services are encapsulated in different Contexts. It is only when we look inside a Context that we see that it encapsulates a network of communicating Roles. We have opened the `BankTransferContext` and see that its Roles are momentarily bound to the bank's Data objects. We see, for example, that the `FromAccount` Role happens to be bound to a Data object in the bank that represents `Account1234`. In addition, the RoleMethod associated with the `FromAccount` Role is injected into the `Account1234` object.

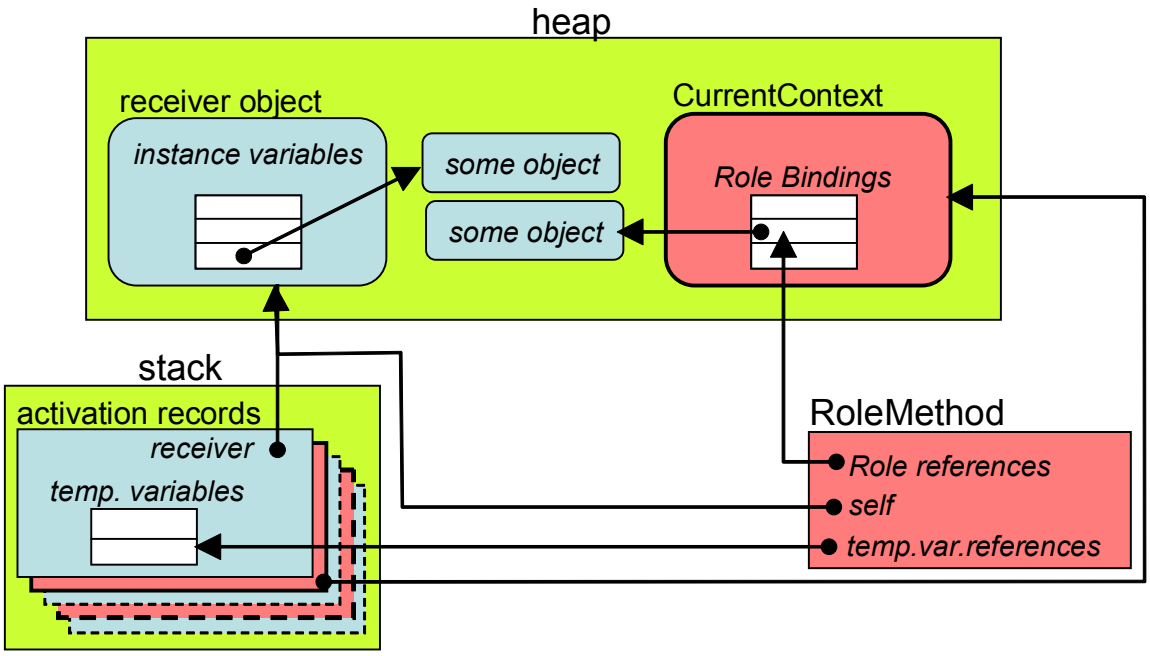
Figure 4: DCI separation of concerns: System state and the different system behaviors.



3. 2 A runtime view of DCI

A DCI Interaction is triggered by a message to a Context object as described in step 2 in the list on page 4. This message triggers the execution of one of the Context's instance methods. Figure 5 shows the activation record for this execution colored red and drawn with a heavy outline. This Context activation record stays on the stack until it is popped off at the termination of the trigger method.

Figure 5: Runtime DCI memory link structure of a binary method.



The trigger method to the Context first initializes the `CurrentContext`'s Role bindings and then starts the Interaction with a message to the first Role and thus triggers the first RoleMethod.

A RoleMethod is not associated with a particular class so RoleMethods cannot access the instance variable in the receiver object. Instead, RoleMethods address Data objects indirectly through the Role name as illustrated in figure 5. This figure also illustrates that RoleMethods

access temporary variables in the same way as instance methods. Note that *self* refers to the current receiver object; i.e., the object that is playing the current Role.

A potential extension of this execution model is to refer to the *CurrentContext* through a special identifier similar to *self*. There would then be an additional pointer from the RoleMethod to the *CurrentContext*, for example called *thisCtx*. This is for further study.

A method that has an activation record above the *CurrentContext* on the stack is executed within this Context. The method can search down the stack to find the top *CurrentContext* and access a Roleplaying object through it.

Our current DCI metamodel only permits one Context to be active at any time (More about this constraint in section 4. 3). This Context is called the *CurrentContext* and can be found by searching the stack down from its top. It is sometimes more convenient to maintain a shadow Context stack; the *CurrentContext* is then found on the top of this stack. Statically typed languages makes it easier to maintain a separate stack for each Context class. The latter solution has been chosen for several of the current DCI implementations.

An important detail is that any object, including a Context object, can play a Role as long as it has the necessary properties. This means that a new Context can be triggered within an executing Interaction.

3. 3 A compile time view of DCI

The code for a RoleMethod uses Role names as identifiers instead of instance variable names. For example, the RoleMethod shown as a vertical rectangle under the *FromAccount* Role in figure 3 (p. 6) could be:

```
FromAccount>>transfer(amount) {
     if (self.balance < amount) self.error ("no funds");
     ToAccount.deposit(amount);
     }
```

Note the *self* variable; it refers to the receiver object, i.e. the object currently playing the *FromAccount* Role.

The above works if our compiler can compile this method within the *BankTransferContext* and generate code that binds the Role name to the appropriate object at runtime. As an example, the *CurrentContext* could be a global variable and the compiler or some kind of macro processor could generate (hidden) code to find it

```
FromAccount>>transfer amount) {
     if (self.balance < amount) self.error ("no funds");
     (CurrentContext.getObjectForRole ("ToAccount").deposit(amount);
     }
```

Or *CurrentContext* could be replaced by code that referenced a ContextStack in a static method in the *BankTransferContext*:

```
FromAccount>>transfer amount) {
  if (self.balance < amount) self.error ("no funds");
   (BankTransferContext.getObjectForRole ("ToAccount" ).deposit(amount);
   }
```

See section 4. 2 below for important details about RoleMethods.

4 Four Constraints

With DCI, a program is decomposed into independent units of code that reflect important concerns that exist right from the end user's mental model to the innermost parts of the program. It is an imperative goal of DCI that it shall be possible to reason about the code in a particular unit with a minimum of interference from other units. This requirement leads to four constraints that are added to the DCI execution model.

4. 1 The coherent selection of roleplaying objects

One of the great powers of "object orientation"is that polymorphism permits variations on a theme defined by a base superclass. DCI blocks off this feature for programming system operations by injecting the identical RoleMethods into all objects playing that role. Instead, the DCI Context gives similar variations on a common theme by selecting different sets of objects to play its Roles. The selection has to be done as an atomic operation in order to ensure that the bound objects represent the Context as a whole. (Independent role binding would endanger the integrity of the Context).

All Roles in a Context
are bound to objects in a single, atomic operation.

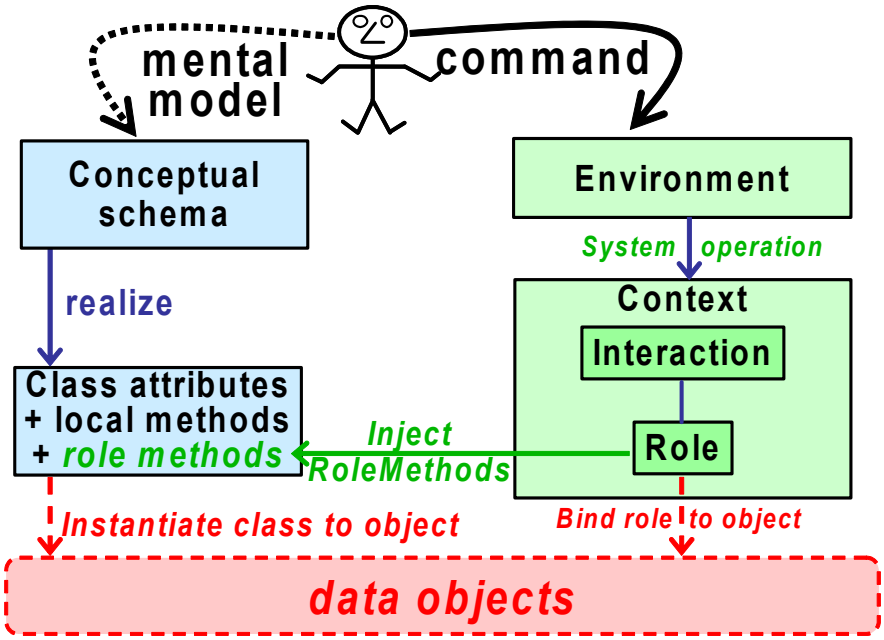
A Role can, at most, be bound to a single object at a given point in time. The above constraint says that it can only be bound to another object by the atomic binding operation that binds all Roles at the same time.

4. 2 The uniqueness of RoleMethod names

A Role is a property of a Context and is named within the Context namespace. Roles declared within different Contexts can, therefore, have the same name without conflict.

RoleMethods are declared within Methodful Roles and Methodful Roles act as namespaces for their RoleMethods. RoleMethods declared within different Roles can, therefore, have the same name without conflict. This appears to be safe, but the injection of RoleMethods into Data objects can give rise to unpleasant surprises. Figure 6 is taken from [Ree-09] and shows an overview of DCI where RoleMethods are injected into the appropriate classes.

Figure 6: A DCI overview model.



A Data class (with its superclasses) forms a namespace for method names. We see from figure 6 that RoleMethods can be injected into Data classes and thus become part of the namespaces of these classes. In addition, different Roles may inject their RoleMethods into the same classes. In some implementations, RoleMethods are injected directly into the object that plays the Role at runtime. All this leads to the following constraint:

The name of a RoleMethod must be unique within the Role and also within all objects that may play this Role.

4. 3 The uniqueness of the CurrentContext

Figure 5 illustrates a stack with more than one Context activation record. We compare this figure with the dynamic scoping example in figure 8 (p. 14) and see that Contexts could be accessed using dynamic scoping. The fact that we *can* do it doesn't mean that we *should* do it. DCI is about powerful and simple mental models for both code writer and code reader. Wikipedia warns that dynamic scoping can be dangerous because it can lead to unreadable code. Multiple active Contexts are, therefore, not permitted in DCI.

Only one DCI Context can be active at a time.

4. 4 DCI only supports single thread execution

A constraint that must be relaxed in a future version of DCI.

5 Conclusion

The DCI execution model extends the POJO model with a capability for controlling the communication between named objects within a network of communicating objects. With DCI, we see the basic capability of computing in a three-layered architecture:

1) *Data storage* is done in an object's state variables. An object's apparent state can be derived, i.e., computed from other state.
2) *Data transformation* is done in an object's *methods*.
3) *Data communication* is done by message interaction in the context of a network of connected objects.
4)

DCI adds data communication
as the third basic capability of computing,
the other two being data transformation and data storage.

6 References

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[UML-09]	*OMG Unified Modeling LanguageTM (OMG UML), Superstructure. Version 2.2*; Object Management Group 2009; http://www.omg.org/spec/UML/2.2/Superstructure/PDF/
[Webster]	http://www.merriam-webster.com
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Appendix 1: Static Memory Management

Figure 7 shows the von Neumann computer architecture. Consider a very simple imaginary computer. Its memory has 256 locations with addresses `0..255`. Its instruction format consists of two bytes, the first is the operation code, the last is a memory address.This imaginary computer has the operation repertoire as shown in table 1.

Figure 7: von Neumann computer architecture.[Wikipeadia]

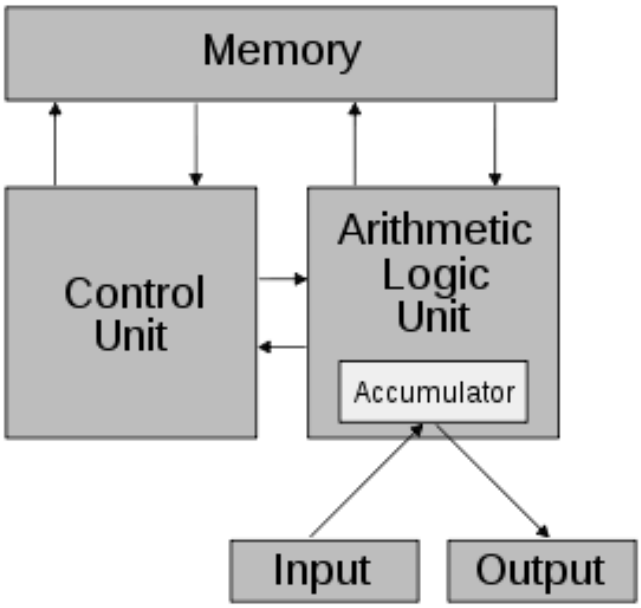


Table 1: Instruction repertoire.

operation code	effect
0	HALT
1	LOAD a value from memory to the accumulator
2	STORE a value from the accumulator to memory
3	ADD a value to the contents of the accumulator
4	JUMP. Value is address of next instruction

6. 1 Binary code

We write code directly for the hardware, no intermediary. The hardware control unit feeds program operations one by one into the Operation register where they are executed.

As an example, put the value `3` into memory slot `100` and `4` into `101` (manually, from the computer console). Then execute the following program.

Table 2: A small example program. (Format: `op/address`)

1	100
3	101
2	102
0	

The memory slots from `100` will now contain `3`, `4`, and `7`.

Memory management is done manually when we assign memory slots to instructions and data.

It is a sobering thought that all computers work more or less as described here even if they have a more extensive operation repertoire, Programming languages are devised to make the programmer's mental model better suited to his or her task. No sophisticated language, metaphor, or paradigm can add to the capabilities of the computer hardware. All they can do is to give the programmer better leverage through reduced capabilities. (There is no leverage without rigidity). Assembly code cannot specify logic based on actual memory addresses. FORTRAN does not support self-modifying code.

An argument against DCI, our new programming paradigm, is that "There is nothing new here, I can do the same in Java". This comparison is irrelevant. Machine code can do all Java does and more, because machine code is what is ultimately executed by the computer. It is better to ask questions about the programmer's tasks and the kinds of mental models that are more effective for those tasks.

DCI programs include explicit specification of the network of interacting objects and their runtime interaction. DCI Programs may, therefore, often be longer than corresponding Java programs. DCI is more restrictive than Java because DCI insists on a stable topology for the runtime communication networks.

6. 2 Assembly programming

Our program in table 2 can be written as follows:

Table 3: An assembly program. (Format: `op/variable`)

LOAD	*I*
ADD	*J*
STORE	*K*
HALT	

We *assemble* the program into some intermediate code and then use a *Loader* to load this code into the computer. The Loader recognizes that there are three variables and it assigns memory slots to them. Memory slots `100`, `101`, and `102`, for example. There is a fixed transformation table for operations as shown in table 1.

6. 3 FORTRAN programming

Our code expressed in FORTRAN is straight forward:

```
I = 3
J = 4
K = I + J
```

Memory management in FORTRAN is static, each and every variable has a fixed storage location. (Even local variables in subroutines have their fixed locations, recursion is not supported by FORTRAN.) The FORTRAN compiler transforms the FORTRAN code into something similar to assembly as illustrated in table 2. A Loader then assigns every variable permanently to a memory location and loads the program into memory.

Memory management for FORTRAN is thus static as it is for assembly and binary.

Appendix 2: Stack Based memory Management

Algol 60 and many of its successors are block structured. Blocks and procedures can either be declared within the root block or nested within other procedures as illustrated in figure 8. The difference from static memory management is that there is now a *runtime system* that dynamically binds variable names to memory locations. Memory is organized in a *LIFO list* of *activation records*. The runtime system binds variable names to slots in activation records according to one of two different strategies:

- *Static (lexical) scoping:* non-local variables are bound based on the code structure; search the code lexically up from the current position in the code text to find the first occurrence of the variable.
- *Dynamic scoping:* non-local variables are bound based on the calling sequence; search the stack down from the current activation record to find the first occurrence of the variable.

The stack is used for many other purposes such as evaluating expressions. Our interest here is that it can be used for dynamic scoping:

> *With dynamic scope, each identifier has a global stack of bindings. Introducing a local variable with name x pushes a binding onto the global x stack (which may have been empty), which is popped off when the control flow leaves the scope. Evaluating x in any context always yields the top binding. In other words, a global identifier refers to the identifier associated with the most recent environment. Note that this cannot be done at compile time because the binding stack only exists at runtime, which is why this type of scoping is called dynamic scoping. (From [Wikipeadia], Scope (programming)).*
>
> *...As such, dynamic scoping can be dangerous and few modern languages use it.*

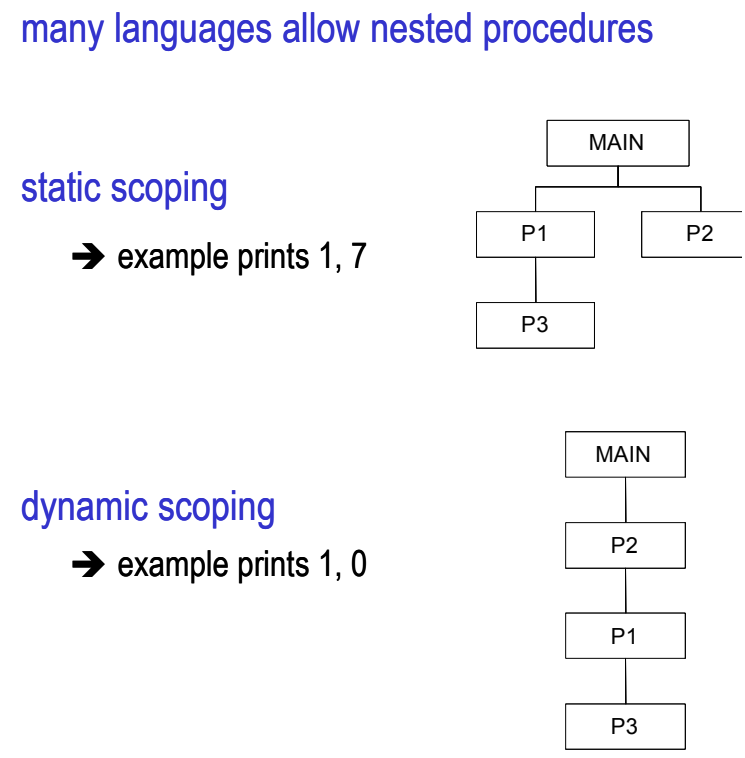
Figure 8: Static and dynamic scoping. (This figure is copied from [Reed-05]).

```
program MAIN;
  var a : integer;

  procedure P1(x : integer);
    procedure P3;
    begin
      print x, a;
    end; {of P3}
  begin
    P3;
  end; {of P1}

  procedure P2;
  var a : integer;
  begin
      a := 0;
      P1(a+1);
  end; {of P2}

  begin
      a := 7;
      P2;
  end. {of MAIN}
```



The bottom-right of figure 8 is an upside-down view of the stack while the code shown on the left is executing P3. The code is excessively complicated, but it does illustrate what can happen at runtime.

THE END