NetCLOS and Parallel Abstractions - Actor and Structure-Oriented Programming on Workstation Clusters with Common Lisp*

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Abstract. In this paper, we describe an extension of Common Lisp which allows the definition of parallel programs within that functional and object-oriented language. In particular, the extensions are the introducing of active objects, sending synchronous and asynchronous messages between them, automatic and manual distribution of active objects to object spaces, and transparent object managing. With these extensions, object-oriented parallel programming on a workstation cluster using different Common Lisp images is possible. These concepts are implemented as an extension of Allegro Common Lisp subsumed by the name NetCLOS. Furthermore, it is shown how NetCLOS can be used to realize parallel abstractions for implementing parallel AI methods at a highly abstract level.

1 Introduction

One of the big problems of Artificial Intelligence (AI) is getting its applications answer in time. Parallel processing is one way to solve this problem. But though there are many parallel implementations of basic AI techniques, there are very few AI applications which use them. This drawback is related due to two reasons:

- Most of these implementations depend on special parallel hardware (e.g., [11, 7, 18]). This hardware is expensive and not widely available. Furthermore, the specification of many applications excludes the use of special hardware (e.g., personal assistant).
- Most of them are written in special parallel programming languages unknown to the application programmer and lacking features important to develop a complete application [34]. Hence, their integration into such an application is difficult.

Especially for AI methods, the proposed parallel languages and models are too different from commonly used languages. They do not provide the flexibility programmers need, and are not integrated into existing languages [21]. Furthermore, in special parallel languages non-parallel aspects are not adequately expressable. Due to the possibly big number of flows of control, parallel programming is a difficult task. Concepts and notions to simplify parallel programming are still a research problem. Besides improving efficiency, distributed problem solving methods can be verified on distributed processors, instead of simulating such methods on sequential machines.

Thus, our goal is to simplify the parallel implementation of standard AI techniques. We think this should be realized by using standard hardware (i.e., a workstation cluster) and extending a language widely used for AI programming in a way that hides any kind of explicit parallel programming from the application programmer. One language often used (as by us) for implementing AI systems like simulation, configuration, diagnosing, information managment systems is Common Lisp. Thus, we extend

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Common Lisp [31] with two levels of features for parallel programming on workstation clusters. The upper level is intended for easy use by the AI programmer inexperienced with parallel programming, while the lower level is intended for implementing the upper level. In the lower level, an integration of an actor-like language [9] in Common Lisp and its object-oriented part CLOS (Common Lisp Object System) is introduced (see Section 3). The upper level realizes parallel abstractions as complex structures and operations on them (Section 4). The use of parallel abstractions is demonstrated with a constraint filtering algorithm and a qualitative simulation task (Section 5). In Section 6, related work is discussed. First, we give a more detailed view of our parallel programming model.

2 Parallel programming using parallel abstractions — the programming model

Our programming model consists of two levels (Figure 1). The top level is the structure-oriented programming level. Parallel abstractions representing complex structures and operations on them are introduced on this level. These may e.g. be an arbritray net, a tree or graph structure. These abstractions are designed and selected to support the development of AI methods. In one example the structure *relaxation net* is used to implement constraint nets (Section 5).

The second level, called NetCLOS[1], is used to implement the structures of the first level on a workstation cluster. It extends Common Lisp with features for parallel and distributed object-oriented programming. The parallel and the distribution aspect of the implementation of a structure can be described independently. The parallel programming is done with active objects. These have their own processes and communicate via synchronous and asynchronous message passing (for a similar model see [1, 33]). To distribute these active objects over a workstation cluster, active objects can be created on every workstation and moved from one workstation to the other. A runtime environment enables distributed garbage collection and transparent remote message passing.

This way we can divide the implementation of the structure types into two steps: A machine-independent description of the potential parallelism using active objects; and a description of the mapping of these active objects to the workstation cluster. In the current implementation of NetCLOS we focus on a workstation cluster. We think for other parallel architectures other parallel extensions may be useful. One example is *Lisp [20] which introduces parallel mechanisms for array processors. Its inclusion in CLOS (named *CLOS) is described in [13]. However, the structure-oriented programming level would be implemented with *CLOS or NetCLOS, but this level does not change for application programmers. Thus, a portability of the structure-oriented level between distinct architectures is ensured.

With NetCLOS basic concurrent and distributed abstractions are introduced in CLOS. The structure-oriented level is oriented towards application programmers, and aims at defining a high level programming language. Furthermore, both levels are implemented as open extendable protocols by using diverse objects for handling the concurrency mechanisms described in the following (like message-handler, object spaces etc.). Thus, we follow a reflective approach for object-based parallel programming (see [4] for further classifications).

3 Extending CLOS with actors

In this section, we describe the lower level (NetCLOS level), which is an extension of Common Lisp and its object-oriented part CLOS (Common Lisp Object System). Features of NetCLOS are:

- Active objects, which include data, methods, a mail queue, and a process for handling incoming messages by calling methods.
- Message passing for synchronous and asynchronous communication between active objects.
- Synchronization operations for delaying requests.

[1] NetCLOS as an extension to Allegro Common Lisp is implemented and can be received from the authors. NetCLOS is implemented using the metaobject protocol of CLOS (see [17] and [12]).

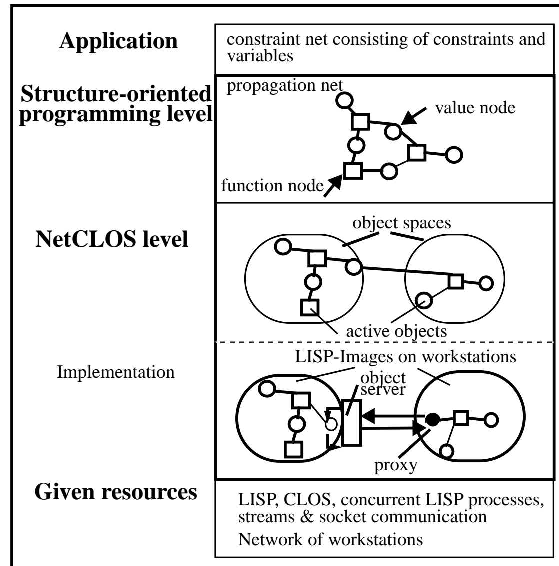

Fig. 1. Levels of used abstractions.

Programming with NetCLOS is done by creating active objects and sending messages between them. These new features are fully integrated in the programming style of CLOS. Distribution of active objects to workstations is widely hidden to the user. Thus, active objects are distributed over a virtual machine consisting of several Lisp images residing on several workstations of a cluster. To allow flexible programming of distributed active objects, automatic distributions as well as explicit moving of active objects is included in NetCLOS.

There are some approaches which include parallel programming in Lisp (see e.g., [34]) but most of them concentrate on the functional part of Lisp. In NetCLOS, the object-oriented part (CLOS) is focussed as an extendable part for parallel programming. With our new approach, we introduce active objects in the spirit of actors [9, 1] in CLOS to make parallel object-oriented programming in Common Lisp possible.

3.1 Design decisions

Following [27], we discuss three dimensions of design issues for concurrent object-oriented programming: object model, internal concurrency, and interaction. The decisions are inspired by the concurrent object-oriented language ABCL/1 [33].

Object model. Because we extend an existing object-oriented language where passive objects reside in the language, we use a heterogeneous object model with passive and active objects. Passive objects are normal CLOS objects, active objects are extended by a mail queue and a process. By buffering incoming messages in a mail queue, active objects synchronize concurrent calls. Passive objects do not synchronize concurrent calls, i.e., they have to be saved by explicit synchronization calls or are used within a single-threaded active object. Thus, using a heterogeneous object model enables an application programmer to select the adequate model for a problem, i.e. both, parallel and sequential parts of a program can exist.

Internal concurrency. Another design decision is whether an active object can process calls sequentially or in parallel. If calls are processed in parallel on the same active object, i.e. on one data source, a high communication rate will be necessary. Because of high communication costs in a workstation cluster, data and processes should reside on the same machine. Yet we decided to process tasks of one active object sequentially.

Interaction. In NetCLOS, object identifications are used to determine the recipient of a message. Message passing can be done in three ways: *future*-messages, which are easy to integrate in a functional context, one-way messages (*past*-messages), as a more flexible but also more complicated tool for communication, and remote procedure calls (*now*-messages) for synchronous communication.

3.2 CLOS - the Common Lisp Object System

CLOS belongs to the ANSI Common Lisp standard [31] and defines the object-oriented part of the language. CLOS includes classes with multiple inheritance, generic functions, declarative method combination, and a metaobject protocol. Classes are defined by slots (instance variables or data fields) and some superclasses. All slots of all superclasses are inherited. Instead of having a message-passing concept as in other object-oriented languages, CLOS includes the more powerful concept of generic functions. A generic function describes a set of methods, i.e., a method is related to a generic function, not to one class. Because a generic function may have more than one discriminating argument, a generic function is related to a set of classes not to one specific class. Instead of passing a message to an object, the generic function is called. The classes of its arguments are used to determine (at runtime) which methods should be used to compute a value for the generic function. Declarative method combinations describe how several applicable methods should be ordered and how their results should be combined. This is done by defining different kinds of methods, e.g., *before-methods* are called before *primary-methods*, etc. The metaobject protocol is used to extend CLOS' behavior portably. For instance, the slot access can be modified to be a remote slot access. So called *metaclasses* can be defined by the user, which enhance the behavior of classes and objects (instances).

3.3 Parallel Programming with NetCLOS

NetCLOS extends CLOS by introducing active objects, three forms of message passing, and explicit synchronization. Because in CLOS a "generic function is called" and no "message is sent", we introduce the notion of sending a message in CLOS. A generic function may have more than one argument, but a message is sent to one active object. Thus, a mechanism is introduced for deciding, which active object has to process the generic function call. This is done by selecting the first argument (an active object) of the call as the receiver of a message. Thus, message passing is defined as a generic function call, which is performed by the active object bound to the first argument. With this scheme, the place (host) where the function is evaluated is selected, the processing itself is done in the usual CLOS way; e.g, dispatching over multiple arguments is not altered. Message passing, as introduced here only determines which active object processes the related method. Furthermore, we follow the notion of other object-oriented languages (like Smalltalk), where a message is sent to an object by giving a message name; the active object selects the appropriate method, which is used to answer the message.

Active Objects An active object includes a mail queue and a process (realized by the multiprocess system of Allegro Common Lisp) (see Figure 2). In the mail queue, messages are stored, which have been sent to the active object. The process reads these messages and calls the applicable methods. The method is processed in the object space (Lisp image) the active object resides in (see Section 3.4). Classes of active objects are defined by using the metaclass `netclos-object`:

```
(defclass <active-object-classname> <superclasses>
          <slots>
          (:metaclass netclos-object))
```

Thus, the distinction between active and passive objects are simply made by selecting the appropriate metaclass.

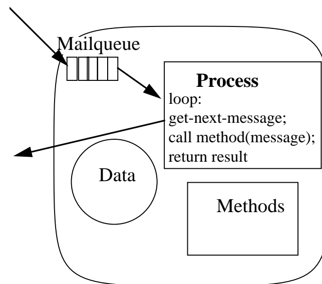

Fig. 2. Parts of an active object.

Sending messages and synchronization Active objects communicate only by using one of three message types (similar to ABCL/1): *past*, *now*, or *future*-messages. *Past*-messages are asynchronous one-way-messages. The caller can continue its work, after a message is sent. After calling the methods related to the message, the recipient does not send a reply message to the caller. Past-messages are declared by the keyword `:past` as in:

```
(defpargeneric <name> :past (<recipient-object> <argument1> ...))
```

Past-messages are used to realize complex request-reply frames.

Now-messages are remote procedure calls, i.e., the caller waits until the recipient accepts the message, computes the request, and sends the reply back. These messages are indicated by the keyword `:now`. Now-messages are used to ensure that the caller is inactive while processing the message. This can be used to realize a sequential interface to an active object or to ensure specific synchronization conditions.

When a *future*-message is sent, a *future* is created. Futures can be seen as simple active objects which can only deal with two messages: the past-message `write-result` and the now-message `touch`. After a future is created, the caller can proceed with its computation. The future sends the request to the recipient. After processing the request the recipient sends the `write-result` message to the future. The caller receives the result by calling `touch` whenever it needs the result of the future-message. If the result is not yet computed, the caller waits for it. `Write-result` is called automatically after the result was computed, `touch` is called explicitly by the NetCLOS user. Future-messages are indicated by the keyword `:future`.

If an active object gets a request, there may be reasons to delay answering requests. This can be done with the synchronization feature `wait-for`. It has the form:

```
(wait-for <message pattern>)
```

When evaluating such a form, the active object stops its computation until a message matching one of the message patterns arrives. The method related to that message is executed and the active object continues working after `wait-for`. A message pattern has the form:

```
(<message-name> <list of arguments> :from <caller>)
```

A message matches a message pattern if the name of the message, the list of arguments, and the caller are the same as in the pattern or are unspecified, indicated via '?'.

3.4 Distributing active objects on a workstation cluster

A NetCLOS program can be written by using active objects and message passing (as reviewed above). The distribution of active objects and their parallel execution is hidden to the programmer using NetCLOS (see Figure 3 for a survey of the following concepts).

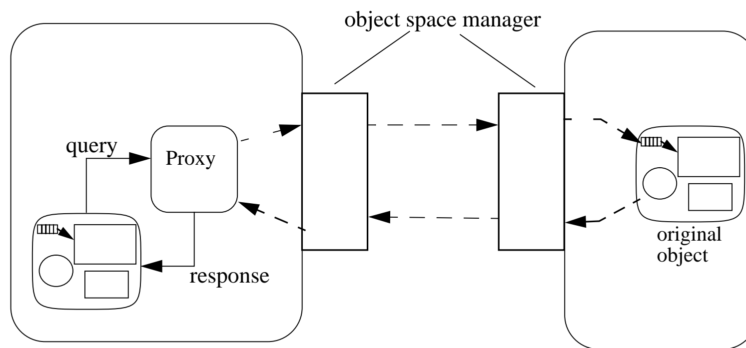

Fig. 3. Transfer of a query via a proxy.

Distribution The distribution model of NetCLOS is based on the notion of one *object space* residing on each workstation of a cluster. An object space contains all information to handle active objects, e.g., all necessary classes and functions are known to each object space.[2] Every active object resides on exactly one object space. But an active object can be referenced from each object space, not only the local one. Thus, the identity of an active object is guaranteed over all object spaces, i.e. each active object is unique and can be referenced from diverse object spaces. When messages are sent or an active object is passed as argument of a message, it makes no difference whether the object is locally or remotely referenced. This holds only for active objects, whereas other data types — like passive objects, lists, arrays, strings, or records — are only referenced locally. If objects of such data types function as arguments of a message, a copy is sent to the recipient, i.e., changes to those types made by the recipient are not known to the caller. Thus, no side effects on such datatypes are allowed. The copy of such an object includes also nested objects (e.g. lists of lists). Cyclic data is handle correctly by creating the same cycles in the remote object. Copying is done by generating a Lisp form, which when evaluated creates the appropriate objects, and sending the Lisp form to the recipient.

There are two alternatives for an application to distribute its active objects to object spaces: One is to move the object explicitly by calling the function `move`[3], the other is to use a predefined distribution class. There are two classes for distribution: one to realize a static distribution by deriving Task Interaction Graphs from the reference structure of the active objects to distribute and another class distributes the active objects dynamically when they are created. For the latter, only a simple scheme is present for sending active objects to object spaces in a round robin manner. For distributing active objects based on Task Interaction Graphs, we use a combination of bisection and Kernighan-Lin (see section 4.1). But extensions of NetCLOS made by subclassing can be defined to realize more sophisticated distribution strategies.

For moving an active object explicitly, the moving behavior of its slots can be specified when defining the active object. When specified with `:follow`, the value of that slot (another active object) is moved in the same object space as the active object itself. When specified with `:stay`, the value of the slot stays in the current object space. Instead of the value the moved active object contains a representative value (i.e., a *proxy*) as slot value.

Remote references Remote references to active objects on other hosts is realized by proxies. A proxy knows the location of the original active object and sends a kernel message to the original active object on a proxy reference to get the referenced value. The necessary infrastructure is internal in NetCLOS. When moving an active object, appropriate proxies are created automatically. If a slot

[2] Special features are defined for distributing new definitions of generic functions and classes and for defining systems (sets of files), which have to be known to all object spaces.

[3] In the current implementation, the function `move` can not be used in generic functions being performed in parallel on one active object, because the process synchronizing the mail queue is not moveable in the Lisp implementation we use. Instead a new process is created when an active object is moved.

is of type `:follow`, a local proxy is created, which refers to the remote slot value. If a slot is of type `:stay`, a remote proxy is created, which refers to the local slot value. Garbage collection is extended to handle proxy references, as the next paragraph describes.

Object spaces An *object space* is realized as a Lisp image and resides on one host; it is assumed that each host processes only one object space. An object space contains some features realizing the functionality of a virtual machine (some realized as light weight processes (lwp) inside one Lisp image).

Object spaces communicate with each other by kernel messages. An object space contains one caller-lwp and one recipient-lwp for each object space it wants to communicate with. The caller-lwp packs the message to be sent (i.e., creates a Lisp form representing the message) and sends it via TCP/IP to the callee object space. The recipient-lwp unpacks the message and evaluates the resulting Lisp form.

Each object space contains an object store containing active objects which are referenced remotely. The store ensures exactly one proxy for each remote object, and it realizes a garbage collection method for remote objects. This is necessary, because the internal garbage collection method of Lisp is image specific and references of proxies (residing in a remote image) to objects are not considered. Thus, with the internal garbage collection method, an object would be garbage collected even if a proxy residing on another space refers to it. The remote garbage collection is carried out by counting remote references to each object, i.e. the reference count indicates in how many object spaces an active object is referenced. If a proxy in an object space is garbage collected, i.e. no more reference to the proxy is present in its object space, the counter of the related object is decremented. If the counter decrements to 0, the object is removed from the object store and, if no local reference is present, can be garbage collected by the internal garbage collector contained in each Lisp image. A problem not yet attended to are garbage collecting cyclic reference structures residing on distinct object spaces (see [19, 2, 28].

Furthermore, each object space contains an *object space manager* (or *object server*). Working with NetCLOS starts by loading NetCLOS into a Lisp image, which creates an initial object space on the host the Lisp image is started — the server host — and an initial manager — the server. This manager starts the virtual machine by giving it a number of (trusted) hostnames. On each host, an object space is started, is initialized by some initialization forms, and the communication links are established, which connect the object spaces to each other. Thus, a fully connected communication structure is created (realized by lwps as described above). Furthermore, the manager ensures an equal global context of classes and functions. When classes and functions are loaded into an object space with the new form `defpsystem`, the manager sends an appropriate message to all object spaces ensuring a loading of the same classes and functions in those other spaces. If one object space stops working (e.g. because the Lisp image quits), it sends a specific message to each object space, which can react appropriately and can proceed working. In the current implementation, only the server can start object spaces, object spaces cannot connect to the server from outside. Thus, client-server structures on the object space level are not yet realizable.

Integration of NetCLOS in CLOS There are two point of views to consider when integrating NetCLOS into CLOS: the implementors view and the application programmers view. From the implementors view, NetCLOS is integrated into CLOS portably, i.e., without changing the implementation of CLOS. Even more, by extending the existing features, a small extension of the behavior of CLOS yields to big extension of expressability. E.g., the slot access is extended by the possibility of defining moving behavior for slots. A slot access protocol inherent in CLOS is extended to handle this moving behavior and thus, every slot access for active objects is changed. From a programmer's point of view, this is done by the same programming interface, i.e., the slot access function does not change to, e.g., special proxy access functions like `proxy-value`. Besides extending the slot access generic function metaclasses are integrated in NetCLOS for describing generic functions to be handled as messages, i.e. for each method call special methods for testing the active object's location (local or remote) and selecting the appropriate send style (now, past, future) are automatically integrated by these metaclasses. Furthermore, for each class c, whose instances can be moved, a subclass *proxy-c* is

created. This class is of type *proxy-class*, a metaclass, which implements proxy behavior. For example, this metaclass creates only instances, which does not contain any slots, but sends slot references as messages to a remote instance, which contains the slots. Thus, with *proxy-c* the instance allocation protocol and the slot access protocol are extended.

This approach of extending CLOS is possible because of the existence of a metaobject protocol [17], which clearly specifies the behavior of diverse CLOS features, like slot access, method combination, and inheritance behavior. The extensions are portable in the sense that each CLOS implementation based on the metaobject protocol can be extended by NetCLOS. The usage of the metaobject protocol is different to a library approach where a number of functions have to be introduced and learned before a parallel program can be written. For further reading on this point, see also [12].

Thus, from a programmer's point of view, the extensions fit well in the programming style of CLOS. Even the programming of message passing instead of generic function calls are acceptable, because it is realized as a special generic function call.

Integration of NetCLOS in Lisp One aspect of Lisp is the usage of closures, i.e. a combination of a function and an environment containing all variable bindings (including free variables) necessary to evaluate the function [8]. In Common Lisp, closures are managed by the Lisp implementation and hidden to extension implementors, like us, i.e. no metaobject protocol for this part of Lisp is given. Thus, we introduce the new construct *remote-let* defining an environment which is activ, when a message is evaluated in an object space. Such an environment is transfered to an object space before the message is sent. It should contain every free variable, which is referenced in the method answering the message.

Other aspects of Lisp like dynamically created functions are not yet handled by the current implementation. However, NetCLOS is used to implement parallel object-oriented programs based on CLOS.

3.5 An example of programming with NetCLOS

This complete (toy-)example shows how future-messages are used. It contains every code necessary for testing the example on a number of hosts (given with `host-names`). It only presumes a lisp image containing NetCLOS (denoted by `<lisp-image-name>`). In `make-parallel-list` a list of arbitrary distributed active-objects is created starting with a normal passive list. In `mappar` a function is called for each element of a list of active objects. If these active objects reside on different machines, the function is computed in parallel. While `mappar` is called for the tail of the list (*) the function is called in parallel for the head of the list (**). If the function is computed the result for the tail is fetched (***). Symbols used from the NetCLOS package are indicated with `nc:`.

```
(defun start-machine (host-names)
   (nc:start-virtual-machine host-names
                             :image <lisp-image-name>))
(defun next-host ()
  (elt (random (length (nc:spaces nc:*manager*)))
       (nc:spaces nc:*manager*)))
(defclass parallel-list ()
   ((head :accessor head :initarg :head)
    (tail :accessor tail :initarg :tail))
  (:metaclass nc:netclos-object))
(defun make-parallel-list (passive-list)
   (cond ((null passive-list) nil)
         (t (make-instance
                'parallel-list
                :head (car ele)
                :tail (make-parallel-list (cdr passive-list))
                :location (next-host)))))
(nc:defpargeneric mappar :future (list function))
```

```
(defmethod mappar ((list null) (func function))
     ()) ;;; for empty lists
(defmethod mappar ((list parallel-list) (func function))
   (let ((tail-result (mappar (tail list) func)) ;;;(*)
     (make-instance 'parallel-list
           :head (funcall func (head list)) ;;; (**)
           :tail (nc:touch tail-result)))))  ;;; (***)
```

The implemented parallel list is used like this:

```
(setq *pl* (make-parallel-list '(a b c d e f h h)))
(mappar  *pl* #'print)
```

Where the symbols are printed in distinct lisp listeners.

4 Introducing parallel abstractions for programming AI applications

Parallel programming is a difficult task, because of the possibly big number of flows of control. In low-level parallel languages the handling of these flows is left to the programmer. To make parallel programming easier, we introduce an additional layer between low-level constructs (as described in NetCLOS) and the application programming level - the structure-oriented programming level (see Figure 1). The main task of this level is the abstraction of parallel flows of control, where a flow of control is directly combined with the structure of the data to be processed.

Consider the control abstractions described in Figure 4. A program with a single flow is a sequential program. Programs with multiple flows can be of different types - independent or dependent flows. The flows are independent of each other if there are no common used data. We distinguish three types of dependency structures. A *fixed* dependency structure is known at developers time[4] and thus, can be expressed by static data structures. A *derived* dependency structure is not known at developers time but functions can be given which are used to compute the dependency structure. This computation is done before the parallel processing takes place. If the dependency structure is computed uring the parallel processing we speak of *dynamic* dependency structure. Each dependency structure demands a distinct load balancing and synchronization strategy. With this scheme not concurrency and distributed mechanisms are described with classes but structure of data. Concurrency mechanisms are introduced for classes of the structure-oriented level and may be totally different for distinct classes. This is no drawback, because experiences show that synchronization is difficult to specify and moreover to reuse, because of the high interdependency between the synchronization conditions for different methods [4].

For programming complex structures classes are introduced, which belong to specific dependency structures. For image processing e.g. each pixel can be computed independently and the size and type of the structure is known in advance. Therefore, a parallel array is used to implement an image. For constraint filtering the structure of a constraint net is not known at developers time but can be computed before parallel processing. Thus, the parallel abstraction *relaxation net* has a derived dependency structure. For the distribution of such a dependency structure static scheduling with Task Interaction Graphs is used. The distribution is realized by the library CHACO [6]. The use of such a library reflects the fact, that results coming from distributed systems are not reimplemented for our needs, but are used and connected to Lisp when necessary.

4.1 An example structure — the parallel bag

An example of a master-worker algorithm for computing a best search is given in Appendix A, it shows a typical communication scheme. A master distributes the work to be done to several workers at hand. But this implementation still contains some application specific functions like `compute-successor`. Thus, it is only useful for the specific problem of computing best search. An abstraction of this

[4] i.e. the time when the application program is written down.

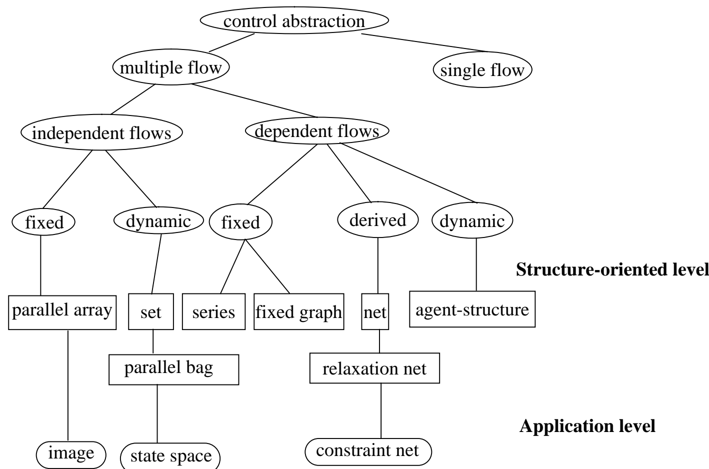

Fig. 4. Control abstractions and their integration in application classes.

communication scheme would enable multiple applications to make use of it. The abstraction *parallel bag* hides the necessary communication scheme (a NetCLOS program) to an application programmer. The view at a parallel bag is as follows: One has a bag where balls can be put into. A ball contains an object, some arguments and a function-name. When a ball is put into the bag, the ball is evaluated by the bag. The bag will call the function with the object and the arguments and put the result in the ball. If the evaluation of the ball is completed, the ball jumps out of the bag and the programmer can catch it. If multiple balls are put into the bag, the parallel bag probably will evaluate them in parallel. Thus, for an application programmer following functions are given: `create-bag`, `create-ball`, `put-ball`, `get-next-result`. The abstraction handles the distribution of balls on the virtual machine and calls the function of each ball for computing the result. In the example, the application specific function `compute-successor` is used as a ball function.

4.2 Another example structure — the relaxation net

Relaxation net is an abstraction implementing parallel discrete relaxation (see [11] for a similar approach). It consists mainly of

- a class of active objects (*value nodes*) acting as shared stores. Accesses to these stores are automatically synchronized, i.e. this is done by the NetCLOS level. These active objects can be used to implement the variables of a constraint net.
- a class of active objects (*function nodes*) which, when activated, computes a function of the content of a set of stores. These active objects can be used to implement constraints.
- a structure class which organizes stores and functional objects into a network and provides for iterated activation and parallel execution of the functional objects (i.e. a relaxation operation). This *relaxation net* can be used to implement a constraint net.

To distributed the *relaxation net* function and value nodes are modeled as tasks of a Task Interaction Graph. To distribute this graph on a workstation cluster we use a combination of bisection [30] and the Kernighan-Lin algorithm [16].

The main operation on relaxation nets is a function, which computes a fixed-point. This function can be processed in parallel if the domain of the function can be partitioned in parts and the function itself can be partitioned in independent component functions (see [32, 11] for details and Appendix

B). To use the parallel abstraction *relaxation net*, the application programmer implements subclasses of the value and function node classes and the structure class *relaxation net*, redefining some methods, i.e. implements a normal object-oriented sequential interface. There is no need for any explicit parallel programming (see Appendix C).

4.3 Another example — implementing distributed AI applications with NetCLOS

In distributed AI besides others the concept of communicating agents is present. Agent structures are not yet implemented with NetCLOS, but can be realized as follows. To implement an agent an active object can be used. On which host an agent proceeds can be fixed by the user or can be decided by the system (realized by a simple distribution scheme of round robin, see section 3.4), e.g. each agent can reside on a distinct object space. Furthermore, it is possible to add new agents dynamically. For diverse agent communication schemes, e.g. direct communication of agents or blackboard architectures, necessary message protocols can be implemented by NetCLOS messages. Concrete steps may be as follows: a virtual machine consisting of n object spaces is started from the master host. Agents possibly of distinct types are created by the master and distributed to the object spaces. A past-message e.g. *do-work* starts the action of each agent, which may perform different problem solving tasks. The agents work in parallel and may communicate by further messages to each other.

5 Experimental results

We tested NetCLOS by implementing a parallel abstraction named *relaxation-net* (see also [11]), which contains a net-like reference structure of active objects and a fixpoint operation on that structure. The net is distributed on a workstation cluster by the abstraction and the operation is executed in parallel on diverse parts of the net, i.e., distribution and parallel processing is done by the abstraction. This abstraction is used for implementing a local propagation algorithm for constraint nets, i.e., on this level only the sequential interface of the parallel abstraction must be known to an application programmer.

To get a gain by parallel execution of a NetCLOS program, one has to take high communication costs into account which are related to the infrastructure of a workstation net, e.g., an ethernet or TCP/IP. Thus, as usual in such a case, the computation time on one host should be high enough to compensate the communication costs. This is also the result of experiments we made. When solving a line-diagram labeling problem [25], we only got a speed up for constraint propagation when raising the number of constraints (see Figure 5). The speed up strongly depends on the communication traffic on the ethernet and on the kind of workstations used, which are typically heterogeneous (e.g. from Sparc Classics to Ultra Sparcs). The distribution strategy does not yet consider such kind of information. Because of using a derived not a dynamic structure the constraint net is first created on one object space and than distributed to the other. This still yields to high distribution costs, which are not included in the presented results. Furthermore, all experiments are executable on only one machine. However, the experiments show that one can get a speed up for constraint propagation, when using NetCLOS.

Because NetCLOS is integrated in Common Lisp its programming environment (profiler, debugger, editor etc.) can be used also for each object space separately. To illustrate parallel issues of programming (e.g. communication costs) specific environment extension would be useful but are still not realized (see e.g. [24]).

In another example, we examined qualitative simulations of electric circuits of fork-lift trucks. For a diagnosing task of such a technical system our conception requires the simulation of all single and some selected multiple faults of technical systems. The simulation is done qualitatively because faults like "lossy wire" cannot expressed quantitatively [15, 23]. However, the necessary simulations can be considered independently and therefore are easy to parallelize. But alternative distributions of the task are possible. For example, each simulation of a fault can be seen as one task, or all simulations of one component (like a resistor or a wire) can be seen as one task. With an parallel abstraction describing such alternatives we could evaluate them and got a quite useful speed up of 3.4 when using 4 workstations and a component wise distribution.

	1Workstation	2Workstations	4Workstations
Stairs (5)	1	0,68	0.34
Stairs(20)	1	1,2	0.75
Stairs(200)	1	1,63	2,08

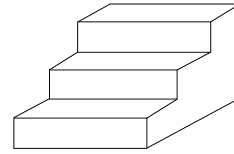

Fig. 5. Speed-up when increasing problem size (given here in number of stairs n of diagrams like the right one) and number of workstations. For 1000 stairs we got a speed up of 3.6 for constraint propagation on 7 machines. The number of constraints is $6n + 7$ and of variables is $4n + 7$.

6 Related work

The work on NetCLOS is derived from concurrent object-oriented programming languages related to actors [9, 1, 33]. Thus, the notion of active objects, proxies, asynchronous and synchronous message passing etc. is similar. However, our main interest is to integrate such concepts into Common Lisp and CLOS as a language used for AI applications. In NetCLOS, the integration of concurrent object programming is done in the CLOS programming style by introducing new subclasses, metaclasses, declarative method combination, slot options, and protocols. Thus, a CLOS programmer can use NetCLOS without learning a new parallel language.

The extension of CLOS by active objects enables parallel object-oriented programming, and thus, parallel abstractions. Other approaches [34] introduce mainly function-oriented parallel programming in Lisp by allowing parallel execution of functional arguments. A precondition for these approaches is a side effect free programming style, which is not realizable in realistic Lisp applications. Furthermore, functional approaches often generate a big number of small tasks, which increase the overhead.

Another Lisp related implementation for parallel programming is Kali Scheme [5]. Besides very similar features like adress spaces, proxies, diverse communication primitives, the main difference is that in Kali Scheme first class continuations and first class procedures are supported for programming in continuation-passing style. The integration of these concepts into Common Lisp is only possible with non-portable access to the Lisp implementation, because of the lack of first class continuations and a metaobject protocol for the functional part of Lisp. However, our interest is more a practical one: First, instead of using Scheme, we use Common Lisp because of its use in application programming for realizing e.g. simulation, configuration, diagnosing, and information managment systems. Second, we use Common Lisp and add the extension modul NetCLOS to it instead of defining a new language to enable the usage of existing Lisp programs.

Other approaches like CMLisp [10] introduces data parallel abstractions. This showed that programming with abstractions can simplify parallel programming, but CMLisp is restricted to run on single instruction multiple data machines (i.e. the Connection Machine 2) and thus, is hardly usable for workstation clusters. This is similar to [11], where a relaxation operation is introduced to solve constraint problems, but the implementation is done on a Sequent Symmetrie, not on a more common workstation cluster.

In [26] a similar parallel programming model as described by us is introduced. E.g., mobility of objects, interoperability, open object architecture, distributed storage management is included in the model. However, our focus is a more practical one, e.g. using Common Lisp instead of EuLisp because a lot of work is done by us in Common Lisp. This can also be seen in the target architecture, which is a virtual shared memory on the KSR-1 in EuLisp and a net of workstations in NetCLOS [3].

A further similar approach is described in [29]. In this approach distributed objects are introduced with the new language DMeroon, which provides a distributed shared memory above which computations may be done. In [29] the internal representation of distributed objects as specific vectors is emphasised. In NetCLOS because based on CLOS such aspects are inherited from CLOS. Also, further aspects like generic function or method invocation are used from CLOS and must not be reimplemented like in DMeroon.

7 Conclusion

A fully integrated concept and implementation (called NetCLOS) of a parallel object-oriented language is presented as an extension to the Common Lisp Object System (CLOS). With NetCLOS, active objects, asynchronous and synchronous message passing, synchronization features, separation of parallel programming and distribution aspects, and transparent remote access are introduced in CLOS. These extensions are integrated into the CLOS programming style by extending generic functions, slot-options and metaclasses. Thereby, a virtual machine consisting of several Lisp images residing on a workstation cluster can be programmed. This is a new extension of Common Lisp in the direction of a parallel object-oriented language using active objects. Other approaches (like, e.g., [34]) extend the functional part of Lisp.

NetCLOS was used to implement a high level programming language based on abstractions for parallelization. The main point of this structure-oriented language is to introduce control abstractions, because multiple flows of control make parallel programming difficult. These control abstractions are realized by giving diverse predefined classes (like parallel-array, net, series) to the application programmer. These classes hide specific synchronization and load balancing schemes. Beside other applications, a constraint system is implemented with this language where constraints and variables are distributed over a workstation net and proceed in parallel. For distribution a Task Interaction Graph model in coordination with bisection and the Kernighan-Lin algorithm is used. For an appropriate problem size a speed up for constraint propagation could be achieved.

NetCLOS as an extension to Allegro Common Lisp ACL 4.3 can be received from the authors. NetCLOS and parallel abstractions might be useful for AI programmers already working with Common Lisp and intending to use a workstation cluster for computation. Especially distributed and parallel applications can be tested with the virtual machine used by NetCLOS. To implement it in Lisp implementations other than Allegro, the implementation of light weight processes and the metaobject protocol must be available.

A A further NetCLOS example

To illustrate the usage of NetCLOS we present a short example implementing a best search. A complex request-reply frame is realized. In the implementation of a master-worker algorithm for parallel best search presented here, after sending requests to diverse workers (see (*)) the master waits for the first incoming response which is not specified in advance (see (**)), thus, described by "?". Using a future, the master would have to decide which reply should be computed first (by calling `touch` to a specific future), not considering if the related worker has finished computation. Thus, for this communication scheme the future mechanism is too restrictive. We therefore use explicit past-messages:

```
(defclass bs-worker ()
    ;;; No Slots
   ()
  (:metaclass netclos-object))

(defclass bs-master ()
   ;;; Some Slots
   ((ordered-node-list :accessor ordered-node-list)
    (solution-list :accessor solution-found :initform nil)
    (free-workers :accessor free-workers
                   :initform (create-workers)))
  (:metaclass netclos-object))

(defpargeneric best-search :now (master root-node))
(defpargeneric request :past (worker node))
(defpargeneric reply :past (master successors))

(defmethod best-search ((master bs-master) (root node))
```

```
   (setf (ordered-node-list master) (list root))
   ;;; Until a solution is found
   (loop until (solution-found master)
      do
      (progn  ;;; Some operations follow
      ;;; While a free worker exists and
      ;;; there are nodes to expand do it:
        (loop while (not (or (endp (free-workers master))
                             (endp (ordered-node-list master))))
               do
               ;; The first free worker gets the next node to
               ;; expand, i.e., a communication takes place (*)
               (progn
                 (request (first (Free-workers master))
                              (first (ordered-node-list master)))
                 ;; The worker is working, yet not free.
                 (pop (free-workers master))
                 ;; The next successor was selected.
                 (pop (ordered-node-list master))))
        ;;; wait for a reply message (**)
        (wait-for (reply ? :from ?))))
    ;;; Give the solution as result
    (solution-found master))

(defmethod reply ((master bs-master) successors)
   ;; Set the worker to be free again. *caller* refers to a global
   ;; variable defined by NetCLOS, set to the caller of a message.
   ;; which is here a worker.
   (push *caller* (free-workers master))
   (loop for node in successors
     until (solution-p node)  ;; Solution found?
     ;;; if not store the new node in the list
     do (insert (ordered-node-list master) node)
     ;;; If found, store the solution node
     finally
     (when (solution-p node)
           (setf (solution-found master) node))))

   ;; A worker expands a node (i.e., computes its successors) and
   ;; sends the expanded node list back to the master which is
   ;; for a worker the caller, indicated by *caller*.
(defmethod request ((worker bs-worker) (node node))
   ;; a communication takes place
    (reply *caller* (compute-successors node)))

      ;;; Definitions of compute-successors, insert,
      ;;; create-workers, and solution-p ommitted because of
      ;;; being ordinary Lisp code.
```

In this example the distribution of active objects of type `bs-worker` is totally done in the function `create-workers` (not shown). There, an appropriate distribution can be processed, e.g., by moving one worker object on each workstation. The code shown does not depend on the distribution of these worker objects. Thus, the programming with active objects and their distribution belong to different and unrelated parts of a NetCLOS program.

B Implementation of a parallel abstraction using NetCLOS

The implementation of a parallel abstraction (here the relaxtion net and the relaxation algorithm) should be done by a programmer familiar with concurrent object-oriented programming. Though it is easy for a CLOS-programmer to use NetCLOS some synchronizations have to be done on this level (see e.g. *wait-for*, *lock*).

The generic function *relax* is implemented as a past-message, i.e. can be processed in parallel. However, the distribution of the relaxation-net is totally separated from the object-oriented part shown here, by subclassing appropriate control abstractions. In Section 4 we choose a derived dependency structure with Task Interaction Graphs for computing the distribution. In *relax-net* for all function nodes (active objects) the function *relax* is called, which can be processed in parallel for each node (depending on the distribution strategy). Value nodes are reserved by the first function node which performs *lock*. *apply-function* is a part of the protocol for using the parallel abstraction. This function must reduce the value-nodes. The termination of the algorithm is controled by a simple count scheme realized by *acknowledge-count* (see [22]).

```
(defpargeneric relax-net :now (net))

(defmethod relax-net ((net relaxation-net))
  (loop for f-node in (function-nodes net)
      do (relax f-node)
      do (incf (acknowledge-count net)))
  (loop until (= (acknowledge-count net) 0)
      do (wait-for (acknowledge))))

(defpargeneric relax :past (f-node))

(defmethod relax ((f-node function-node))
  (if (> (acknowledge-count f-node) 0)
      (acknowledge *caller*)
    (setf (parent f-node) *caller*))
  (let ((values ()))
    (loop for v-node in (value-nodes-by-total-order node)
        do (lock v-node)
        collect (get-value v-node) into values)
    (setf values (apply-function f-node values))
    (loop for v-node in (value-nodes-by-total-order node)
        for value in values
        do (write-value v-node value)
        do (incf (acknowledge-count f-node))
        do (unlock v-node))))

(defpargeneric write-value :now (v-node value))

(defmethod write-value ((v-node value-node) value)
  (if (new-value-p v-node value)
      (progn (if (> (acknowledge-count v-node) 0)
                 (acknowledge *caller*)
               (setf (parent v-node) *caller*)))
    (set-value v-node value)
    (loop for f-node in (function-nodes v-node)
        do (relax f-node)
        do (incf (acknowledge-count v-node))))
  (progn (acknowledge *caller*)
         (setf (parent v-node) nil)))

(defpargeneric acknowledge :past (acknowledgeable))
```

```
(defmethod acknowledge ((obj acknowledgeable))
  (decf (acknowledge-count obj))
  (when (and (parent obj) (= 0 (acknowledge-count obj))
             (acknowledge (parent obj))
             (setf (parent obj) nil))))
```

C Implementation of an AI application using parallel abstractions

To use a relaxation net for implementing e.g. a constraint net following implementation by an AI application programmer should be done. The implementation consists of subclassing the classes given by the parallel abstraction and defining new methods for specific generic functions belonging to these classes.

```
(defclass constraint-net (relaxation-net)
  ()
  (:metaclass netclos-object))

(defclass constraint (function-node)
  ((relation :accessor relation :initarg :relation))
  (:metaclass netclos-object))

(defclass variable (value-node)
  ((domain :reader get-value :writer set-value
           :initarg :domain))
  (:metaclass netclos-object))

(defmethod function-node-class ((net constraint-net))
  (find-class 'constraint))

(defmethod value-node-class ((net constraint-net))
  (find-class 'variable))

(defmethod apply-function ((constraint constraint) domains)
  (loop for i from 0 upto (length domains)
      for domain in domains
      collect (filter domain constraint i))))

(defmethod new-value-p ((var variable) domain)
  (< (length domain) (length (get-value var))))
```

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