

Drift: an imperative programming environment for the cloud

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“If I had more time, I would have written a shorter letter.”

– Blaise Pascal

1 Introduction

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1.1 Goal of this work

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1.2 Structure of this work

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2 Distributed Programming

In 1937 a paper titled “*On computable numbers, with an application to the Entscheidungsproblem*”, written by Alan Turing, was published [1]. In it Turing defines what is now known as a *Turing machine*, a theoretical machine model for executing arbitrary computation. He demonstrates how to formulate instructions for this machine in order to configure its execution behavior and goes so far as to show how this machine could even receive another machine configuration as its input and then execute what the other machine would have done, thereby effectively emulating the given machine.

But he wasn’t the only one thinking about computation. As summarized by Denning in [2], Kurt Gödel, Alonzo Church and Emil Post all contributed to the task of exploring the boundaries of computation, setting the tone for the next 80 years of research concerning *computation*, *computers* and *automation*.

Of all the proposed approaches of how to tackle the concept of computation and turning it into a tool that could be understood and used by delivering a theoretical framework, one could argue that Turing’s machine model emerged as a winner because, although not at the time, it turned out to be closest to what machines became to be. How they were structured and how they basically operated. Still, to this day.

So in order to use or *program* these machines, these computers, programming languages were developed and over the decades have gone through their own evolutionary process [3] with the first generation using binary machine instructions to today’s languages that allow for higher level programming styles like *object oriented programming* [4] or *functional programming* [5].

2.1 Language Evolution

But no matter what mainstream programming language one looks at today, they all seem to have one thing in common, which also gets replicated by each new language that arrives: they are all focussing on describing computation. Computation executed

by a single core machine. Because for most of the last century, this was the problem we were facing.

However, with the advent of commodity multicore hardware [6] the problem domain changed. Today even a single machine isn't a single machine anymore, but rather a group of multiple CPU cores that can operate and compute independent of each other. Unfortunately mainstream languages are still struggling with delivering language concepts and *semantics* that allow for utilizing this new hardware. In Fig.1 one can see a very minimal multithreaded program written in Python, one of the most used languages today [7].

```
from threading import Thread

def count(n):
    while n > 0:
        n -= 1

t1 = Thread(target=count,args=(1000000,))
t1.start()

t2 = Thread(target=count,args=(1000000,))
t2.start()

t1.join()
t2.join()
```

Figure 1: Python multithreading example

As was shown by Beazley in [8] this multithreaded version is up to two times *slower* than the single threaded version and the reason for this is the so called *Global Interpreter Lock* (GIL) used by the Python interpreter which basically prevents multiple native threads from truly executing in parallel.

This is supposed to show how slow adoption and adjustment in the mainstream programming language market is happening, even for a problem domain that, as I would like to argue, is not even the most recent set of problems programmers today need to deal with.

This shows how important it is to reevaluate existing programming languages, their implementations and their methodologies whenever the underlying machine, system or problem domain changes dramatically.

Now one could argue that Python might have been a bad example and that other mainstream languages offer better adoption of multithreaded programming. Fig 2 shows another two examples of how threading is expressed in programming today, namely using the programming languages *Java* [9] and *Go* [10]. Although Java and its virtual runtime environment, the *Java Virtual Machine* (JVM) offer the capability of true concurrent execution of threads, threads still only exist as a library feature, not as a language primitive. They are created by overwriting specific methods that are inherited from either another class or an interface and are used like any other *object* in Java, an object oriented programming language.

This is supposed to represent the approach that has been favoured in programming language design of how to deal with a changing environment. Every new or extending aspect is hidden behind the *function call*, a core feature of the language. The result is that the language itself and its semantics virtually never change, and the true meaning of a plain function call is expressed on an external napkin so to speak. This eliminates

all possibilities for the compiler or any other tooling to aid in the development process because to the compiler the function call that is supposed to start a new thread looks exactly the same as any other function call.

Example 2b shows a newer language called *Go*. In Go threads are called *go routines* because their semantics are defined within the language itself and are created by the keyword *go*. On the one hand this allows any compiler or other tooling to automatically check, at compile time, whether certain rules of behavior are implemented correctly by the programmer but on the other hand it also delivers guarantees of said behavior to the programmer because these go routines will behave the same independent of the execution environment in which this code is run. Said behavior could vary when threads are only implemented as a library.

```
class Demo extends Thread {  
  
    public void run(){  
        System.out.println("foo");  
    }  
  
    public static void main(String args[]) {  
        Demo obj = new Demo();  
        obj.start();  
    }  
}
```

(a) Java threading example

```
package main  
import "fmt"  
  
func f(from string) {  
    for i := 0; i < 3; i++ {  
        fmt.Println(from, ":",  
            i)  
    }  
}  
  
func main() {  
    go f("goroutine")  
}
```

(b) Go threading example

Figure 2: Threading examples in Java and Go

This shows that language designs do react to dramatic change of the underlying machine model. They include important aspects of the execution environment and hardware as core features of the language in order to provide a programming environment sweetspot: as close to the hardware to be still implemented efficiently but abstract enough so programming becomes intuitive, productive and less error prone. Just like the Turing machine hit that sweetspot on the theoretical side.

However, compared to the switch from single core to multi core CPU systems, the more dramatic paradigm shift in my view was the advent of the *internet*, or large scale networking in general, because it dawned what is now known as the *information age*. Although this is a rather broad term, describing global change in almost all areas of modern society, I believe these changes can also be seen in the area of computing and computation. Because in order to deliver new products like: the world wide web, internet search, internet advertising, social networks, social media, music streaming,

video streaming, messenger services, navigation/maps, e-commerce etc. companies had to build massive computer networks in order to either store massive amounts of data or to simply scale their product to millions or billions of users and although almost all of the current products, apps, or services could not exist without the computation that is implemented inside their core parts, it is *communication* that has become the main obstacle for building large scale *information systems*.

2.2 Distributed Objects

So how did the tools, the programming languages we use, react to this paradigm shift? Well, Fig.3 shows an exemplary client and server implementation using a framework called *Java Remote Method Invocation* (RMI) which implements the more abstract request-and-response concept of *Remote Procedure Calls* (RPC).

```
public class ServerOperation extends UnicastRemoteObject implements
    RMIInterface {

    private static final long serialVersionUID = 1L;

    @Override
    public String helloTo(String name) throws RemoteException {
        return "hello to " + name;
    }
}
```

(a) Java RMI server providing the remote method 'helloTo()'

```
public class ClientOperation {

    private static RMIInterface look_up;

    public static void main(String[] args) {

        look_up = (RMIInterface) Naming.lookup("//localhost/MyServer");
        String response = look_up.helloTo("Frank");
    }
}
```

(b) Java RMI client calling the remote method 'helloTo()'

Figure 3: Java Remote Method Invocation example

The underlying concept that tries to unify object oriented programming and a dis-

tributed or networked system is often summarized as *distributed objects* [11]. As the names suggest, in this programming model, objects cannot only exist in the local address space but can also reside on remote machines with their methods hence being invoked remotely which by itself is not a bad idea.

But when one looks at how languages and frameworks implemented this new model one can see the same pattern as with multithreading libraries because the remote functionality and remote method calls are implemented by inheriting and overwriting certain methods on the server side and on the client side by instantiating a remote object and calling a remote method on that object. Unfortunately using the exact same syntax as for any local function call.

The difference of course is, that the remote procedure call, being remote, has to deal with different error and failure scenarios than any local method call. Hence it might throw some sort of remote exception which, from the view point of the client can be totally surprising, because syntactically there is no indication whatsoever that this is an action that involves the network or any remote machine.

The lesson here of course is the same as with concurrency support in programming languages because the underlying system changed in nontrivial ways but the distributed objects community tried to apply the same object oriented programming concepts and languages to this new domain, neglecting any additional and unique problems of this new setting and hiding all new functionality behind core language features, so that any new semantics were only available on a napkin and tool support was nearly impossible.

Unfortunately today, one could argue that the same approach is being used again in the context of highly distributed systems built after the microservice paradigm [12]. Fig.4 shows an example of a Python binding for using the *Amazon Web Services* (AWS) service called *Simple Storage Service* (S3) [13], [14].

```
import boto

s3 = boto.connect_s3()
bucket = s3.create_bucket('media.yourdomain.com')

key = bucket.new_key('examples/first_file.csv')
key.set_contents_from_filename('/home/frank/first_file.csv')

key.set_acl('public-read')
```

Figure 4: Amazon AWS S3 storage example using the Python interfacing library 'boto'.

This service is supposed to provide a remote storage solution, by storing arbitrary data objects behind unique keys. As can be seen in the official example [15] depicted in Fig.4 the unique names are being written using the same format as the widely used UNIX file systems. The example shows how a local file is being uploaded to the service.

This showcases that Amazon S3 is mostly used as a service providing a remote file system to its clients.

But again, from the language perspective of the Python interpreter, these remote calls are just normal *local* function calls because the semantics and functionality of the S3 service only exist in the informal documentation provided by Amazon without any formal specification and without any chance of automated tool support regarding syntax (parameters) or semantics.

This might be acceptable from a business perspective because already existing systems can easily be extended to use these new services but this puts all the responsibilities in the hands of the programmer and also enables vendor lock-in because the semantics are defined by the company providing the abstractions and not only can they change them whenever they choose, but also other companies can have a vastly different APIs and semantics.

2.3 The Actor Model

In the same way that new programming languages embrace the multicore nature of todays CPUs, I believe distributed programming and the languages that are used to build highly distributed systems should embrace the distributedness of the systems they describe and should provide special syntax and semantics for the unique problems inherent to the distributed systems domain and there are ideas and languages that support this view, as for example presented by Waldo et al. in [16].

On the language side an alternative paradigm to programming called the *Actor Model* [17], [18] has started to become widely adopted by the distributed systems community and implemented by languages like *Erlang* [19], [20] or *Pony* [21].

Since its perception in 1973 by Hewitt et al. [17], the actor model has received a great amount of attention in the academic community and has also been used to model concurrent computation as an alternative to the threading model. It is therefor also closely related to numerous process calculi like Hoare's *Communicating Sequential Processes* [22] and the Milner's *Pi Calculus* [23].

Erlang is an actor based functional programming language developed by Ericsson, a multinational telecommunications equipment and services company and was designed to be used by their telecommunications infrastructure.

The core concepts of the actor model as outlined in [24] and [18] can be summarized as follows. The actor model treats *actors* (or processes) as its universal primitives of computation. These actors are autonomous in the sense that each actors executed behavior is independent of the concurrent existence of other actors. However, in order to interact with others, actors can send and receive messages as

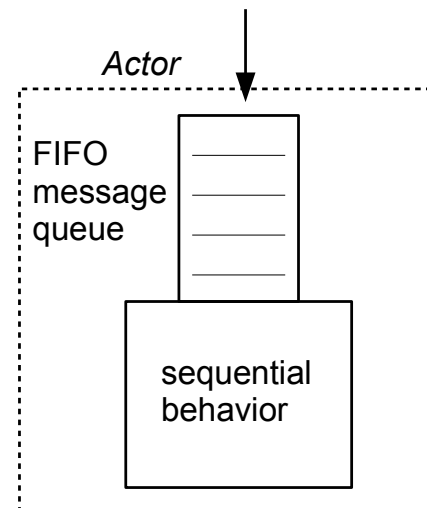


Figure 5: Concept of an *Actor* as defined by the actor model.

illustrated in Fig.5. So each actor consists of its single threaded behavior and a single input message queue.

The actor can now decide whether or not and how to react to its incoming messages and can also send messages directly to other actors. Its behavior itself though is single threaded. The concurrent nature of an actor based system lies within the actor model itself because of the actors being executed independent of each other.

This also means that the only means of communication, namely message passing, is *asynchronous* by default. The actor model itself does not define any receipt or acknowledgement mechanism for messages received by an actors input queue. Any such communication protocol must be implemented by the actors themselves, e.g. by programming their behavior to send an acknowledgement to the sender once a message is processed. This means that, using the plain actor model, a sender cannot only not infer whether or not its message was processed or perceived by its receiver, it can't even infer whether or not the message ever reached the receiver.

This seems ludicrous compared to the implicit safety and messaging guarantees promised by the *distributed objects* approach presented in chapter 2.2 where synchronous messaging is as *easy* as a local function call. But this seemingly pessimistic approach to messaging turns out to be acceptably close that what must be anticipated when dealing with messaging in highly distributed systems on the data center and cloud scale.

So again the actor model seems to provide a sweetspot because on the one hand it encompasses characteristic properties of highly distributed systems, i.e. virtually no message delivery guarantees, thereby forcing the developer to deal with these circumstances in her program structure and application design and on the other hand provides small, independent and single threaded units of computation in order to build more abstract and higher level distributed applications.

```
-module (send_recv).
-export([export_all]).

serve() ->
  receive
    Request ->
      io:format("received request~n"),
      serve()
  end.

run() ->
  Pid = spawn(?MODULE, serve, []),
  Pid ! Request,
  ok.
```

Figure 6: Erlang example of how to spawn an Actor using the *spawn* function and how to use the messaging operator *!*

Since Erlang is an actor based language, Fig.6 shows a small example. It spawns an actor executing the user-defined *serve()* function. Spawning an actor is done using the built-in *spawn()* function. The *serve()* function contains a *receive-loop*, another Erlang built-in indicated by the *receive* keyword. This loop listens for incoming messages and tries to match any incoming message to any of the given patterns. So it can be thought of as the combination of an implicit event loop and a switch-case statement.

In the case of this example any message that consists of only a single atom will be matched to the user-defined Request

pattern, triggering a simple console print and a recursive call to restart the receive loop. This is important because when the receive loop is entered it will wait for incoming messages indefinitely unless a timeout is specified. When a message arrives at the inbox that can be matched against one of the provided patterns it will be processed as programmed. When there are multiple messages in the actors inbox that could be matched against some provided pattern only one of them is being process and it is up to the actor when to reenter the receive loop in order to process the remaining messages.

To address the actor or process created by the call to *spawn()* a process identifier (PID) is returned by *spawn*, which is the only way to attain such an identifier. In order to send messages to this PID Erlang provides the messaging operator *'!'*.

This shows that message passing is an integral part of the core language, including its pessimistic delivery guarantees (none), and specified by the language itself. These semantics are therefor not loosely defined in some library documentation that could change any minute but are guaranteed to the programmer, independent of the language implementation or execution environment.

Unfortunately there is a down side to this approach. Since the actor model focusses so heavily on its actors, the result is that the actual description of the system happens implicitly and indirectly. It is more like the system *emerges* out of all the little steps and interactions of its components. To the effect that, given a running system of maybe a hundred or a thousand actors [25], how would one come to understand what the system as a whole is doing?

There is no other option than to just pick any actor and start reading its code. This means one is forced to reverse engineer the behavior of the entire system from the internal behavior of its parts which, needless to say, can be quite error prone and introduces nontrivial cognitive overhead. In other words, there is no way to take a look at the system from the birds-eye perspective because most people believe this implies introducing some form of global state which would be against any of the goals of the actor model with its asynchronous message passing and independent processes.

3 Related Work

This chapter will present different ideas and projects which have served as motivation and inspiration not only for the *Drift* language but for the entire *Drift* project.

First two talks by Rich Hickey will be presented and the relevant aspects will be extracted. The first talk discusses the necessity and design of a “Language of the System”, especially in the context of highly distributed systems and the second talk introduces the concepts of *place oriented programming* and *value oriented programming* with an emphasis on the importance of immutable data in programming language design.

Then, as a representative of the *functional programming* approach, *Cuneiform*, a functional scientific workflow language and *HiWay*, its distributed execution engine will

be introduced. Both of which are being developed here at the Humboldt University of Berlin at the department of bioinformatics (WBI) and have served as a major source of inspiration and opposing concepts.

After that, core concepts of UNIX-like operating system design and more importantly of the UNIX shell *bash* as one representative of a typical UNIX shell are being introduced. Especially a mapping between the language constructs of the *bash* shell and core concepts of functional programming languages will be presented.

Furthermore a new distributed data base project will be introduced which tries to combine the functional programming concepts of immutable data and value orientation with the distributed data base context of data accretion, distributed logging, time series data and streaming.

Then a talk by Bret Victor will be summarized in which he presents his idea of *immediate feedback* in the context of programming and tooling for programming. In this talk he showcases multiple prototypes which show how to interactively visualize code and how this could be used to aid the process of developing software. The most relevant feature presented will be a *time bar* which allows to interactively go back and forth through past states of the code and the actively running program.

At last the source code version control system *git* will be introduced because it shows how a seemingly stateful system on the user facing side can be implemented on top of an immutable, append only file system of objects addressed by hashes of hashes.

3.1 The Language of the System

Rich Hickey is most widely known as the creator and *Benevolent Dictator for Life* (BDFL) [26] of *Clojure* [27], [28], [29], [30], a functional programming language and Lisp [31], [32] dialect. Clojure runs on the Java virtual machine to allow Java and Clojure interop in order to utilize the extensive collection of already existing Java libraries.

Clojure is therefor not a *pure* [33] functional programming language but should rather be considered a pragmatist's compromise of having immutable data by default but allowing for easy I/O and statefulness whenever needed.

Although Clojure's *front end* (its syntax) looks a lot like Lisps syntax, which is notorious for its extensive use of parenthesis, Clojure's *back end* (its implementation) focusses heavily on very modern features like *software transactional memory* [34] and *persistent data structures* [35] aimed at highly concurrent programming.

Hickey himself has been promoting these features as necessary upgrades to the object oriented view on programming in order to fully utilize multicore architectures and is an avid visitor of conferences of programming language design. He therefor has a considerable collection of talks and lectures in which he explains his rationale behind his design decisions [36], [37].

One of his more relevant talks regarding the work presented here is called "The Language

of the System”¹ held at *Clojure Con* 2012 [38], [39]. In it Hickey criticizes what has already been outlined in chapter 2.3, namely that distributed *systems* today are being built indirectly by programming individual units and components and then running them simultaneously, hoping that a distributed system will almost magically emerge but lacking any description whatsoever of that system as a whole.

The reason for this, he claims, is that the languages and tools we use to build each individual component have been developed to do exactly this: describe *programs*, describe encapsulated self-contained blocks of computation. They don’t provide any means of describing how to compose these components, because they don’t provide any primitives for how they *communicate*.

As can be seen in Fig.7 he draws parallels to how we haven been building our programs in order to derive similar properties for our system composition and description. For example he proposes that the language of the system too, would have primitives just like the programming languages that we have been using so far. But instead of having primitives of computation like built-in data types and arithmetic operators, in the systems context these primitives would be primitives of *communication* like communication protocols or data formats. On top of which simple core services need to be available in order to compose higher level application logic, just like core libraries like the GNU C library (glibc) [40] or any other standard library of any common programming language provide essential building blocks for programmers to compose their programs.

So the relevance of this talk to the work presented here is, that it sparked the question of whether or not it would be possible to build such a composition language of the system that allowed a global perspective without introducing global state and how such a language would look like.

The other talk by Hickey which is relevant to this work and which I would like to summarize here is called “The value of values” and was held at the GOTO Conference

Program	System
Application libs	Application as services
Runtime and core libs	Simple Services
Language primitives	Protocols and formats

Figure 7: Slide-excerpt from the talk “The Language of the System” by Rich Hickey that draws parallels between the composition of (local) programs and distributed systems.

¹In the context of this talk and for the rest of the work presented here the word *system* does not mean *low-level* or *bits and bytes* as in operating system but rather means the system as a whole as from a bird’s-eye view and more as described by something like systems theory.

2012 as well as the JaxConf 2012 [41], [42], [43], [44]. Probably being his most famous talk, in it Hickey bootstraps his views on programming and language design by putting *immutable data* at the center of programming and deriving the advantages of core functional programming concepts from that. He introduces two programming paradigms, namely *place-oriented programming* and *value-oriented programming*. A *place* in Hickey’s view literally represents a place in reality. Something where one can put things and where they reside. If one replaces the thing that already resides in a place with some other thing, the information of that exchange is never recorded. Places don’t record their exchange *history* so to speak. Every exchange *overwrites* the current content of that place. To the effect that the value received from querying a place depends on the point in *time* when the query was executed. The value of the place is inherently intertwined with time, which is what is generally known as *state*. This represent the bulk of programming language history. It even represents the slots on the band of a Turing machine, which can be overwritten by said Turing machine with symbols defined in its alphabet. We have built hardware like memory and hard drives but also our software like data bases and file systems after this principle. They provide slots of storage which can carry a value but can be overwritten so the new value replaces the old and the value received from querying a place depends on the moment in time of the query.

In order to exemplify this concept, Fig.8 shows a very basic representation of what could be a *SQL* table. This table stores data using the schema of (*ID*, *First Name*, *Last Name*, *Email*).

STUDENT ID	FIRST NAME	LAST NAME	EMAIL
954731	Frank	Lange	foo@bar.com

a) SQL-like student table containing old email address

STUDENT ID	FIRST NAME	LAST NAME	EMAIL
954731	Frank	Lange	bar@foo.com

b) Same table after the update of the email address

Figure 8: Place-orientation exemplified by a SQL table, each cell being a place.

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Selbständigkeitserklärung

Ich erkläre hiermit, dass ich die vorliegende Arbeit selbständig verfasst und noch nicht für andere Prüfungen eingereicht habe. Sämtliche Quellen einschließlich Internetquellen, die unverändert oder abgewandelt wiedergegeben werden, insbesondere Quellen für Texte, Grafiken, Tabellen und Bilder, sind als solche kenntlich gemacht. Mir ist bekannt, dass bei Verstößen gegen diese Grundsätze ein Verfahren wegen Täuschungsversuchs bzw. Täuschung eingeleitet wird.

Berlin, den February 9, 2017

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