Liquid IT : Toward a better compromise between development scalability and performance scalability not definitive

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Abstract

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Résumé

Internet étend nos moyens de communications, et réduit leur latence ce qui permet de développer l'économie à l'échelle planétaire. Il permet à chacun de mettre un service à disposition de milliards d'utilisateurs, en seulement quelques heures. La plupart des grands services actuels ont commencé comme de simples applications créées dans un garage par une poignée de personnes. C'est cette facilité à l'entrée qui a permis jusqu'à maintenant une telle croissance sur le web. Google, Facebook ou Twitter en sont quelques exemples. Au cours du développement d'une application, il est important de suivre cette croissance, au risque de se faire rattraper par la concurrence. Le développement est guidé par les besoins en terme de fonctionnalités, afin de vérifier rapidement si le service peut satisfaire l'audience. On parle d'approche modulaire des fonctionnalités. Des langages tel que Ruby ou Java se sont imposés comme les langages du web, justement parce qu'ils suivent cette approche qui permet d'intégrer facilement de nouvelles fonctionnalités.

Si une application répond correctement aux besoins, elle atteindra de manière virale un nombre important d'utilisateurs. Son audience peut prendre plusieurs ordres de grandeurs en quelques jours seulement, ou même en quelques heures suivant comment elle est relayée. Une application est dite *scalable* si elle peut absorber ces augmentations d'audience. Or il est difficile pour une application suivant l'approche modulaire d'être *scalable*.

Au moment où l'audience commence à devenir trop importante, il est nécessaire de modifier l'approche de développement de l'application. Le plus souvent cela implique de la réécrire complètement en utilisant des infrastructures *scalables* qui imposent des modèles de programmation et des API spécifiques, qui représentent une charge de travail conséquente et incertaine. De plus, l'équipe de développement dois concilier cette nouvelle approche de développement *scalable*, avec la demande en fonctionnalités. Aucun langage n'a clairement réussi le compromis entre ces deux objectifs.

Pour ces raisons, ce changement est un risque pour la pérennité de l'application. D'autant plus que le cadre économique accorde peu de marges d'erreurs, comme c'est le cas dans la plupart des start-up, mais également dans de plus grandes structures.

Cette thèse est source de propositions pour écarter ce risque. Elle repose sur les deux observations suivantes. D'une part, Javascript est un langage

qui a gagné en popularité ces dernières années. Il est omniprésent sur les clients, et commence à s'imposer également sur les serveurs avec Node.js. Il a accumulé une communauté de développeurs importante, et constitue l'environnement d'exécution le plus largement déployé. De ce fait, il se place maintenant de plus en plus comme le langage principal du web, détrônant Ruby ou Java. D'autre part, l'exécution de Javascript s'assimile à un pipeline. La boucle événementielle de Javascript exécute une suite de fonctions dont l'exécution est indépendante, mais qui s'exécutent sur un seul cœur pour profiter d'une mémoire globale.

L'objectif de cette thèse est de maintenir une double représentation d'un code Javascript grâce à une équivalence entre l'approche modulaire, et l'approche pipeline d'un même programme. La première répondant aux besoins en fonctionnalités, et favorisant les bonnes pratiques de développement pour une meilleure maintenabilité. La seconde proposant une exécution plus efficace que la première en permettant de rendre certaines parties du code relocalisables en cours d'exécution.

Nous étudions la possibilité pour cette équivalence de transformer un code d'une approche vers l'autre. Grâce à cette transition, l'équipe de développement peut continuellement itérer le développement de l'application en suivant les deux approches à la fois, sans être cloisonné dans une, et coupé de l'autre.

Nous construisons un compilateur permettant d'identifier les fonctions de Javascript et de les isoler dans ce que nous appelons des Fluxions, contraction entre fonctions et flux. Un conteneur qui peut exécuter une fonction à la réception d'un message, et envoyer des messages pour continuer le flux vers d'autres fluxions. Les fluxions sont indépendantes, elles peuvent être déplacées d'une machine à l'autre.

Nous montrons qu'il existe une correspondance entre le programme initial, purement fonctionnel, et le programme pivot fluxionnel afin de maintenir deux versions équivalentes du code source. En ajoutant à un programme écrit en Javascript son expression en Fluxions, l'équipe de développent peut le rendre *scalable* sans effort, tout en étant capable de répondre à la demande en fonctionnalités.

Ce travail s'est fait dans le cadre d'une thèse CIFRE dans la société Worldline. L'objectif pour Worldline est de se maintenir à la pointe dans le domaine du développement et de l'hébergement logiciel à travers une activité de recherche. L'objectif pour l'équipe Dice est de conduire une activité de recherche en partenariat avec un acteur industriel.

Contents

Chapter 1

Introduction

When the amazed 7 years old I was laid eyes on the first family computer, my life goal became to know everything there is to know about computers. This thesis is a mild achievement. It compiles my PhD work on *bridging the gap between development scalability, and performance scalability, in the case of real-time web applications.*

illustration: amazed child in front of a computer

This work is the fruit of a collaboration between the Worldline and the Inria DICE (Data on the Internet at the Core of the Economy) team from the CITI (Centre d'Innovation en Télécommunications et Intégration de services) at INSA de Lyon. For Worldline, this work fall within a larger work named Liquid IT, on the future of the cloud infrastructure and development. As defined by Worldline, Liquid IT aims at decreasing the time to market of a web service, allows the development team to focus on service specifications rather than technical twists and ease service maintenance. The purpose of my work, was to separate development scalability from performance scalability, to allow a continus development from prototyping phase, until runtime on thousands of clusters. On the other hand, the DICE team focus on the consequences of technology on economical and social changes at the digital age. This work falls within this scope as the development of web services is driven by economical factors.

1.1 Web development

The growth of web platforms is partially due to Internet's capacity to allow very quick releases of a minimal viable product (MVP). In a matter of hours,

it is possible to release a prototype and start gathering a user community around. *"Release early, release often"*, and *"Fail fast"* are the punchlines of the web entrepreneurial community. It is crucial for the prosperity of such project to quickly validate that the proposed solution meets the needs of its users. Indeed, the lack of market need is the first reason for startup failure.[1] That is why the development team quickly concretises an MVP and iterates on it using a feature-driven, monolithic approach. Such as proposed by imperative languages like Java or Ruby.

1.2 Performance requirements

If the service successfully complies with users requirements, its community might grow with its popularity. If it can quickly respond to this growth, it is scalable. However, it is difficult to develop scalable applications with the feature-driven approach mentioned above. Eventually this growth requires to discard the initial monolithic approach to adopt a more efficient processing model instead. Many of the most efficient models distribute the system on a cluster of commodity machines.

Once split, the service parts are connected by an asynchronous messaging system. Many tools have been developed to express and manage these service parts and their communications. However, these tools impose specific interfaces and languages, different from the initial monolithic approach. It requires the development team either to be trained or to hire experts, and to start over the initial code base. This shift causes the development team to spend development resources in background without adding visible value for the users. It is a risk for the evolution of the project as the second and third reasons for startup failures are running out of cash, and missing the right competences.

1.3 Problematic and proposal

These shifts are a risk for the economaical evolution of a web application by disrupting the continuity in its developpement. The main question I address in this thesis is how to avoid these shifts, so as to allow a continuous development? That is to reconcile the reactivity required in the early stage

[1] `https://www.cbinsights.com/blog/startup-failure-post-mortem/`

of development and the performance increasingly required with the growth of popularity. To answer this question, I propose in this thesis a solution based on an equivalence between two different programming paradigms. On one hand, there is the imperative, functional, asynchronous programming model, embodied by Javascript. On the other hand, there is the dataflow, distributed, programming model, embodied by the concept of fluxions introduced in chapter 5.

This thesis contains two main contributions. The first contribution is a compiler allowing to split a program into a pipeline of stages depending on a common memory store. The second contribution, steming from the first one, is a second compiler, allowing to make the stages of this pipeline independent. With these two contributions, it is possible to build a compiler that links an imperative representation with a flow-based representation. The imperative representation carries the functional modularization of the application, while the flow-based representation carries its execution distribution. A development team shall then use these two representations to continuesly iterate over the implementation of an application, while keeping both maintainability and performance.

1.4 Thesis organization

This thesis is organized in four main chapters. Chapter 2 introduces the context for this thesis and explains in greater details the objective I briefly described above. It presents the challenge to build web applications at a world wide scale, without jamming the organic evolution of its implementation. It concludes drawing a first answer to this challenge. Chapter 3 presents the works surrounding this thesis, and how they relate to it. It defines into the notions outlined in the precedent chapter to help the reader understand better the context. At the end of this chapter, I present clearly the problematic addressed in this thesis. Chapter 4 presents the first contribution allowing to represent a program as a pipeline of stages. We introduce Dues to encapsulate these stages, based on Javascript Promises. Chapter 5 presents the second contribution allowing to make these stages independend. We introduce Fluxion to encapsulate these stages. Chapter **??** concludes this thesis, and draw the possible perspectives beyond this work.

Chapter 2

Context and objectives

Contents

2.1 Introduction

This chapter presents the general context for this work, and leads to a definition of the scope of this thesis. Section 2.2 presents the context of web development, and the motivations that led the web to become a software platform. It presents briefly the main languages available for prototyping a web application, and a great section is dedicated to a trending language among these : Javascript. Section 2.3 presents the problematic of developing web server for large audiences. It explains why the languages presented in the previous section often fail to grow with the project they initially supported very efficiently. It concludes that this rupture is an economical risk. Finally, section 2.4 presents the proposition of this thesis. That is to allow a continuous development from the initial prototype up to the releasing and maintenance of the complete product.

2.2 The Web as a platform

2.2.1 From Operating Systems to the World Wide Web

The production and distribution cost for another unit of a software application is virtually null. The market is only limited by the platform a software can be deployed on. The bigger the platform, the wider the market. The Internet and particularly the Web spreads the scalability of software distribution world wide with a near zero latency. It eventually became the main distribution medium for software, and the wider market there can possibly be.

Similarly to operating systems, Web browsers started as software products with the ability to run scripts to extend their possibilities. It led the web to become the platform, replacing operating systems. Now, with web services, or Software as a Service (SaaS), the distribution medium of software is so transparent that owning a software product to have an easier access is no longer relevant. It stimulates a competly new business model based on a free access for the user, while claiming value for their data. We explore in the next paragraphs the different languages that allowed this new business model to emerge.

2.2.2 The Languages of the Web

In the 80's and early 90's, with Moore's law predicting exponential increase in hardware performance, development time became more expensive than hardware. Higher-level languages replaced lower-level languages. The economical gain in development time compensated the worsen performances. During the web early development, most of the now popular programming languages were released, Python(1991), Ruby(1993), Java(1994), PHP(1995) and Javascript(1995).

Java, developed by Sun Microsystems, imposes itself early as a language of choice and never really decreased. The language is executed on a virtual machine, allowing to write an application once, and to deploy it on heterogeneous machines. The software industry quickly adopted it as its main development language. However, because of the heavy adoption by the software industry, Java lose the hype that drove the community innovation and creativy. It struggles to keep up with the latest trends in software development.

Python is the second best language for everything. It is a general purpose language, currently popular for data science. In 2003, the release of the Django web framworks brought the language to the web development scene.

Ruby was almost unknown until the release of Rails in 2005. With the release of this web framework, Ruby took-off and is still in active use.

PHP was initially designed to build personal web pages. It might be one of the easiest language to start web development, but even though there is some success story, it is generally unfit to grow projects to industrial size. It is on a slow decline since a few years according to several language popularity indexes.

Since a few years, Javascript is slowly becoming the main language for web development. It is the only choice in the browser. Because of this unavoidable position, it became fast (V8, ASM.js) and convenient (ES6, ES7). And since 2009, it is present on the server as well with Node.js This omnipresence became an advantage. It allows to develop and maintain the whole application with the same language.

2.2.3 Explosion of Javascript popularity

2.2.3.1 In the beginning

Javascript was created by Brendan Eich at Netscape around May 1995, and released to the public in September. At the time, Java was quickly adopted as the default language for web servers development, and everybody was betting on pushing Java to the client as well. The history proved them wrong.

Javascript was released as a scripting engine on Netscape navigator. Microsoft released their browser Internet Explorer 3 in June 1996 with a concurrent implementation of Javascript. At the time, because of the differences between the two implementations, web pages had to be designed for a specific browser. This competition was fragmenting the web. To stop this fragmentation, Netscape submitted Javascript to Ecma International for standardization in November 1996. In June 1997, ECMA International released ECMA-262, the first specification of ECMAScript, the standard for Javascript. A standard to which all browser should refer for their implementations.

The initial release of Javascript was designed in a rush. The version released in 1995 was finished within 10 days. And, it was intended to be simple enough to attract unexperienced developers. For these reasons, the language was considered poorly designed and unattractive by the developer community.

illustration: the ugly duckling

Why does Javascript suck?[1]
Is Javascript here to stay?[2]
Why Javascript Is Doomed.[3]
Why JavaScript Makes Bad Developers.[4]
JavaScript: The World's Most Misunderstood Programming Language[5]
Why Javascript Still Sucks[6]
10 things we hate about JavaScript[7]
Why do so many people seem to hate Javascript?[8]

[1] http://whydoesitsuck.com/why-does-javascript-suck/
[2] http://www.javaworld.com/article/2077224/learn-java/is-javascript-here-to-stay-.html
[3] http://simpleprogrammer.com/2013/05/06/why-javascript-is-doomed/
[4] https://thorprojects.com/blog/Lists/Posts/Post.aspx?ID=1646
[5] http://www.crockford.com/javascript/javascript.html
[6] http://www.boronine.com/2012/12/14/Why-JavaScript-Still-Sucks/
[7] http://www.infoworld.com/article/2606605/javascript/146732-10-things-we-hate-about-JavaScript.html
[8] https://www.quora.com/Why-do-so-many-people-seem-to-hate-JavaScript

But things evolved drastically since. One of the reason for the success of Javascript is the *View Source* menu that reveals the complete source code of any web site. It allows the community to pick, improve and reproduce the best techniques [9]. Another reason is that all web browsers include a Javascript interpreter, making Javascript the most ubiquitous runtime in history [23]. Javascript is distributed freely, with all the tools needed to reproduce and experiment on the largest communication network in history. Anybody can seize this opportunity to incrementally build and share the best tools they can. This open collaboration is the reason for the popularity the Web and Javascript with.

2.2.3.2 Rising of the unpopular language

Javascript started as a programming language to implement short interactions on web pages. The best usage example was to validate some forms on the client before sending the request to the server. This situation hugely improved since the beginning of the language. Nowadays, there is a lot of web-based application replacing desktop applications, like mail client, word processor, music player, graphics editor...

ECMA International released several version in the few years following the creation of Javascript. The third version contributed to give Javascript a more complete and solid base as a programming language. From this point on, the consideration for Javascript kept improving.

In 2005, James Jesse Garrett released *Ajax: A New Approach to Web Applications*, a white paper coining the term Ajax [25]. This paper explains the advantage on user experience of this technique. It uses Javascript to reload the content inside a web page without requesting a full page from the server, but only the new content. Javascript rose outside of simple user interactions and allows to develop richer applications inside the browser, from user interactions to network communications. The first web applications to use Ajax were Gmail, and Google maps[10].

Because of the difference of implementations, AJAX still present heterogeneous interfaces among browsers. Around this time, the community realeased Javascript framework with the goal to straighten differences in implementa-

[9] `http://blog.codinghorror.com/the-power-of-view-source/`

[10] A more in-depth analysis of the history of Ajax, given by late Aaron Swartz `http://www.aaronsw.com/weblog/ajaxhistory`

tion, and assist the development. Prototype[11] and DOJO[12] are early famous examples, and later jQuery[13] and underscore[14]. These frameworks took some responsibilities to the large success of Javascript and of the web technologies.

illustration: Javascript with superpowers

In the meantime, in 2004, the Web Hypertext Application Technology Working Group[15] was formed to work on the fifth version of the HTML standard. The name is misleading, it is really about giving Javascript superpowers. It features geolocation, file API, web storage, canvas drawing element, audio and video capabilities, drag and drop, browser history manipulation, and many mores. The releases of HTML5 and ECMAScript 5, in 2008 and 2009, represent a mile-stone in the development of web-based applications. Around the same time, Google released V8 for its browser Chrome. It is a Javascript interpreter improving drastically the execution performance. Javascript became the programming language of web, becoming the rising application platform.

Taking advantage of this trend, Node.js pushed Javascript to the server as well in 2009. Javascript is often associated with an event-based paradigm to react to concurrent user interactions. This event-based paradigm proved to be also very efficient for a web server to react to concurrent requests. Javascript is now the only language able to build a complete web service, from the client to the server.

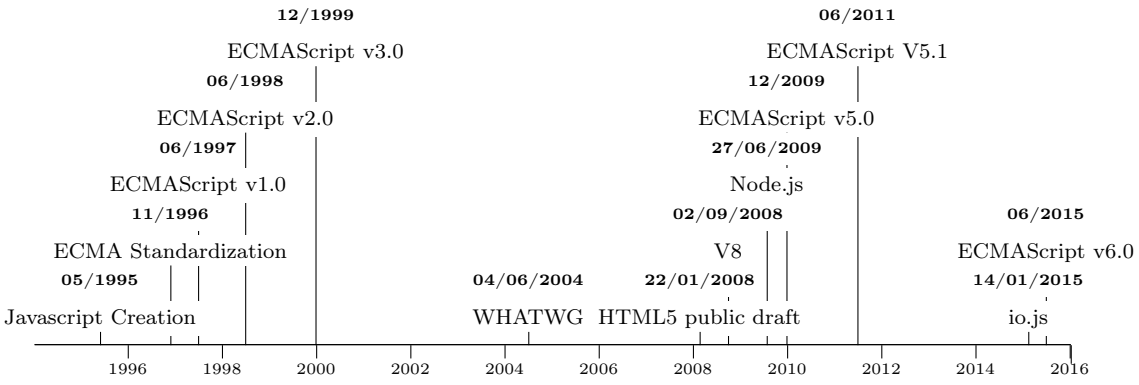
2.2.3.3 Current situation

"When JavaScript was first introduced, I dismissed it as being not worth my attention. Much later, I took another look at it and discovered that hidden in the browser was an excellent programming language."

—Douglas Crockford

The rise of Javascript is obvious on the web and the open source communities. It also seems to be rising in the software industry. But it is difficult to give an accurate representation of the situation because the software industry often try to keep an edge by keeping a fog of war. In the following

[11] `http://prototypejs.org/`
[12] `https://dojotoolkit.org/`
[13] `https://jquery.com/`
[14] `http://underscorejs.org/`
[15] `https://whatwg.org/`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ECMA Standardization
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Javascript Creation
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WHATWG
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ECMAScript V5.1
12/2009
ECMAScript v5.0
27/06/2009
Node.js
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V8
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HTML5 public draft
06/2015
ECMAScript v6.0
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2016

paragraphs, I report some indexes that represent the situation globally, both in the open source community and in the more opaque software industry.

Available resources According to the TIOBE Programming Community index, Javascript ranks 8th, as of October 2015, and it was the most rising language in 2014. This index measure the popularity of a programming language with the number of results on many search engines. However, the number of pages doesn't represent the number of readers. This measure is controversial, and might not be representative.

Alternatively, Javascript ranks 7th on the PYPL, as of October 2015. The PYPL index is based on Google trends to measure the number of requests on a programming language. However, it is not representative as it is limited to google searches.

From these indexes, the major programming language is Java, then C/C++, C# and Python. These languages are still the most widely taught, and used to write softwares.

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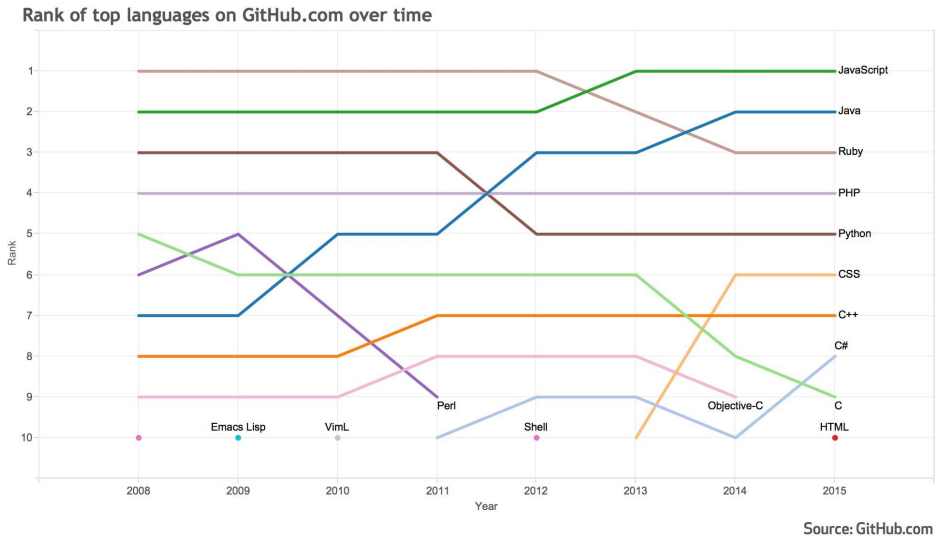
TODO graphical ranking of TIOBE and PYPL

Developers collaboration platforms Online tools of collaboration gives an indicator of the number of developers and project using certain languages. Javascript is the most used language on *Github*, the most important collaborative development platform, with around 9 millions users. It represents more than 320 000 repositories, while the second language is Java with more than 220 000 repositories.



Javascript is the language the most cited on *StackOverflow*, the most important Q&A platform for developers. It is a good representation of the activity around a language. Javascript represent more than 960 000 questions, while the second is Java with around 940 000 questions.

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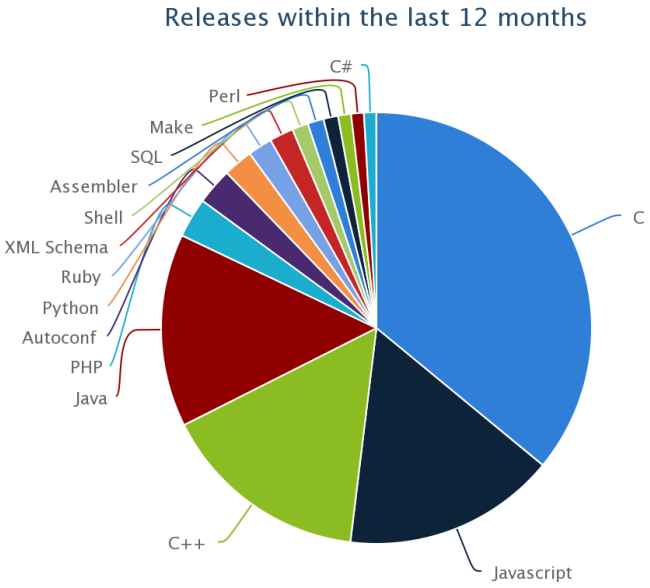
According to *Black Duck Software*, Javascript is the second language used in open source projects. C is first, C++ third and Java fourth. These four languages represent about 80% of all programming language usage in open source communities.

⚠ TODO graphical ranking of the tags in StackOverflow



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Black Duck

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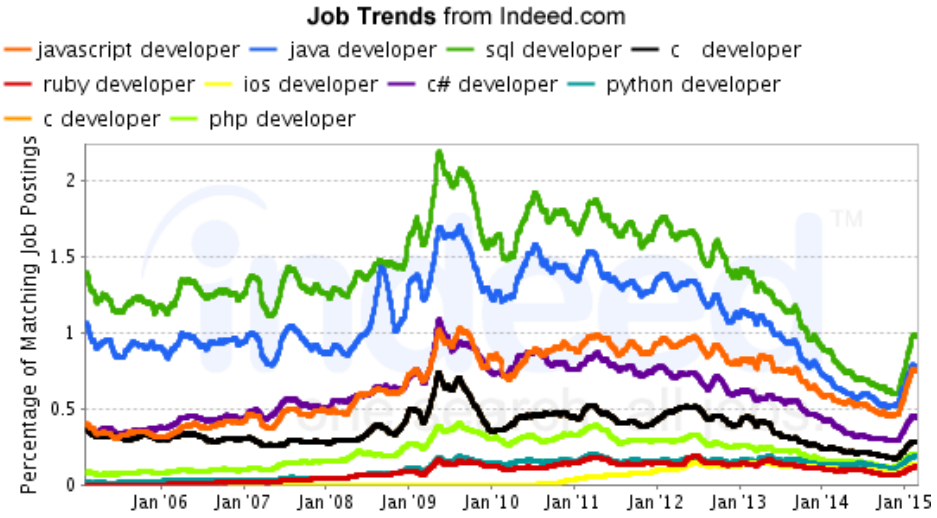
TODO redo this graph, it is ugly.

Jobs The actors of the software industry tends to hide their activities trying to keep on edge on the competition. All these previous metrics are representing the visible activity about programming language, but are barely representative of the software industry. The trends on job openings give some hints on the direction the software industry is heading towards. Javascript is the third most wanted skill, according to *Indeed*, right after SQL and Java. And over the last 5 years, Javascript almost closed the gap with the first and second position. Moreover, according to *breaz.io*, Javascript developers get more opportunities than any other developers. This position indicate that Javascript is increasingly adopted in the software industry.



TODO redo this graph, it is ugly.

All these metrics represent different faces of the current situation of the Javascript adoption in the development community and industry. It is widely used in open source projects, everywhere on the web, and in the software industry. With the evolution of web applications development and increased interest in this domain, Javascript is assuredly one of most important language in the times to come.

This section presented the languages used to build web applications. In the next section presents the realities and technical challenges to assure their performance against billions of users.

2.3 Highly concurrent web servers

2.3.1 Concurrency

The Internet allows communication at an unprecedented scale. There is more than 16 billions connected devices, and it is growing fast[16] [**Hilbert2011**]. A large web application like google search receives about 40 000 requests per seconds[17]. Such a web application needs to be highly concurrent to manage this amount of simultaneous requests. In the 2000s, the limit to break was

[16] `http://blogs.cisco.com/news/cisco-connections-counter`
[17] `http://www.internetlivestats.com/google-search-statistics/`

10 thousands simultaneous connections with a single commodity machine[18]. Nowadays, in the 2010s, the limit is set at 10 millions simultaneous connections[19]. With the growing number of connected devices on the internet, concurrency is a very important property in the design of web applications. Moreover, the concurrency needs to be scalable to adapt to this growth of audience, as explained in the next paragraph.

2.3.1.1 Scalability

The traffic of a popular web application such as Google search remains stable because of its popularity. The importance of the average traffic soften the occasional spikes. However, the traffic of a less popular web application is much more uncertain. For example, it might become viral when it is efficiently relayed in the media. The load of the web application increases with the growth of audience. The available resources needs to increase to meet this load. This growth can be steady enough to plan the increase of resources ahead of time, or it might be erratic and challenging. An application is scalable, if it is able to increasingly spread over resources to react to the increasing growth of audience. And if the load on these resources is linearly proportional to the increasing growth, instead of exponentially proportional.

2.3.1.2 Time-slicing and Parallelism

Concurrency is achieved differently on hardware with a single or several processing units. On a single processing unit, the tasks are executed sequentially, interleaved in time, while on several processing units, the tasks are executed simultaneously, in parallel. If the tasks are independent, they can be executed in parallel as well as sequentially. This parallelism is scalable, as the independent tasks can stretch the computation on the resources so as to meet the required performance.

However, the tasks within an application need to coordinate together to modify the application state. This coordination limits the parallelism and impose to execute some tasks sequentially. It limits the scalability. The type of possible concurrency, sequential or parallel, is defined by the interdependencies of the tasks.

[18] `http://www.kegel.com/c10k.html`

[19] `http://c10m.robertgraham.com/p/manifesto.html`

2.3.2 Interdependencies

It is easy to understand the parallelism in a cooking recipe because the interdependencies between operations are trivial. It seems obvious that melting chocolate is independent from whipping up egg whites. This distinction between chocolate and egg whites is trivial. While the distinctions within the state of an application are more intricate. This makes concurrent application more difficult to understand.

2.3.2.1 State Coordination

The global state of an application impose the coordination between the tasks. This coordination happens either by sending messages, or by modifying a shared memory. If the tasks are independent enough, the coordinations can be done with message passing. Each task sends messages to indicate the modifications of the state with consequences outside its scope. However, if the tasks are too dependent, the overhead of message passing tends to impact performances. They need to share and coordinate their accesses to the state. Each access needs to be exclusive to avoid corruption. I address in the next paragraphs the different scheduling strategies, and how they assure this exclusivity.

2.3.2.2 Task Scheduling

There are two scheduling strategies to execute tasks sequentially on a single processing unit : preemptive scheduling and cooperative scheduling. The coordination is different with the two scheduling strategies.

illustration: feu rouge et rond point

Preemptive scheduling is used to assure fairness between the tasks, such as in a multi-tasking operating system. The scheduler allows a limited time of execution for each task, before preempting it. However, as the preemption happens unexpectedly, the developer needs to assure exclusivity by locking the shared state before access. Locking is known to be hard to manage by developers, and to impact performances, so it is set aside for the remaining of this chapter.

On the other hand, in cooperative scheduling, a task is allowed to run until it yields the execution back to the scheduler. Each task is an atomic execution : it has an exclusive access on the memory. As the developer doesn't need to explicitly assure exclusivity, it is easier to write concurrent programs efficiently with this scheduling strategy.

2.3.2.3 Invariance

In concurrent computation, it is important to assure the invariance of a state during its manipulation. This assurance is given by the exclusive access of an atomic execution on the state. It allows the developer to group operations inside this atomic execution, so as to avoid corruption of the state.

When the tasks remains isolated and communicate by message passing, there is no risk of corrupted state. The invariance is assured by the isolation of the state specified by the developer, and by the atomicity of the message processing. On the other hand, in a cooperative scheduling application, each task is atomic, so the developer always has an exclusive access to the global state. This atomicity assures the invariance.

The difference is that in the message passing paradigm, the developer defines the state isolation inducing the execution isolation, while with cooperative scheduling, the developer defines only the execution isolation. It is difficult for developer to isolate state, but it provides good performances through parallelism. While it is easier to assure atomic execution with cooperative scheduling, but it is unable to provide parallelism. On one hand, the state is distributed and isolated to improve performance scalability. On the other hand, the code is organized logically to improve maintainability. The impact of these two organizations on performance scalability and development scalability is at the heart of this thesis.

2.3.3 Disrupted Development

2.3.3.1 Scalable Concurrency

illustration: heating chipset / parallel chipsets

Around 2004, the speed of sequential execution on a processing unit plateaued[20]. Manufacturers started to arrange transistors into several processing units to keep increasing overall performance while avoiding overheating problems. Therefore, the performance of the sequential execution required by the cooperative scheduling plateaued as well. Isolating tasks is the only option to achieve high concurrency on this parallel hardware. But this isolation is in contradiction with the best practices of software development. It implies a rupture between performance and maintainability.

[20] https://cartesianproduct.wordpress.com/2013/04/15/the-end-of-dennard-scaling/

2.3.3.2 The Case for Modularity

The best practices in software development advocate to gather features logically into distinct modules. This modularity allows a developer to understand and contribute to an application one module at a time, instead of understanding the whole application. It allows to develop and maintain a large code-base by a multitude of developers bringing small, independent contributions.

This modularity avoids a different problem than the isolation required by parallelism. The former intends to structure code to improve maintainability, while the latter improve performance through parallel execution. These two organizations are conflicting in the design of the application. In the next paragraph, I argue this conflict disrupts the development of a web application.

2.3.3.3 Technological shift

Between the prototyping, and the maturation of a web application, the needs are radically different. I argue that during the initiation of a web application project, the economical constraint holds on the pace of development. The development reactivity is crucial to meet the market needs[21]. The development team opt for a popular and accessible language to leverage the advantage of its community. It is only after a certain threshold of popularity that the economical constraint on performance requirements exceed the one on development. The development team shift to an organization providing parallelism.

This shift brings two risks. The development team needs to rewrite the code base to adapt it to a completely different paradigm. The application risks to fail because of this challenge. And after this shift the development pace slow down. The development team cannot react as quickly to user feedbacks to adapt the application to the market needs. The application risks to fall in obsolescence.

The risks implied by this rupture proves that there is economically a need for a solution that continuously follows the evolution of a web application. We present in the next section the proposition of this thesis for such a solution. It would allow developers to iterate continuously on the implementation focusing simultaneously on performance, and on maintainability.

[21] `https://www.cbinsights.com/blog/startup-failure-post-mortem/`

2.4 Proposition

In the previous section, I presented two implementation organizations to improve either performance scalability, or development scalability. However, these two organizations are incompatible, which imply ruptures in the development. This thesis argues that a compiler should bridge the gap between the two organizations, so as to allow a continuous development. This section presents the two programming models representing each an organization. Then it presents the possibility of an equivalence between the two. This equivalence is detailed further in the the chapter 4 and 5 of this thesis.

2.4.1 Architecture of web applications

2.4.1.1 Real-time streaming web services

We focus on web applications processing streams of requests from users in soft real-time. Such applications receive requests from clients using the HTTP protocol and must respond within a finite window of time. They are generally organized as sequences of tasks to modify the input stream of requests to produce the output stream of responses. The stream of requests flows through the tasks, and is not stored. On the other hand, the state of the application remains in memory to impact the future behaviors of the application. This state might be shared by several tasks within the application, and imply coordination between them.

The next paragraphs present two programming models to express web applications based on the invariance paradigms presented in the previous section. The event-loop execution engine is based on the cooperative scheduling, and the pipeline architecture is based on isolated tasks communicating by message passing. This thesis is based on the similarities between these two programming models.

2.4.1.2 Event-loop

The event-loop is an efficent execution model for concurrent applications on a single processing unit using non-blocking communications. It relies on a queue storing the received messages before being processed one after the other by the loop. On each reception, the loop executes a task to process the received message. While processing the message, the task can initiate new communications, leading in turn to the queuing of more messages, which

trigger more tasks, and so on. The scheduling of execution is cooperative, each task is executed atomically and exclusively, until it yields execution, to continue with the next task in queue.

In Javascript, these tasks are defined during the communication initiation. The function called to initiate the execution expects as argument a function to continue the execution at the reception of communication result. This function is called a callback or a continuation.

In this model, the input stream of data flows through a sequence of callbacks to be processed until the application outputs it. This stream is never stored, except as a buffer between two callbacks. On the contrary, The state ramins in memory to be shared by all callbacks. Because Javascript is of higher-order, the callbacks as well as their execution contexts are part of this state. They are called closures.

*

This execution model is similar to the pipeline architecture presented in the next paragraph.

⚠ TODO schema of an event-loop

2.4.1.3 Pipeline

The pipeline software architecture is composed of isolated stages communicating by message passing to leverage the parallelism of a multi-core hardware architectures. It is well suited for streaming application, as the stream of data flows from stage to stage. Each stage has an independent memory to hold its own state. As the stages are indendent, the state coordination between the stages are communicated along with the stream of data.

*

⚠ TODO schema of a pipeline

Each stage is organized in a similar fashion than the event-loop presented above. It receives and queues messages from upstream stages, processes them one after the other, and outputs the result to downstream stages. The difference is that in the pipeline architecture, each task is executed on an isolated stage, whereas in the event-loop execution model, all tasks share the same queue, loop and memory store.

Both paradigms encapsulate the execution in tasks assured to have an exclusive access to the memory. However, they provide two different models to provide this exclusivity resulting in two distinct ways for the developer to assure the invariance on the application state. Contrary to the pipeline architecture, the event-loop provide a common memory store allowing the best practice of software development to improve maintainability. It is pos-

sibly the reason of the wide adoption of this programming model by the community of developers.

This thesis proposes to provide an equivalence between the two memory models for streaming web applications. The next subsection describes further the similarities and differences between the two models. The equivalence would allow a compiler to transform an application expressed in one model into the other. With such a tool, a development team could rely on the common memory store of the event-loop execution model, and focus on the maintainability of the implementation. And compile continuously during the development the event-loop implementation to the pipeline architecture to assure that the execution can be distributed on a parallel architecture.

2.4.2 Equivalence

2.4.2.1 Rupture point

The execution of the pipeline architecture is well delimited in isolated stages. Each stage has its own thread of execution, and is independent from the others. On the contrary, the code of the event-loop is linear because of the continuation passing style and the common memory store. However, the execution of the different callbacks are as distinct as the execution of the different stages of a pipeline. The call stacks of two callbacks are distincts. Therefore, an asynchronous function call represents the rupture between two call stacks. It is a rupture point, and is equivalent to a data stream between two stages in the pipeline architecture.

Both the pipeline architecture and the event-loop present these rupture points. The detection of rupture points allows to map a pipeline architecture onto the implementation following the event-loop model. To allow the transformation from one to the other, this thesis studies the possibility to detect rupture points, and to distribute the global memory into the parts defined by these rupture points. The detection of rupture points is addressed in chapter 4.

2.4.2.2 Invariance

The transformation should preserve the invariance as expressed by the developer to assure the correctness of the execution. The partial ordering of events

in a system, by opposition to total ordering, is sufficient to assure this correctness. The global memory is a way to assure the total ordering of events, and the message passing coordination is a way to assure partial ordering of events. Therefore, to assure the correctness of the execution of a system, the state coordination with a global memory is equivalent to message passing coordination. And it is possible, at least for some rupture points, to transform the global memory coordination into message passing while conserving the correctness of execution.

In order to preserve the invariance assured by the event-loop model after the transformation, each stage of the pipeline needs to have an exclusive access to memory. The global memory needs not to be splited into parts and distributed into each of the stages. To assure the missing coordinations assured by the shared memory between the stages, the transformation should provide equivalent coordination with message passing. The isolation and replacement of the global memory is fully address in chapter 5

With this compiler, it would be possible to express an application following the design principles of software development, hence maintainable. And yet, the execution engine could adapt itself to any parallelism of the computing machine, from a single core, to a distributed cluster. Because of the equivalence between these two models, the development team could iterate testing the two models for their different concerns about the implementation : performance and maintainability.

The goal of conciling these two concerns is not new. The next chapter presents all the results from previous works needed to understand this work, up to the latest results in the field.

Chapter 3

Software Design

Contents

3.1 Introduction

Computer applications are economically constrained by the cost of both development, and exploitation. The growth of the web and Software as a Service (SaaS) revealed the importance of these constraints, as the same entity need to carry both development and exploitation in scale of unprecedented size. This chapter draws a broad view of this duality in software systems projects, to finally refine the scope on the subject of interest, and to define the problematic of this thesis.

Similarly to many problem solving discipline, in software development the best practices advocate to decompose a problem into many subproblems. That is to organize the code into independent units, *e.g.* modular programming, structured design [59], hierarchical structure [20] and object-oriented programming. These approaches focus on improving the readability, maintainability and comprehensibility of an implementation. These approaches assure the scalability and evolution of the implementation of software systems.

The Moore's law [48] and Dennard's MOSFET scaling [**Dennard2007**] promised an exponential evolution of the processing power, hence the software industry could always rely on the hardware to increase the execution speed. But eventually, the clock speed of processors plateaued [1][**Bohr2007**]. The increasing number of transistors predicted by Moore's law needed to be reorganized as several execution units into the same processor. The hardware could not anymore increase the execution speed without any additional development effort.

The best practices of software development then inherited two goals : to assure the evolution of implementation by decomposing it into subproblems, as well as to decompose the execution onto the several execution units. As D. L. Parnas showed in 1972 [54], these two decompositions are hardly reconcilable. It seems impossible to develop a software following a decomposition that satisfies both the evolution, and an efficient parallel execution.

As the economic constraint shifted from development to performance, and with the incentive to leverage the execution power of parallel architectures, intensive work was done to provide tools and models to organize the execution on multiple execution units. Though, these works often ignore the best

[1] `https://cartesianproduct.wordpress.com/2013/04/15/the-end-of-dennard-scaling/`

practices regarding maintainability. Increasing performance then implies to increase exponentially the required development effort.

There has been many attempts at reconciling the two goals into a single approach. But none seems really convincing enough to be widely adopted. Throughout this chapter, the different works from the community are classified into three categories : focus on implementation evolution, focus on parallel execution in section 3.3, or reconciliation of the two in section **??**. And finally, section 3.5 presents the objectives for this thesis.

3.2 Software Design

In order to improve and maintain a software system, it is important to holds in mind the mental representation behind its conception. Architects, and mechanical engineer draw codified plans to share their mental representations with other architects and building teams. Similarly software developers write source codes. But because the source code represents both the plan and its execution, the second aspect tends to shadow the first, and the mental representation is lost in technical details and optimizations. It then becomes hard or even impossible to quickly grasp the purpose of the system without this mental representation. Even the initial authors would have difficulties to understand the system after some times. This problem becomes even more critical as the system grows in size. Therefore, it is important to decompose the system into smaller subsystem easier to grasp individually. Such decomposition improves the readability and comprehensibility hence maintainability of the implementation of a software system. This section shows the theoretical tools for this decomposition, and their application in programming languages.

3.2.1 Modularity

3.2.1.1 Structured Programming

illustration: spaghetti programming

The growing size and complexity of software systems eventually urges the developers to split the problem into isolated subproblems. To respond to this problem, Dijkstra firstly developed the concept of Structured Programming [**Dijkstra1970**]. D. Knuth cited C. Hoare to define it as *the systematic use of abstraction to control a mass of details, and also a means of documentation*

which aids program design [**Knuth1974**]. Dijkstra formalized this procedure on two levels, at a fine grain and at a coarse grain [19, 20].

The `goto` statement allows to jump anywhere in the code. It makes the flow of control hard to follow and understand. It is called spaghetti code. Dijkstra advocated instead to decompose the implementation into structures and reusable functions to decompose the larger problem into many independent subproblems at a fine grain [19]. It is the precursor of many later programming trends.

illustration: lasagna programming

He also proposed to design complex systems with a hierarchical structure [20]. It decomposes a system into layers at a coarser grain. Each layer would abstract a design problem for the upper layers. This work established grounds for what is know called modular programming.

3.2.1.2 Modular Programming

Modular programming advocates to design a software system as an assembly of modules communicating with each other. The goal of using modular programming is twofold. It allows to limit the understanding required to contribute to a module [59]. And it reduces development time by allowing several developers to simultaneously implement different modules [**Cataldo2006**, 65].

The criteria to decompose the system into well defined modules are coupling and cohesion [59]. The coupling defines the strength of the interdependence between modules. It is opposed to cohesion which defines how strongly the features inside a module are related. Low coupling between modules and high cohesion inside modules imply a better readability and comprehensibility, hence a better maintainability of the implementation of the system.

These two criteria defines how modular is the implementation. However, it doesn't define how well this organization will accept evolutions of the specification of the problem.

3.2.2 Design Choices

The result of modular organization is that the modification on the implementation are easier to conduct within a module, than on the modules organization. The impacts of the evolution of the problem should be concentrated as much as possible within the modules, and not in the modular organization, to reduce the overall impact on the implementation. The information hiding

principle, and the separation of concerns are two similar approach to keep modifications within the modules.

3.2.2.1 Information Hiding Principle

The information hiding principle advocates to encapsulate a specific design choice in each module to isolate the evolution on this choice from impacting the rest of the implementation [54]. In this article, D. Parnas opposes the organization of modules following the information hiding principle from the one following a pipeline approach to parallelize the execution. The former organization supports the development evolution, while the latter is more favorable to the performance of parallel execution. This opposition shows that a program cannot trivially follow an organization that support both development evolution, and performance. However, D. Parnas advocates the use of an assembler to conciliate the two approaches.

3.2.2.2 Separation of Concerns

The Separation of Concern is a design principle advocating that each module is responsible for one and only one specific concern [**Tarr1999**, **Hursch1995**]. For example, the separation of the form and the content in HTML / CSS, or the OSI model for the network stack. Each concern evolves independently without impacting the rest of the implementation.

However, this definition is orthogonal to the original meaning coined by Dijkstra [**Dijkstra1982**]. It is interesting to note this difference, as it is related directly to this thesis. The initial definition was about analyzing independently how a system meets different concerns. Dijkstra gives the example of analyzing independently correctness and efficiency. It is impossible to encapsulate correctness, or efficiency in a module, they concern the whole system. In this respect, this thesis is oriented towards dissociating the concern of development evolution and of performance. That is to be able to reason on the maintainability of a program, independently than of its performance, and vice versa. It is the challenge presented by D. Parnas when he opposed the two concerns in [54].

This thesis investigates further this opposition to dissociate the concern of evolution and the concern of performance in the case of a web application. The next subsection investigates the first concern, and presents the major programming models used to improve the evolution of an application.

3.2.3 Programming Models

Programming languages used in the industry were designed following programming models favoring the use of the best practices mentioned above. This section presents two programming models : object oriented programming and functional programming.

3.2.3.1 Object Oriented Programming

Alan Kay, who coined the term, states that Object Oriented Programming (OOP) is about message-passing, encapsulation and late binding. (There is no scholar reference for that, only a public mail exchange[2].) This original definition is an evolution upon modular programming. It helps encapsulate both the data, and the functions to process this data in an isolated, loosely coupled module. The very first OOP language was Smalltalk [**Goldberg1984**]. It defined the core concept of OOP. It is inspired by LISP and by the definition of the Actor Model, which we will define in the next section.

Object-Oriented Programming abandoned late-binding and adopted a stricter approach with the concepts of class, inheritance and polymorphism. The major languages of the software industry feature this stricter Object-Oriented approach. We can cite C++ and Java as the emblematic figures of OOP [**Gosling2000**, **Stroustrup1986**].

Though, the field test seems to have had reason of this stricter version. The trends in programming language seems to digress from the pure Object-Oriented approach to evolve toward a more dynamic approach, closer to Functional Programming. Indeed Javascript, Ruby and Python adopt functional features such as dynamic typing and higher-order functions [**Ecma1999**][3].

3.2.3.2 Functional Programming

The formal definition of Functional Programming resides in manipulating only mathematical expressions - instead of operation statements - and forbidding state mutability. However, the functional programming concepts implemented in programming language are more mitigated, and resides in higher-order functions and lazy evaluation. Two features that major programming languages now commonly present. Higher-order functions and

[2] `http://userpage.fu-berlin.de/~ram/pub/pub_jf47ht81Ht/doc_kay_oop_en`
[3] `https://www.ruby-lang.org/en/about/`

lazy evaluation help loosen the couple between modules, and improve their re-usability. *In fine*, it helps developers to write applications that are more maintainable, and favorable to evolution [**Hughes1989**].

Higher-Order Function Languages providing higher-order functions allows to manipulate functions like any other primary value : to store them in variables, or to pass them as arguments. Higher-order functions replace the needs for most modern object oriented programming design patterns [4].

Closures Most languages use closures to implement lexical scope with higher-order functions [60]. A closure is the association of a function and the lexical context from its creation. It allows this function to access variable from this context, even when invoked outside the scope of this context. For example when passed as an argument to another module.

It loosen the couple between modules, and helps define more generic and reusable modules. However, it increase their dependencies during the execution. Indeed, by exchanging closures, two modules intricately share their contexts of execution.

Functional programming greatly improves the resilience of implementation to the evolution of their specification. However, it requires a global memory to share the context of execution among modules. We will see in the next section that sharing memory makes parallelism difficult. At the regard of this insight, the concern of evolution and the concern of performance seem hardly compatible.

3.3 Software Efficiency

Programming started with a sequential nature. The Moore's law [48] and Dennard's MOSFET scaling [**Dennard2007**] were wrongly interpreted to promise the exponential evolution in the sequential performance of the processing unit.

The first models of computation, like the Turing machine and lambda-calculus, were sequential and based on a global memory state. A formalism was missing to represent concurrent computations. This section presents the

[4] `http://stackoverflow.com/a/5797892/933670`

most important works on formalisms for parallel computation. They tackled the problems of determinacy, state synchronization and correctness of execution in a formalism based on a network of concurrent processes, asynchronously communicating via messages. This section first presents the works on the programming models based on this formalism. Then it presents the huge improvements we recently witnessed in the field of distributed stream processing due to the need of performance from the web to process large stream of requests,

3.3.1 Concurrency Theory

The mathematical models are a ground for all following work on concurrent programming, we briefly explain them in the next paragraphs. There are two main formal models for concurrent computations. The Actor Model of C. Hewitt and the Pi-calculus of R. Milner. Based on these definitions, we explain the importance of determinism for correctness, and the reasons that made asynchronous message-passing prevail.

3.3.1.1 Models

Actor Model The Actor model allows to express the computation as a set of communicating actors [**Clinger1981**, 33, 32]. In reaction to a received message, an actor can create other actors, send messages, and choose how to respond to the next message. All actors are executed concurrently, and communicate asynchronously. An asynchronous communication implies that the sender continues its execution immediately after sending the message, before receiving the result of the initiated communication.

The Actor model was presented as a highly parallel programming model, but intended for Artificial Intelligence purposes. Its success spread way out of this scope, and it became a general reference and influence.

π-calculus R. Milner presented a process calculus to describe concurrent computation : the Calculus of Communicating Systems (CCS) [44, 47]. It is an algebraic notation to express identified processes communicating through synchronous labeled channels. The π-calculus improved upon this earlier work to allow processes to be communicated as values, hence to become mobile [21, 46, 45]. Therefore, similarly to Actors, in Pi-calculus processes can dynamically modify the topology. However, contrary to the Actor model,

communications in Pi-calculus are based on simultaneous execution of complementary actions, they are synchronous.

3.3.1.2 Determinism and Non-determinism

Because of the synchronous communication used by π-calculus, the concurrent executions and the communications are both deterministic. THerefore, the result of the concurrent system is assured to be deterministic. The correctness of the execution of deterministic systems is guaranteed.

On the other hand, the asynchronous communications used by Actors are non-deterministic. The message sent can take an infinite time to be received. Therefore, the result of the concurrent system is not assured to be deterministic.

But the communication in reality are subject to various faults and attacks [**Lamport1982**]. And the wait required by synchronous communications negatively impact performances of the system because of the difference of latency between communication, and execution. The Actor model was explicitly designed to take these physical limitations in account [**Hewitt1977a**]. The non-determinism in the asynchronous communications is hidden by the organization of the system. The total ordering of messages possible with synchronous communication is too strong a requirement for correctness. As Lamport showed [40], and Reed related later [57], causal order is sufficient to build a correct distributed system. The ordering of messages is only local to an actor, while between actors, messages are causally ordered. The execution will either terminate correctly, or not terminate at all because of a failure in the communications.

Eventually, following works adopted asynchronous communications as it is hardly realistic to build a distributed system based on synchronous communications.

3.3.2 Concurrent Programming

As demonstrated by the theory, concurrency boils down to causality expressed with message passing. There exist several programming model over this theoretical view.

3.3.2.1 Independent Processes

The theory advocates asynchronous message-passing, but it doesn't precise the granularity of the communicating entities. In the Actor Model, everything is an actor, even the simplest types, like numbers, similarly in OOP, everything is an object. In practice, this level of granularity is unachievable due to overhead from the asynchronous communications. Most implementations adopt a granularity on the process or function level.

The first concept using message passing was the coroutine. Conway defines coroutines as an autonomous program which communicate with adjacent modules as if they were input and output subroutines [16]. It is the first definition of a pipeline to implement multi-pass algorithms. Similar works include the Communicating Sequential Processes (CSP) [**Brookes1984**, 34], and the Kahn Networks [37, 38].

These programming models don't allow to dynamically modify the topology of the application. Coroutines and processes are defined statically in the source of the application. We shall come back to this limitation later in this thesis in chapter 5.

As we saw in last section, higher-level programming is helping modularity. The absence of this feature in the concurrent programming model is a limitation. On of the instrumental gaol of this thesis is to allow to bring higher-level programming in parallel programming, without the need for manual synchronization, as we will see in the next section.

3.3.2.2 Synchronization

These programming models allowed parallel execution on several processing units, so there is a need to shared resources among processing units, like a common memory store, or network interface. Multiprogramming was used to allow different programs to be executed concurrently in isolated processes, and to share resources [20]. To synchronize the different processes over these resources, and avoid conflicting accesses, it is crucial to assure the mutual exclusion. For this purpose, Djikstra introduced the Semaphore [**Dijkstra**]. Similar works include guarded commands [18], guarded region [**Hansen1978a**] and monitors [35]. They are all kinds of locks to assure mutual exclusion.

Multi-Threading As we saw earlier, a common memory storage helps to follow the best practice, and is easier to develop with. These lock mechanisms were used in Multi-Threading to provide this common memory storage for concurrent programming. Threads are light processes sharing the same memory execution context within an isolated process. It seems to be an easy solution to parallelize sequential execution on parallel execution units with a common memory store. But because of the preemptive scheduling, threads require to lock each and every shared memory cell. It is known that this heavy need for synchronization leads to bad performances, and is difficult to develop with [4].

Lock-Free Data-Structures An interesting alternative to locks are the wait-free and lock-free data-structures [**Lamport1977**, **Herlihy1988**, **Herlihy1990**, **Herlihy1991**, **Anderson1990**]. They are based on clever use of atomic read and write operations on a shared memory to provide concurrent safe version of common data-structures algorithms. Therefore no locking is necessary for the algorithm to be highly concurrent, while conserving a common memory store However, even if they are theoretically infinitely scalable, they are hard to come with, and are not fit for every problem.

Scalability Limitation Amdahl [7] and later Ghunter [28] theorized the speedup gains with parallelism for a sequential program. They concludes that sharing resources protected by mutual exclusion eventually decreases performances when increasing parallelism [30, 29, 51, 27].

The concurrent process sharing resources need to be scheduled sequentially, and not in parallel, as the contention of locking negatively impact the performance. To increase the parallelism and performance, it implies to reduce the shared resources between concurrent processes.

PGAS Sharing resources eventually limits scalability, hence distribution of the memory is unavoidable. The Partitioned Global Address Space (PGAS) model replaces the need for a common memory store. It provides the developers with a uniform memory access on a distributed architecture. Each computing node executes the same program, and provide its local memory to be shared with all the other nodes. The PGAS programming model assure the remote accesses and synchronization of memory across nodes, and enforces locality of reference, to reduce the communication overhead. Known

implementation of the PGAS model are Chapel[**Chamberlain2007**], X10 [**Charles2005**]. Unified Parallel C [**El-Ghazawi2006**], CoArray Fortran [**Numrich1998**] and OpenSHMEM [**Chapman2010**].

These programming models are promising. However, they focus rather on scientific application with intensive computing such as matrix multiplication, and leave out streaming applications, such as web services.

3.3.2.3 Programming languages

Some programming languages features message-passing and isolation of actors directly to give the responsibility to developers to assure high parallelism. To some extent, these languages succeeded in industrial contexts. However, they largely remain elitist solutions for specific problems more than a general, and accessible tool. I present some examples below.

Scala is an attempt at unifying the object model and functional programming [**Odersky2004**]. Akka[5] is a framework based on Scala, to build higly scalable and resilient applications.

Erlang is a functional concurrent language designed by Ericsson to operate telecommunication devices [**JoeArmstrong**, **Nelson2004**]

CUDA, OpenCL are data parallel API to allow imperative code to run onto accelerators such as GPUs or FPGAs [**Stone2010**].

The field of concurrent programming is so vast it is impossible to relate here every of its branch. The previous examples are only the best known. The next focus focuses on streaming real-time applications.

3.3.3 Stream Processing Systems

All the solutions previously presented are designed to build general distributed systems. We focus on real-time applications as defined by [31]. A real-time application must respond to a variety of simultaneous requests within a certain time. Otherwise, input data may be lost or output data may lose their significance. Such applications are often connected to the internet and use the web as an interface, which implies to process high volumes streams of requests. Moreover, because these systems are key to business, their reliability and latency are of critical importance. These requirements are challenging to meet in the design of such system. It present the state of the art to design such systems with these challenging requirements.

[5] `http://akka.io/`

3.3.3.1 Data-stream management systems

Database Management Systems (DBMS) historically processed large volume of data, and they naturally evolved into Data-stream Management System (DSMS) to processed data streams as well. They concurrently run SQL-like requests on continuous data streams. The computation of these requests spread over a distributed architecture. Among the early works, we can cite NiagaraCQ [14, 50], Aurora [1, 3, 9] which evolved into Borealis [2], AQuery [**Lerner2003**], STREAM [**Arasu2003**, **Arasu2005**] and TelegraphCQ [39, 13]. More recently, we can cite DryadLINQ [36, 66], Timestream [55] and Shark [**Xin2013**].

However, these solutions implies to understand two paradigms of language, the SQL paradigm, and the imperative paradigm. The difference between these two paradigms creates a rupture in the design of the system. The SQL parts difficulty merge with the imperative structure. This rupture impacts the maintainability of the system as it is not straightforward to reorganize the logic between the two paradigms.

3.3.3.2 Dataflow pipeline

An alternative model to process data stream efficiently is the pipeline architecture. It inspires from dataflow to integrate the two conflicting programming paradigms into one.

SEDA is a precursor in the design of pipeline-based architecture for real-time applications for the internet [64]. It organizes an application as a network of event-driven stages connected by explicit queues. It is based on previous works [26, 53].

Several projects followed and adapted the principles in this work. StreaMIT is a language to help the programming of large streaming application [61]. Storm [62] is designed by and used at Twitter calculate metrics on streams of tweets such as the trending topics. Among other works, there are CBP [41] and S4 [52], that were designed at Yahoo, Millwheel [5] designed at Google and Naiad [**Murray2013**] designed at Microsoft.

Similarly to the programming models presented in section 3.3.2.3 these frameworks are elitist and not accessible to a large community of developers. Indeed, the pipeline architecture present a distributed storage, which is hardly compatible with the best practices. It impacts maintainability. For this reason, there are some works on reconciling the concurrent programming

models with the modular programming model favoring maintainability. The next section presents these reconciliations.

3.4 Reconciliations

3.4.1 Contradiction

The decomposition of an application into a pipeline, as shown in the two previous sections, is incompatible with the modular design advocated by the separation of concerns. The problem of incompatibility between the modular design and the parallel execution of a pipeline architecture is the following. There need to be a common understanding on the structure of the communication from one stage to the next. The modular design defines that this common ground, the interface, be the most resilient possible to focus the evolution within a module. While the pipeline architecture (and more generally the concurrent programming models) defines these interfaces as the communications between the stages of the execution. With the evolution of the problem specification, when a stage needs to be modified, it is most likely that these changes will affect the previous or next stages.

Most project use languages supporting the modular design at the beginning, when they need to evolve the most. They then switch to the pipeline architecture only when the requirement of performance overcomes the requirement of evolution. Moreover, as the team knows that they will eventually throw away their code to upgrade it to a different paradigm, there is little effort to follow the best practice to make maintainable code. It results in a large effort of development to compensate this rupture. In this section, we present the state of the art to reconciliate the two organizations, and avoid this rupture. First we see the design patterns to fit both organization onto a same source code. Then we see the compilation tentatives to switch from one to the other.

3.4.2 Design patterns

As we explained in the previous sections, the two different organization, modular and parallel, seems intuitively incompatible. However, it might be possible to find specific organizations that are both modular and parallel, and fit both requirements of maintainability and performance.

3.4.2.1 Algorithmic Skeletons

Algorithmic skeletons are general computational framework for distributed computing proposing predefined patterns that fit certain type of problems [**Cole1988**, **Gonzalez-Velez2010**, 17, 43]. A developer expresses its problem as a specific case of a skeleton. It simplifies the design and implementation of the communications, hence the developer can focus on its problem independently of the distributed communications, and their performance overhead.

As there is similtudes between SQL-like languages, functional structures, and algorithmic skeletons, the latter can be seen as a tentative to merge the more descriptional features of the former into imperative programming. Indeed, among the Algorithmic skeletons, we can cite Map / reduce, which are functional structures, but are somehow equivalent to the select and aggregate functions of SQL. The pipeline architecture for data stream processing presented in section 3.3.3.2 can be considered as algorithmic skeletons.

However, they introduce limitations and difficulties, as the developer must fit its problem into the skeletons. Developers needs to think in terms of message passing instead of a global memory, which, as we saw in previous section, is incompatible with best practices.

3.4.2.2 Microservices & SOA

Another approach in an industrial context is the Service Oriented Architectures (SOA). It allows developers to express an application as an assembly of services connected to each others. It shows well the difference between Information Hiding Principles and Separation of Concerns, as a service doesn't encapsulate a design choice, but a specific task. SOA is in contradiction with the former, but consistent with the latter.

More recently, in the web service development communities, emerged the term of microservices, following the trends of SOA. It to choose and deacrease the granularity of the fitting between modular organization and parallel execution. Using Microservices implies that software developers can manage the two organizations at a sufficiently fine level. As said in section 3.3.2.3 and 3.3.3.2, it is an elitist point of view. Most developers are unable to manage efficiently the two organizations.

Moreover, in these solutions, higher-order programming is impossible. As we showed earlier in section 3.2.3.2, higher-order programming is important

for modular design and maintainability. The next section present some work on compiling from one organization into the other. By keeping the modular programming model, the compilation approach allows higher-level programming.

3.4.3 Compilation

Another approach to conciliate performance and maintainability, is to transform the source from one organization into the other. *It is a mistake to attempt high concurrency without help from the compiler* [11]. When showing the incompatibility between the two organization, D. Parnas already advocated conciling the two methods using an assembler to transform the development organization into the execution organization [54]. I present in the this section the state of the art in compilation-based parallelization.

3.4.3.1 Parallelism Extraction

Generally, there is three type of parallelism, data, task and pipeline parallelism. Some works explore the extraction of the three types indistincly [**Li2012**]. Other works focused on the task parallelism [58]. However, huge works has been done on the data parallelization, to parallelize the loops inside a sequential program [**Mauras1989**, **Yuki2013**, 6, 10, 56] Indeed, the loops represent most of the execution time in scientific applications, so an important speedup is expected from this data parallelization. C. Hermann studied the parallelization of loop in a functional language with higher-order programming and immutable data [**Herrmann2000**]. However, there is few works to parallelize higher-order programming languages, with mutable data. Closures often complicates the dependencies between iterations. To conserve higher-order programming, N. Matsakis proposed to forbid the mutation of the parent closure of a loop, so that the iterations can be executed in parallel while accessing the immutable closure[42].

All these approaches are based on synchronous execution and Amdahl's law states that even if a slight portion of execution is sequential, the expected speedup is limited [7, 15]. Another approach to break free from the sequential structure is to split the sequential execution into following, parallelizable tasks to form a pipeline [**Kamruzzaman2013**, 22]. This thesis focus solely on pipeline parallelism.

Pipeline parallelism is relevant for multi-pass algorithms [16], and it is particularly efficient for stream processing applications as we saw in section 3.3.3.2. For these applications, sequentiality is no longer relevant, as the different stages of the execution are repeated for each message in the stream. Only causality is necessary, and it opens a possible pipeline parallelism.

3.4.3.2 Static analysis

In order to extract parallelism, compilers analyze the source code of applications. The compiler analyzes the control flow to detect the dependencies between statements to parallelize them. As these dependencies are linked to memory access, it is important to have a good memory representation. The point-to analysis, presented by L. Andersen [8] is a common approach to extract the memory representation. It analyzes the modification of pointers through the control flow, to help extract properties from programs. It is used in security to assure the safeness of an implementation, for example in Javascript [**Chudnov2015**].

3.4.3.3 Annotations

Extracting parallel dataflow from an imperative, sequential implementation is a hard problem [**Johnston2004a**]. Some works proposed to rely on annotations from the developer to help the extraction [**Vandierendonck2010a**, 22]. However, it still requires developers indicate the independence of the memory or the execution. In this regard, this solution is similar to concurrent programming present in 3.3.2, and are unable to fix the rupture between performance and maintainability.

All the solution presented throughout this chapter are elitist, as they tend to rely on the developer to reconcile the two organizations. They are not satisfactory as they are too hardly accessible for most developers. It finally results in frail implementations, that require great efforts of development to assure their performance in the first place, and then to maintain.

3.5 Objectives

The section 3.2 shows modularity is the best organization to improve maintainability of an application. This organization is best supported by a functional approach. Indeed, higher-order programming improves readability and

	Maintainability	Performance	Both
General	Functional Programming	Message-passing	Loop parallelization
Web	Javascript	Pipeline architecture	ø

Table 3.1 – Summary of the state of the art

maintainability. However, higher-order programming, and modular programming in general, requires the use of a global memory store.

The section 3.3 shows that to attain scalability, an application needs to be organized to distribute its memory store into independent silos to multiply the exclusive accesses. Still, many works provide this global memory store interface to developers, because it is the best way to support the modularity advocated in section 3.2. This incompatibility between these two organization, and their goals is responsible for the shifts operated during the life of an application. Huge developing efforts are made to translate manually from one organization into the other, and to maintain the implementation despites its unmaintainable nature.

In section 3.4, we show different tentatives to reconciles the two organizations. Most are satisfactory for specific domains, such as the high-performance computing. It is profitable, as the expected speedup of developing an application with an adapted programming model compensates the huge development effort. However, none are satisfactory in the case of web applications because the need for performance is always uncertain. The development effort is not required at the beginning, hence its cost cannot be justified. It is only when the audience increases, often with the revenue, that the cost for the development effort can be justified. This situation illustrate the need for a programming model reconciling the two concerns, of maintainability and performance.

Our objectives is to find an equivalence between these two organization, specifically for the case of web applications. To do so, we focus on the Javascript programming language, and specifically, the node.js interpreter. As explained in the end of chapter 2, the execution model of Javascript is similar to a pipeline. We intend to split a node.js application into a parallel pipeline of stages.

The contribution of this thesis is organized in two chapters, as illustrated in figure 3.1. In chapter 4 I present the extraction of a pipeline of operations from a Javascript application. I show that such pipeline is similar to the

one exposed by Promises, and I propose a simpler alternative to the latter called Dues. However, these operations still require a global memory for coordination so they are not executed in parallel. In chapter 5, we present the isolation of the operations into isolated containers called Fluxions.

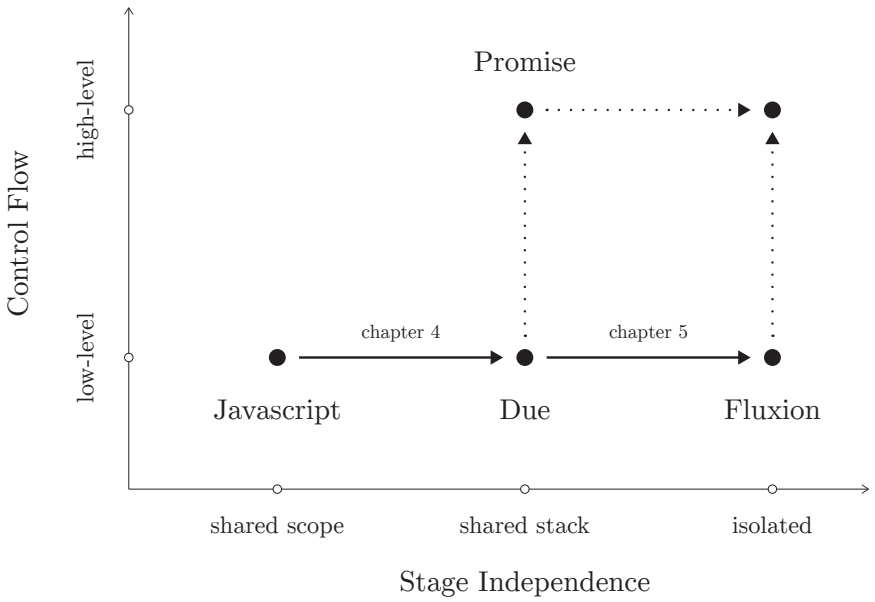


Figure 3.1 – Roadmap for this work

Chapter 4

Pipeline extraction

4.1 Introduction

The previous chapter presented globally the state of the art in designing systems to scale in performance, and in maintenance. It refined the scope of this thesis to the study of the opposition between maintenance scalability and performance scalability in streaming web applications. It concluded with the objectives of this thesis, which is to find an equivalence between the two opposed organizations. The maintenance scalability organization, supported by modular programming, higher-order programming and a global memory store. The performance scalability organization, supported by the parallelism of memory and exuction distribution. The equivalence between these two organization is in two steps, as presented in figure 3.1. This chapter presents the first step in this equivalence. That is to identify and extract a pipeline of execution inside an application following the first organization. In this work, we focus on Javascript, and specifically node.js applications. In this chapter, I define further the higher-order programming concepts.

In Javascript, functions are first-class citizens ; it allows to manipulate them like any object, and to link them to react to asynchronous events, *e.g.* user inputs and remote requests. These asynchronously triggered functions are named callbacks, and allow to efficiently cope with the distributed and inherently asynchronous architecture of the Internet. To execute a suite of asynchronous functions, callbacks are nested one into the other. This nesting, if not organized properly, can result in unreadable layer of callbacks,

commonly presented as *callback hell*[1], or *pyramid of doom*.

Promises are another way to organize a suite of asynchronous operations avoiding this callback hell. They organize the operations as a well-defined pipeline. Moreover, Promises provide additional control over the asynchronous execution flow, than callbacks. They are part of the next version of the Javascript language, ECMAScript 6[2]. To avoid the equivalence being unnecessarily incomplete, we present an alternative to Promise, called Due. Due organize the operations like Promises, as a well-defined pipeline, while discarding the unnecessary additional control over the asynchronous flow.

This chapter present an equivalence, and a compiler to identify the pipeline of operating underlying in a Javascript application using callbacks, and extract it to express it as Dues. This compiler has been tested over 64 *Node.js* packages from the node package manager (npm[3]). 55 packages were incompatible with the compiler, 9 packages were compiled with success.

Callbacks, Promises and Dues are further defined in section 4.2. Section 4.3 explains the transformation from imbrications of callbacks to sequences of Dues. Section 5.3 presents a compiler to automate the application of this equivalence. And finally, the developed compiler is evaluated in section 5.4.

4.2 Definitions

4.2.1 Callback

A callback is a function passed as a parameter to a function call. It is invoked by the callee to continue the execution with data not available in the caller context. We distinguish three kinds of callbacks.

Iterators are functions called for each item in a set, often synchronously.

Listeners are functions called asynchronously for each event in a stream.

Continuations are functions called asynchronously once a result is available.

[1] `http://maxogden.github.io/callback-hell/`
[2] `http://people.mozilla.org/~jorendorff/es6-draft.html`
[3] `https://www.npmjs.com/`

As we will see later, Promises are designed as placeholders for a unique outcome. Iterators and Listeners are invoked multiple times resulting in multiple outcomes. Only continuations are equivalent to Promises. Therefore, we focus on continuations in this paper.

Callbacks are often mistaken for continuations; the former are not inherently asynchronous while the latter are. In a synchronous paradigm, the sequentiality of the execution flow is trivial. An operation needs to complete before executing the next one. In an asynchronous paradigm, parallelism is trivial, but the sequentiality of operations needs to be explicit. Continuations are the functional way of providing this control over the sequentiality of the asynchronous execution flow.

A continuation is a function passed as an argument to allow the callee not to block the caller until its completion. The caller is able to continue the execution while the callee runs in background. The continuation is invoked later, at the termination of the callee to continue the execution as soon as possible and process the result; hence the name continuation. It provides a necessary control over the asynchronous execution flow. It also brings a control over the data flow which essentially replaces the `return` statement at the end of a synchronous function. At its invocation, the continuation retrieves both the execution flow and the result.

The convention on how to hand back the result must be common for both the callee and the continuation. For example, in *Node.js*, the signature of a continuation uses the *error-first* convention. The first argument contains an error or `null` if no error occurred; then follows the result. Listing 4.1 is a pattern of such a continuation. However, continuations don't impose any conventions; indeed, other conventions are used in the browser.

```
my_fn(input, function continuation(error, result) {
  if (!error) {
    console.log(result);
  } else {
    throw error;
  }
});
```

Listing 4.1 – Example of a continuation

The callback hell occurs when many asynchronous calls are arranged to be executed sequentially. Each consecutive operation adds an indentation level, because it is nested inside the continuation of the previous operation. It produces an imbrication of calls and function definitions, as shown in listing 4.2. We say that continuations lack the chained composition of multiple

asynchronous operations. Promises allow to arrange such a sequence of asynchronous operations in a more concise and readable way.

```
my_fn_1(input, function cont(error, result) {
  if (!error) {
    my_fn_2(result, function cont(error, result) {
      if (!error) {
        my_fn_3(result, function cont(error, result) {
          if (!error) {
            console.log(result);
          } else {
            throw error;
          }
        });
      } else {
        throw error;
      }
    });
  } else {
    throw error;
  }
});
```

Listing 4.2 – Example of a sequence of continuations

4.2.2 Promise

In a synchronous paradigm, the sequentiality of the execution flow is trivial. While in an asynchronous paradigm, this control is provided by continuations. Promises provide a unified control over the execution flow for both paradigms. The ECMAScript 6 specification[4] defines a Promise as an object that is used as a placeholder for the eventual outcome of a deferred (and possibly asynchronous) operation. Promises expose a `then` method which expects a continuation to continue with the result; this result being synchronously or asynchronously available.

Promises force another control over the execution flow. According to the outcome of the operation, they call one function to continue the execution with the result, or another to handle errors. This conditional execution is indivisible from the Promise structure. As a result, Promises impose a convention on how to hand back the outcome of the deferred computation, while classic continuations leave this conditional execution to the developer.

```
var promise = my_fn_pr(input)

```

[4] https://people.mozilla.org/~jorendorff/es6-draft.html#sec-promise-objects

```
promise.then(function onSuccess(result) {
  console.log(result);
}, function onError(error) {
  throw error;
});
```

Listing 4.3 – Example of a promise

Promises are designed to fill the lack of chained composition from continuations. They allow to arrange successions of asynchronous operations as a chain of continuations, by opposition to the imbrication of continuations illustrated in listing 4.2. That is to arrange them, one operation after the other, in the same indentation level.

The listing 4.4 illustrates this chained composition. The functions `my_fn_pr_2` and `my_fn_pr_3` return promises when they are executed, asynchronously. Because these promises are not available synchronously, the method `then` synchronously returns intermediary Promises. The latter resolve only when the former resolve. This behavior allows to arrange the continuations as a flat chain of calls, instead of an imbrication of continuations.

```
my_fn_pr_1(input)
.then(my_fn_pr_2, onError)
.then(my_fn_pr_3, onError)
.then(console.log, onError);

function onError(error) {
  throw error;
}
```

Listing 4.4 – A chain of Promises is more concise than an imbrication of continuations

The Promises syntax is more concise, and also more readable because it is closer to the familiar synchronous paradigm. Indeed, Promises allow to arrange both the synchronous and asynchronous execution flow with the same syntax. It allows to easily arrange the execution flow in parallel or in sequence according to the required causality. This control over the execution leads to a modification of the control over the data flow. Programmers are encouraged to arrange the computation as series of coarse-grained steps to carry over inputs. In this sense, Promises are comparable to some coarse-grained data-flow programming paradigms, such as Flow-based programming [49].

4.2.3 From continuations to Promises

As detailed in the previous sections, continuations provide the control over the sequentiality of the asynchronous execution flow. Promises improve this control to allow chained compositions, and unify the syntax for the synchronous and asynchronous paradigm. This chained composition brings a greater clarity and expressiveness to source codes. At the light of these insights, it makes sense for a developer to switch from continuations to Promises. However, the refactoring of existing code bases might be an operation impossible to carry manually within reasonable time. We want to automatically transform an imbrication of continuations into a chained composition of Promises.

We identify two steps in this transformation. The first is to provide an equivalence between a continuation and a Promise. The second is the composition of this equivalence. Both steps are required to transform imbrications of continuations into chains of Promises.

Because Promises bring chained composition, the first step might seem trivial as it does not imply any imbrication to transform into chain. However, as explained in section 4.2.2, Promises impose a control over the execution flow that continuations leave free. This control induces a common convention to hand back the outcome to the continuation.

In the Javascript landscape, there is no dominant convention for handing back outcomes to continuations. In the browser, many conventions coexist. For example, *jQuery*'s `ajax`[5] method expects an object with different continuations for success, errors and various other events during the asynchronous operation. *Q*[6], a popular library to control the asynchronous flow, exposes two methods to define continuations: `then` for successes, and `catch` for errors. On the other hand, the *Node.js* API always used the *error-first* convention, encouraging developers to provide libraries using the same convention. In this large ecosystem the *error-first* convention is predominant. All these examples use different conventions than the Promise specification detailed in section 4.2.2. They present strong semantic differences, despite small syntactic differences.

To translate these different conventions into the Promises one, the compiler would need to identify them. Such an identification might be possible with static analysis methods such as the points-to analysis [63], or a program

[5] `http://api.jquery.com/jquery.ajax/`
[6] `http://documentup.com/kriskowal/q/`

logic [24, 12]. However, it seems impracticable because of the number and semantical heterogeneity of these conventions. Indeed, in the browser, each library seems to provide its own convention.

In this paper, we are interested in the transformation from imbrications to chains, not from one convention to another. The *error-first* convention, used in *Node.js*, is likely to represent a large, coherent code base to test the equivalence. Indeed contains currently more than 125 000 packages. For this reason, we focus only on the *error-first* convention. Thus, our compiler is only able to compile code that follows this convention. The convention used by Promises is incompatible. We propose an alternative specification to Promise following the *error-first* convention. In the next section we present this specification called Due.

The choice to focus on *Node.js* is also motivated by our intention to compare later the chained sequentiality of Promises with the data-flow paradigm. *Node.js* allows to manipulate streams of messages. This proved to be efficient for real-time web applications manipulating streams of user requests. Both Promises and data-flow arrange the computation in chains of independent operations.

4.2.4 Due

A Due is an object used as placeholder for the eventual outcome of a deferred operation. Dues are a simplification of the Promise specification. They are essentially similar to Promises, except for the convention to hand back outcomes. They use the *error-first* convention, like *Node.js*, as illustrated in listing 4.5. The implementation of Dues and its tests are available online[7]. A more in-depth description of Dues and their creation follows in the next paragraphs.

```
1  var my_fn_due = require('due').mock(my_fn);
2
3  var due = my_fn_due(input);
4
5  due.then(function continuation(error, result) {
6    if (!error) {
7      console.log(result);
8    } else {
9      throw error;
10   }
11 });
```

Listing 4.5 – Example of a due

[7] https://www.npmjs.com/package/due

A due is typically created inside the function which returns it. In listing 4.5, line 1, the `mock` method wraps `my_fn` in a Due-compatible function. The rest of this code is similar to the Promise example, listing 4.3.

We illustrate in listing 4.6 the creation of a Due through the `mock` method. At its creation, line 6, the Due expects a callback containing the deferred operation, which is `my_fn` here. This callback is executed synchronously with the function `settle` as argument to settle the Due, synchronously or asynchronously. The `settle` function is pushed at the end of the list of arguments. The callback invokes the deferred operation with this list of arguments, and the current context, line 8. When finished, the latter calls `settle` to settle the Due and save the outcome. Settled or not, the created Due is always synchronously returned. Its `then` method allows to define a continuation to retrieve the saved outcome, and continue the execution after its settlement. If the deferred operation is synchronous, the Due settles during its creation and the `then` method immediately calls this continuation. If the deferred operation is asynchronous, this continuation is called during the Due settlement.

```
1  Due.mock = function(my_fn) {
2    return function mocked_fn() {
3      var _args = Array.prototype.slice.call(arguments),
4          _this = this;
5
6      return new Due(function(settle) {
7        _args.push(settle);
8        my_fn.apply(_this, _args);
9      })
10   }
11 }
```

Listing 4.6 – Creation of a due

The composition of Dues is the same than for Promises (see section 4.2.2). Through this chained composition, Dues arrange the execution flow as a sequence of actions to carry on inputs.

This simplified specification adopts the same convention than *Node.js* for continuations to hand back outcomes. Therefore, the equivalence between a continuation and a Due is trivial. Dues are admittedly tailored for this paper, hence, they are not designed to be written by developers, like Promises are. They are an intermediary step between classical continuations and Promises. We present in section 4.3 the equivalence between continuations and Dues.

4.3 Equivalence

We present the transformation from a nested imbrication of continuations into a chain of Dues. We explain the three limitations imposed by our compiler for this transformation to preserve the semantic. They preserve the execution order, the execution linearity and the scopes of the variables used in the operations.

4.3.1 Execution order

Our compiler spots function calls with a continuation, which are similar to the abstraction in (4.1). It wraps the function fn into the function $fn_{\mathbf{due}}$ to return a Due. And it relocates the continuation in a call to the method **then**, which references the Due previously returned. The result should be similar to (4.2). The differences are highlighted in bold font.

$$fn([arguments], continuation) \tag{4.1}$$

$$fn_{\mathbf{due}}([arguments])\mathbf{.then}(continuation) \tag{4.2}$$

The execution order is different whether *continuation* is called synchronously, or asynchronously. If fn is synchronous, it calls the *continuation* within its execution. It might execute *statements* after executing *continuation*, before returning. If fn is asynchronous, the continuation is called after the end of the current execution, after fn. The transformation erases this difference in the execution order. In both cases, the transformation relocates the execution of *continuation* after the execution of fn. For synchronous fn, the execution order changes ; the execution of *statements* at the end of fn and the continuation switch. The latter must be asynchronous to preserve the execution order.

4.3.2 Execution linearity

Our compiler transforms a nested imbrication of continuations, which is similar to the abstraction in (4.3) into a flatten chain of calls encapsulating them,

like in (4.4).

$$
\begin{aligned}
&fn1([arguments], cont1\{\\
&\quad declare\ variable \leftarrow result\\
&\quad fn2([arguments], cont2\{\\
&\quad\quad print\ variable\\
&\quad \})\\
&\})
\end{aligned}
\tag{4.3}
$$

$$
\begin{aligned}
&\textbf{declare variable}\\
&fn1_{\textbf{due}}([arguments])\\
&\textbf{.then}(cont1\{\\
&\quad variable \leftarrow result\\
&\quad fn2_{\textbf{due}}([arguments])\\
&\})\\
&\textbf{.then}(cont2\{\\
&\quad print\ variable\\
&\})
\end{aligned}
\tag{4.4}
$$

An imbrication of continuations must not contain any loop, nor function definition that is not a continuation. Both modify the linearity of the execution flow which is required for the equivalence to keep the semantic. A call nested inside a loop returns multiple Dues, while only one is returned to continue the chain. A function definition breaks the execution linearity. It prevent the nested call to return the Due expected to continue the chain. On the other hand, conditional branching leaves the execution linearity and the semantic intact. If the nested asynchronous function is not called, the execution of the chain stops as expected.

4.3.3 Variable scope

In (4.3), the definitions of *cont*1 and *cont*2 are overlapping. The *variable* declared in *cont*1 is accessible in *cont*2 to be printed. In (4.4), however, definitions of *cont*1 and *cont*2 are not overlapping, they are siblings. The *variable* is not accessible to *cont*2. It must be relocated in a parent function

to be accessible by both *cont*1 and *cont*2. To detect such variables, the compiler must infer their scope statically. Languages with a lexical scope define the scope of a variable statically. Most imperative languages present a lexical scope, like C/C++, Python, Ruby or Java. The subset of Javascript excluding the built-in functions `with` and `eval` is also lexically scoped. To compile Javascript, the compiler must exclude programs using these two statements.

4.4 Compiler

We build a compiler to automate the application of this equivalence on existing Javascript projects. The compilation process contains two important steps, the identification of the continuations, and the generation of chains.

4.4.1 Identification of continuations

The first compilation step is to identify the continuations and their imbrications. The nested imbrication of callbacks only occurs when they are defined *in situ*. The compiler detects a function definition within the arguments of a function call. This detection is based on the syntax, and is trivial.

Not all detected callbacks are continuations, but the equivalence is applicable only on the latter. A continuation is a callback invoked only once, asynchronously. Spotting a continuation implies to identify these two conditions. There is no syntactical difference between a synchronous and an asynchronous callee. And it is impossible to assure a callback to be invoked only once, because the implementation of the callee is often statically unavailable. Therefore, the identification of continuations is necessarily based on semantical differences. To recognize these differences, the compiler would need to have a deep understanding of the control and data flows of the program. Because of the highly dynamic nature of Javascript, this understanding is either unsound, limited, or complex. Instead, we choose to leave to the developer the identification of compatible continuations among the identified callbacks. They are expected to understand the limitations of this compiler, and the semantic of the code to compile.

We provide a simple interface for developers to interact with the compiler. We built this interface around the compiler in a web page available online[8] to

[8] `compiler-due.apps.zone52.org`

reproduce the tests. The web technologies allow to quickly build an interface for a wide variety of computing devices.

This interaction prevents the complete automation of the individual compilation process. However, we are working on an automation at a global scale. We expect to be able to identify a continuation only based on the name of its callee, *e.g.* `fs.readFile`. We built a service to gather these names along with their identification. The compiler queries this service to present to the developer an estimated identification. After the compilation, it sends back the identification corrected by the developer to refine the future estimations. In future works, we would like to study the possibility for such a service to assist, and ease the compilation process.

4.4.2 Generation of chains

The compositions of continuations and Dues are arranged differently. Continuations structure the execution flow as a tree, while a chain of Dues imposes to arrange it sequentially. A parent continuation can execute several children, while a Due allow to chain only one. The second compilation step is to identify the imbrications of continuations, and trim the extra branches to transform them into chains.

If a continuation has more than one child, the compiler tries to find a single legitimate child to form the longest chain possible. This legitimate child is the only parent among its siblings. If there are several parents among the children, none are the legitimate child. The non legitimate children start a new tree. This step transform each tree of continuations into several chains of continuations that translate into sequences of Dues. The code generation from these chains is straightforward from the equivalence.

4.5 Evaluation

To validate our compiler, we compile several Javascript projects likely to contain continuations. We present the results of these tests.

The compilation of a project requires user interaction. To conduct the test in a reasonable time, we limit the test set to a minimum. We search the *Node Package Manager* database to restrict the set to *Node.js* projects. We refine the selection to web applications depending on the web framework *express*, but not on the most common Promises libraries such as *Q* and *Async*.

We refine further the selection to projects using the test frameworks *mocha* in its default configuration. We use these tests to validate the compiler. The test set contains 64 projects. This subset is very small, and cannot represent the wide possibilities of Javascript. However, we believe it is sufficient to represent a majority of common cases.

For each project, we verify that is is correctly tested, and passes the tests. During the compilation, we identify the compatible continuations among the detected callbacks. We apply the unmodified test on the compilation result. The compilation result should pass the tests as well. This is not a strong validation, but it assures the compiler to work as expected in most common cases.

Of the 64 projects tested, almost a half, does not contain any compatible continuations. We reckon that these projects use continuations the compiler is unable to detect. The other projects were rejected by the compiler because they contain `with` or `eval` statements, they use Promises libraries we didn't filter previously. 9 projects compiled successfully. The compiler did not fail to compile any project of the initial test set.

Over the 9 successfully compiled projects, the compiler detected 172 callbacks. We manually identified 56 of them to be compatible continuations. The false positives are mainly the listeners that the web applications register to react to user requests.

One project contains 20 continuations, the others contains between 1 and 9 continuations each. On the 56 continuations, 36 are single. The others 20 continuations belong to imbrications of 2 to 4 continuations. The result of this evaluation prove the compiler to be able to successfully transform imbrications of continuations.

On the 64 projects composing the test set

29 (45.3%) do not contain any compatible continuations,

10 (15.6%) are not compilable because they contain `with` or `eval` statements,

5 (7.8%) use less common asynchronous libraries we didn't filter previously,

4 (6.3%) are not syntactically correct,

4 (6.3%) fail their tests before the compilation,

3 (4.7%) are not tested, and

10 (14.0%) compile successfully.

The compiler do not fail to compile any project. The details of these projects are available in Appendix **??**.

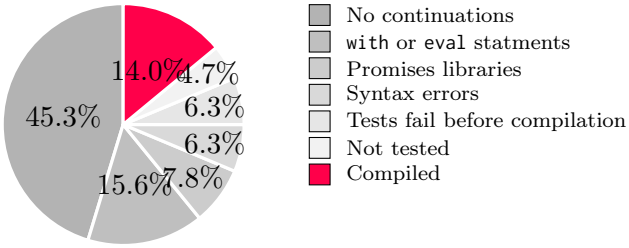


Figure 4.1 – Compilation results distribution

Chapter 5

Pipeline isolation

5.1 Introduction

The previous chapter presented a compiler to identify and extract the underlying pipeline in a Javascript application. However, all the operations are not independent, and cannot be executed in parallel, to support the performance scalability. This chapter present the second contribution of this thesis. The equivalence between a memory shared among all the operations and independent memory for each operation in a pipeline. It tackles the problems arising from the translation of the global memory synchronization into message passing.

This equivalence is implemented as a compiler, improving upon the previous one. The compiler transforms a Javascript application into a network of independent parts communicating by message streams and executed in parallel. We named these parts *fluxions*, by contraction between a flux and a function.

Section 5.2 describes the execution model that executes fluxions in parallel, and assure their communications. The compiler, and the equivalence are described in section 5.3. Section 5.4 a real-case test of compilation, and expose the limits of this compiler.

5.2 Fluxional execution model

In this section, we present an execution model to provide scalability to web applications. To achieve this, the execution model provides a granularity of

parallelism at the function level. Functions are encapsulated in autonomous execution containers with their state, so as to be reallocated and executed in parallel. This execution model is close to the actors model, as the execution containers are independent and communicate by messages. The communications are assimilated to stream of messages, similarly to the dataflow programming model. It allows to reason on the throughput of these streams, and to react to load increases.

The fluxional execution model executes programs written in our high-level fluxionnal language, whose grammar is presented in figure 5.1. An application ⟨program⟩ is partitioned into parts encapsulated in autonomous execution containers named *fluxions* ⟨flx⟩. In the following paragraphs, we present the *fluxions*. Then we present the messaging system to carry the communications between *fluxions*. Finally, we present an example application using this execution model.

5.2.1 Fluxions

A *fluxion* ⟨flx⟩ is named by a unique identifier ⟨id⟩ to receive messages, and might be part of one or more groups indicated by tags ⟨tags⟩. A *fluxion* is composed of a processing function ⟨fn⟩, and a local memory called a *context* ⟨ctx⟩. At a message reception, the *fluxion* modifies its *context*, and sends messages on its output streams ⟨streams⟩ to downstream *fluxions*. The *context* handles the state on which a *fluxion* relies between two message receptions. In addition to message passing, the execution model allows *fluxions* to communicate by sharing state between their *contexts*. The fluxions that need to synchronize together are grouped with the same tag, and loose their independence.

There are two types of streams, *start* and *post*, which correspond to the nature of the rupture point yielding the stream. We differentiate the two types with two different arrows, double arrow (`>>`) for *start* rupture points and simple arrow (`->`) for *post* rupture points. The two types of rupture points are further detailed in section 5.3.1.1.

5.2.2 Messaging system

The messaging system assures the stream communications between fluxions. It carries messages based on the names of the recipient fluxions. After the

⟨program⟩ ⊨ ⟨flx⟩ | ⟨flx⟩ *eol* ⟨program⟩
⟨flx⟩ ⊨ `flx` ⟨id⟩ ⟨tags⟩ ⟨ctx⟩ *eol* ⟨streams⟩ *eol* ⟨fn⟩
⟨tags⟩ ⊨ `&` ⟨list⟩ | *empty string*
⟨streams⟩ ⊨ `null` | ⟨stream⟩ | ⟨stream⟩ *eol* ⟨streams⟩
⟨stream⟩ ⊨ ⟨type⟩ ⟨dest⟩ [⟨msg⟩]
⟨dest⟩ ⊨ ⟨list⟩
⟨ctx⟩ ⊨ `{`⟨list⟩`}`
⟨msg⟩ ⊨ `[`⟨list⟩`]`
⟨list⟩ ⊨ ⟨id⟩ | ⟨id⟩ , ⟨list⟩
⟨type⟩ ⊨ `>>` | `->`
⟨id⟩ ⊨ *Identifier*
⟨fn⟩ ⊨ *imperative language and stream syntax*

Figure 5.1 – Syntax of a high-level language to represent a program in the fluxionnal form

execution of a fluxion, it queues the resulting messages for the event loop to process.

The execution cycle of an example fluxional application is illustrated in figure 5.2. Circles represent registered fluxions. The source code for this application is in listing 5.1 and the fluxional code for this application is in listing 5.2. The fluxion *reply* has a context containing the variable `count` and `template`. The plain arrows represent the actual message paths in the messaging system, while the dashed arrows between fluxions represent the message streams as seen in the fluxionnal application.

The *main* fluxion is the first fluxion in the flow. When the application receives a request, this fluxion triggers the flow with a `start` message containing the request, ②. This first message is to be received by the next fluxion *handler*, ③ and ④. The fluxion *handler* sends back a message, ⑤, to be enqueued, ⑥. The system loops through steps ③ through ⑥ until the queue is empty. This cycle starts again for each new incoming request causing another `start` message.

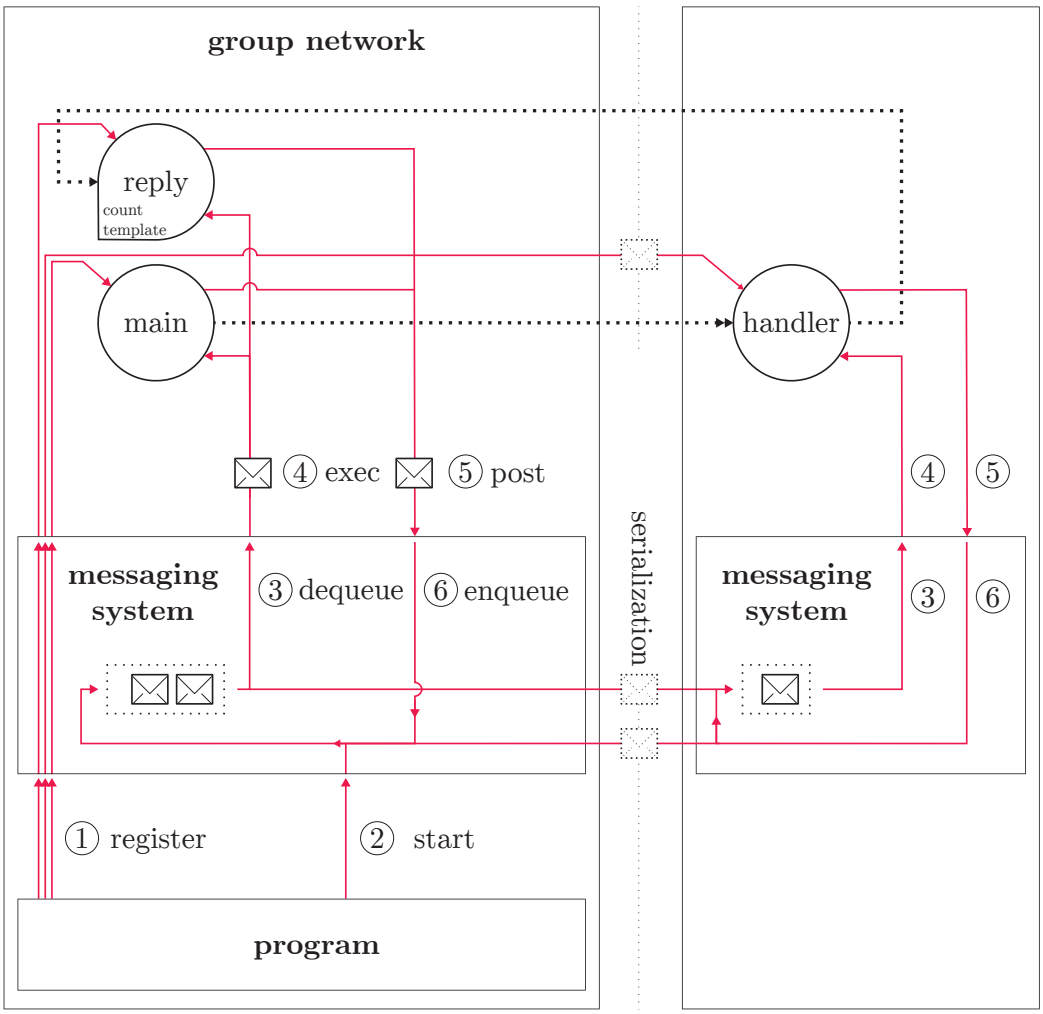


Figure 5.2 – The fluxionnal execution model in details

5.2.3 Service example

To illustrate the fluxional execution model, and the compiler, we present in listing 5.1 an example of a simple web application. This application reads a file, and sends it back along with a request counter.

```
1 var app = require('express')(),
2     fs = require('fs'),
3     count = 0;
4
5 app.get('/', function handler(req, res){
6   fs.readFile(__filename, function reply(err, data) {
```

```
7     count += 1;
8     res.send(err || template(count, data));
9   });
10 });
11
12 app.listen(8080);
```

Listing 5.1 – Example web application

The `handler` function, line 5 to 11, receives the input stream of request. The `count` variable at line 3 increments the request counter. This object needs to be persisted in the fluxion *context*. The `template` function formats the output stream to be sent back to the client. The `app.get` and `res.send` functions, respectively line 5 and 8, interface the application with the clients. And between these two interface functions is a chain of three functions to process the client requests : `app.get` $\twoheadrightarrow$ `handler` $\rightarrow$ `reply`. This application is transformed into the high-level fluxionnal language in listing 5.2 which is illustred in Figure 5.2.

```
1  flx main & network
2  >> handler [res]
3    var app = require('express')(),
4        fs = require('fs'),
5        count = 0;
6
7    app.get('/', >> handler); //
8    app.listen(8080);
9
10 flx handler
11 -> reply [res]
12   function handler(req, res) {
13     fs.readFile(__filename, -> reply); //
14   }
15
16 flx reply & network {count, template}
17 -> null
18   function reply(error, data) {
19     count += 1; //
20     res.send(err || template(count, data)); //
21   }
```

Listing 5.2 – Example application expressed in the high-level fluxional language

The application is organized as follow. The flow of requests is received from the clients by the fluxion `main`, it continues in the fluxion `handler`, and finally goes through the fluxion `reply` to be sent back to the clients. The fluxions `main` and `reply` have the tag `network`. This tag indicates their dependency over the network interface, because they received the response

from and send it back to the clients. The fluxion `handler` doesn't have any dependencies, hence it can be executed in parallel.

The last fluxion, `reply`, depends on its context to holds the variable `count` and the function `template`. It also depends on the variable `res` created by the first fluxion, `main`. This variable is carried by the stream through the chain of fluxion to the fluxion `reply` that depends on it. This variable holds the references to the network sockets. It is the variable the group `network` depends on.

Moreover, if the last fluxion, `reply`, did not relied on the variable `count`, the group `network` would be stateless. The whole group could be replicated as many time as needed.

This execution model allows to parallelize the execution of an application. Some parts are arranged in pipeline, like the fluxion `handler`, some other parts are replicated, as could be the group `network`. This parallelization improves the scalability of the application. Indeed, as a fluxion contains its state and expresses its dependencies, it can be migrated. It allows to adapt the number of fluxions per core to adjust the resource usage in function of the desired throughput.

Our goal, as described in the introduction, is not to propose a new programming paradigm with this high-level language but to automate the architecture shift. We present the compiler to automate this architecture shift in the next section.

5.3 Fluxionnal compiler

The source languages we focus on should present higher-order functions and be implemented as an event-loop with a global memory. Javascript is such a language : it doesn't require an event-loop, but it is often implemented on top of an event-loop. *Node.js* is an example of such an implementation. We developed a compiler that transforms a *Node.js* application into a fluxional application compliant with the execution model described in section 5.2.

The chain of compilation is described in figure 5.3. From the source of a *Node.js* application, the compiler extracts an Abstract Syntax Tree (AST) with `esprima`. From this AST, the analyzer step identifies the limits of the different application parts and how they relate to form a pipeline. This first step outputs a pipeline representation of the application. Section 5.3.1 explains this first compilation step. In the pipeline representation, the stages

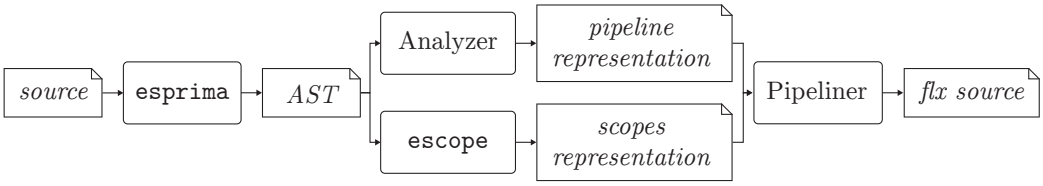


Figure 5.3 – Compilation chain

are not yet independent and encapsulated into fluxions. From the AST, `escope` produces a representation of the memory scopes. The pipeliner step analyzes the pipeline representation and the scopes representation to distribute the shared memory into independent groups of fluxions. Section 5.3.2 explains this second compilation step.

5.3.1 Analyzer step

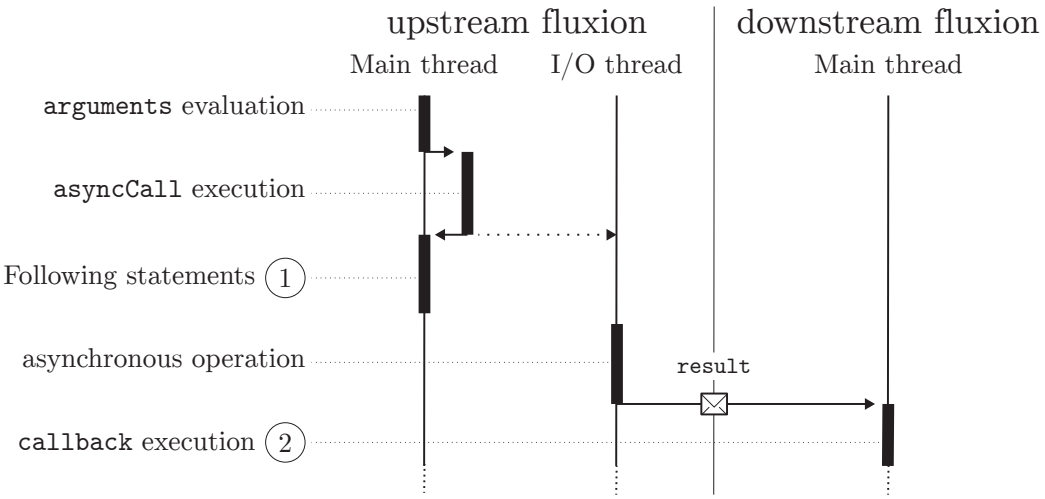
The limit between two application parts is defined by a rupture point. The analyzer identifies these rupture points, and outputs a representation of the application in a pipeline form, with application parts as the stages, and rupture points as the message streams of this pipeline.

5.3.1.1 Rupture points

A rupture point is a call of a loosely coupled function. It is an asynchronous call without subsequent synchronization with the caller. In *Node.js*, I/O operations are asynchronous functions and indicate such rupture point between two application parts. Figure 5.4 shows an example of a rupture point with the execution of the two application parts isolated into fluxions. The two application parts are the caller of the asynchronous function call on one hand, and the callback provided to the asynchronous function call on the other hand.

A callback is a function passed as a parameter to a function call. It is invoked by the callee to continue the execution with data not available in the caller context. We distinguish three kinds of callbacks, but only two are asynchronous : listeners and continuations. Similarly, there are two types of rupture points, respectively *start* and *post*.

Start rupture points are indicated by listeners. They are on the border




```
1 asyncCall(arguments, function callback(result){ ② });
2 // Following statements ①
```

Figure 5.4 – Rupture point interface

between the application and the outside, continuously receiving incoming user requests. An example of a start rupture point is in listing 5.1, between the call to `app.get()`, and its listener `handler`. These rupture points indicate the input of a data stream in the program, and the beginning of a chain of fluxions to process this stream.

Post rupture points are indicated by continuations. They represent a continuity in the execution flow after an asynchronous operation yielding a unique result, such as reading a file, or querying a database. An example of a post rupture points is in listing 5.1, between the call to `fs.readFile()`, and its continuation `reply`.

5.3.1.2 Detection

The compiler uses a list of common asynchronous callees, like the `express` and file system methods. This list can be augmented to match asynchronous callees individually for any application. To identify the callee, the analyzer walks the AST to find a call expression matching this list.

After the identification of the callee, the callback needs to be identified as

well to be encapsulated in the downstream fluxion. For each asynchronous call detected, the compiler test if one of the arguments is of type `function`. Some callback functions are declared *in situ*, and are trivially detected. For variable identifier, and other expressions, the analyzer tries to detect their type. To do so, the analyzer walks back the AST to track their assignations and modifications, and to determine their last value.

5.3.2 Pipeliner step

A rupture point eventually breaks the chain of scopes between the upstream and downstream fluxion. The closure in the downstream fluxion cannot access the scope in the upstream fluxion as expected. The pipeliner step replaces the need for this closure, allowing application parts to rely only on independent memory stores and message passing. It determines the distribution using the scope representation, which represents the variables' dependencies between application parts. Depending on this representation, the compiler can replace the broken closures in three different ways. We present these three alternatives with the example figure 5.5.

Scope If a variable is modified inside only one application part in the current *post* chain, then the pipeliner adds it to the context of its fluxion.

In figure 5.5, the variable `a` is updated in the function `add`. The pipeliner step stores this variable in the context of the fluxion `add`.

Stream If a variable is modified inside an application part, and read inside downstream application parts, then the pipeliner makes the upstream fluxion add this variable to the message stream to be sent to the downstream fluxions. It is impossible to send variables to upstream fluxions, without race conditions. If the fluxion retro propagates the variable for an upstream fluxion to read, the upstream fluxion might use the old version while the new version is on its way.

In figure 5.5, the variable `b` is set in the function `onReq`, and read in the function `add`. The pipeliner step makes the fluxion `onReq` send the updated variable `b`, in addition to the variable `v`, in the message sent to the fluxion `add`.

Exceptionally, if a variable is defined inside a *post* chain, like `b`, then this variable can be streamed inside this *post* chain without restriction on

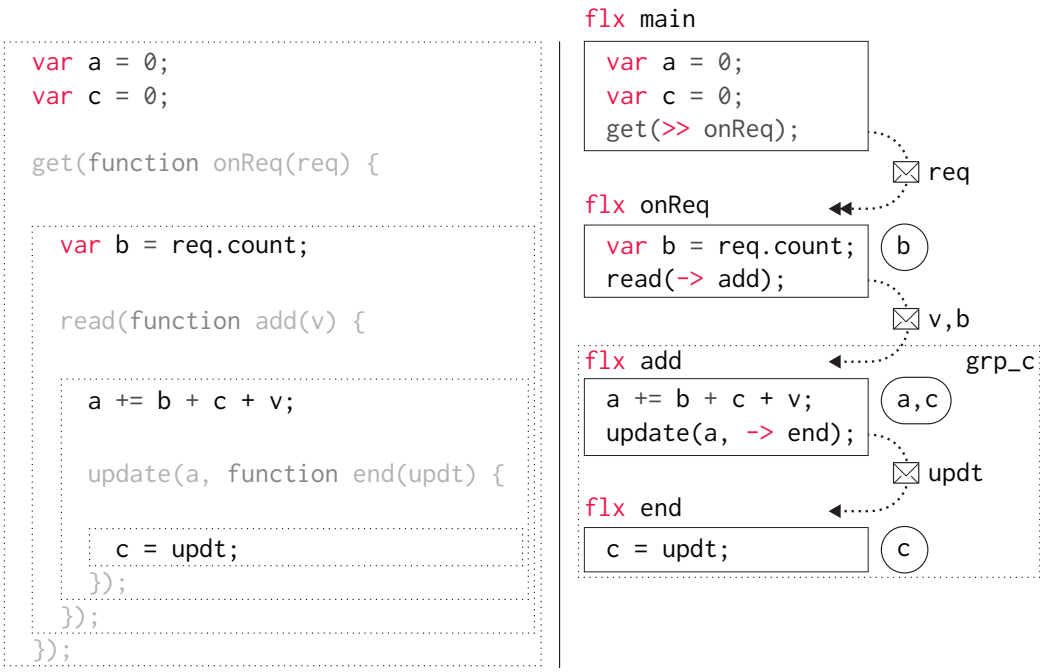


Figure 5.5 – Variable management from Javascript to the high-level fluxionnal language

the order of modification and read. Indeed, the execution of the upstream fluxion for the current *post* chain is assured to end before the execution of the downstream fluxion. Therefore, no reading of the variable by the upstream fluxion happens after the modification by the downstream fluxion.

Share If a variable is needed for modification by several application parts, or is read by an upstream application part, then it needs to be synchronized between the fluxions. To respect the semantics of the source application, we cannot tolerate inconsistencies. Therefore, the pipeliner groups all the fluxions sharing this variable within a same tag. And it adds this variable to the contexts of each fluxions.

In figure 5.5, the variable `c` is set in the function `end`, and read in the function `add`. As the fluxion `add` is upstream of `end`, the pipeliner step groups the fluxion `add` and `end` with the tag `grp_c` to allow the two fluxions to share this variable.

5.4 Real case test

The goal of this test is to prove the possibility for an application to be compiled into a network of independent parts. We want to show the current limitations of this isolation and the modifications needed on the application to circumvent these limitations.

We present a test of our compiler on a real application, gifsockets-server[1]. This application was selected from the `npm` registry because it depends on `express`, it is tested, working, and simple enough to illustrate this evaluation. It is part of the selection from a previous work.

This application is a real-time chat using gif-based communication channels. The server transforms the received text into a gif frame, and pushes it back to a never-ending gif to be displayed on the client. Listing 5.3 is a simplified version of this application.

```
1  var express = require('express'),
2      app = express(),
3      routes = require('gifsockets-middleware'),
4      getRawBody = require('raw-body');
5
6  function bodyParser(limit) {
7    return function saveBody(req, res, next) {
8      getRawBody(req, {
9        expected: req.headers['content-length'],
10       limit: limit
11     }, function (err, buffer) {
12       req.body = buffer;
13       next();
14     });
15   };
16 }
17
18 app.post('/image/text', bodyParser(1 * 1024 * 1024), routes.writeTextToImages);
19 app.listen(8000);
```

Listing 5.3 – Simplified version of gifsockets-server

On line 18, the application registers two functions to process the requests received on the url `/image/text`. The closure `saveBody`, line 7, returned by `bodyParser`, line 6, and the method `routes.writeTextToImages` from the external module `gifsockets-middleware`, line 3. The closure `saveBody` calls the asynchronous function `getRawBody` to get the request body. Its callback handles the errors, and calls `next` to continue processing the request with the next function, `routes.writeTextToImages`.

[1] `https://github.com/twolfson/gifsockets-server`

5.4.1 Compilation

We compile this application with the compiler detailed in section 5.3. The function call `app.post`, line 18, is a rupture point. However, its callbacks, `bodyParser` and `routes.writeTextToImages` are evaluated as functions only at runtime. For this reason, the compiler ignores this rupture point, to avoid interfering with the evaluation.

The compilation result is in listing 5.4. The compiler detects a rupture point : the function `getRawBody` and its anonymous callback, line 11. It encapsulates this callback in a fluxion named `anonymous_1000`. The callback is replaced with a stream placeholder to send the message stream to this downstream fluxion. The variables `req`, and `next` are appended to this message stream, to propagate their value from the `main` fluxion to the `anonymous_1000` fluxion.

When `anonymous_1000` is not isolated from the `main` fluxion, the compilation result works as expected. The variables used in the fluxion, `req` and `next`, are still shared between the two fluxions. Our goal is to isolate the two fluxions, to be able to safely parallelize their executions.

```
1  flx main
2  >> anonymous_1000 [req, next]
3    var express = require('express'),
4        app = express(),
5        routes = require('gifsockets-middleware'), //
6        getRawBody = require('raw-body');
7
8    function bodyParser(limit) { //
9      return function saveBody(req, res, next) { //
10       getRawBody(req, { //
11         expected: req.headers['content-length'], //
12         limit: limit
13       }, >> anonymous_1000);
14     };
15   }
16
17   app.post('/image/text', bodyParser(1 * 1024 * 1024), routes.writeTextToImages);
         //
18   app.listen(8000);
19
20 flx anonymous_1000
21 -> null
22   function (err, buffer) { //
23     req.body = buffer; //
24     next(); //
25   }
```

Listing 5.4 – Compilation result of gifsockets-server

5.4.2 Isolation

In listing 5.4, the fluxion `anonymous_1000` modifies the object `req`, line 23, to store the text of the received request, and it calls `next` to continue the execution, line 24. These operations produce side-effects that should propagate in the whole application, but the isolation prevents this propagation. Isolating the fluxion `anonymous_1000` produces runtime exceptions. We detail in the next paragraph, how we handle this situation to allow the application to be parallelized. This test highlights the current limitations of the compiler, and presents future works to circumvent them.

5.4.2.1 Variable `req`

The variable `req` is read in fluxion `main`, lines 10 and 11. Then it is associated in fluxion `anonymous_1000` to `buffer`, line 23. The compiler is unable to identify further usages of this variable. However, the side effect resulting from this association impacts a variable in the scope of the next callback, `routes.writeTextToImages`. We modified the application to explicitly propagate this side-effect to the next callback through the function `next`. We explain further modification of this function in the next paragraph.

5.4.2.2 Closure `next`

The function `next` is a closure provided by the `express Router` to continue the execution with the next function to handle the client request. Because it indirectly relies on network sockets, it is impossible to isolate its execution with the `anonymous_1000` fluxion. Instead, we modify `express`, so as to be compatible with the fluxionnal execution model. We explain the modification below.

```
1  flx main & express
2  >> anonymous_1000 [req, next]
3    var express = require('express'),
4        app = express(),
5        routes = require('gifsockets-middleware'), //
6        getRawBody = require('raw-body');
7
8    function bodyParser(limit) { //
9      return function saveBody(req, res, next) { //
10       getRawBody(req, { //
11         expected: req.headers['content-length'], //
12         limit: limit
13       }, >> anonymous_1000);
14     };
```

```
15   }
16
17   app.post('/image/text', bodyParser(1 * 1024 * 1024), routes.writeTextToImages);
           //
18   app.listen(8000);
19
20 flx anonymous_1000
21 -> express_dispatcher
22   function (err, buffer) { //
23     req.body = buffer; //
24     next_placeholder(req, -> express_dispatcher); //
25   }
26
27 flx express_dispatcher & express //
28 -> null
29   merge(req, msg.req);
30   next(); //
```

Listing 5.5 – Simplified modification on the compiled result

Originally, the function `next` is the continuation to allow the anonymous callback on line 11, to continue the execution with the next function to handle the request. To isolate the anonymous callback, this function is replaced on both ends. The result of this replacement is illustrated in listing 5.5. The `express Router` registers a fluxion named `express_dispatcher`, line 27, to continue the execution after the fluxion `anonymous_1000`. This fluxion is in the same group `express` as the `main` fluxion, hence it has access to network sockets, to the original variable `req`, and to the original function `next`. The call to the original `next` function in the anonymous callback is replaced by a placeholder to push the stream to the fluxion `express_dispatcher`, line 24. The fluxion `express_dispatcher` receives the stream from the upstream fluxion `anonymous_1000`, merges back the modification in the variable `req` to propagate the side effects, before calling the original function `next` to continue the execution, line 30.

After the modifications detailed above, the server works as expected for the subset of functionalities we modified. The isolated fluxion correctly receives, and returns its serialized messages. The client successfully receives a gif frame containing the text.

5.4.3 Future works

We intend to implement the compilation process presented into the runtime. A just-in-time compiler would allow to identify callbacks dynamically evaluated, and to analyze the memory to identify side-effects propagations instead of relying only on the source code. Moreover, this memory analysis would

allow the closure serialization required to compile application using higher-order functions.

Chapter 6

Conclusion

Appendix A

Language popularity

A.1 PopularitY of Programming Languages (PYPL)

[1] The PYPL index uses Google trends[2] as a leading indicator of the popularity of a programming language. It search for the trend for each programming language by counting the number of searches of this language and the word "tutorial".

PYPL for May 2015

[1] http://pypl.github.io/PYPL.html
[2] https://www.google.com/trends/

Rank	Change	Language	Share	Trend
1		Java	24.1%	-0.9%
2		PHP	11.4%	-1.6%
3		Python	10.9%	+1.3%
4		C#	8.9%	-0.7%
5		C++	8.0%	-0.2%
6		C	7.6%	+0.2%
7		Javascript	7.1%	-0.6%
8		Objective-C	5.7%	-0.2%
9		Matlab	3.1%	+0.1%
10	2× ↑	R	2.8%	+0.7%
11	5× ↑	Swift	2.6%	+2.9%
12	1× ↓	Ruby	2.5%	+0.0%
13	3× ↓	Visual Basic	2.2%	-0.6%
14	1× ↓	VBA	1.5%	-0.1%
15	1× ↓	Perl	1.2%	-0.3%
16	1× ↓	lua	0.5%	-0.1%

A.2 TIOBE

[3]

The TIOBE index uses many search engines as an indicator of the current popularity of programming languages. It count the number of pages each search engine find when queried with the language name and the word "programming". This indicator indicates the number of resources available, and the discussions about a given programming language.

Javascript was the most rising language of 2014 in the TIOBE index.

TIOBE for April 2015

[3] http://www.tiobe.com/index.php/content/paperinfo/tpci/index.html

Apr 2015	Apr 2014	Change	Programming Language	Ratings	Change
1	2	↑	Java	16.041%	-1.31%
2	1	↓	C	15.745%	-1.89%
3	4	↑	C++	6.962%	+0.83%
4	3	↓	Objective-C	5.890%	-6.99%
5	5		C#	4.947%	+0.13%
6	9	↑	JavaScript	3.297%	+1.55%
7	7		PHP	3.009%	+0.24%
8	8		Python	2.690%	+0.70%
9	-	2× ↑	Visual Basic	2.199%	+2.20%

A.3 Programming Language Popularity Chart

[4]

The programming language popularity chart indicates the activity of a given language in the online communities. It uses two indicators to rank languages : the number of line changed in github of, and the number of questions tagged with a certain language.

Javascript is ranked number one in this index. The Javascript community is particularly active online, and in the open source.

indeed.com

A.4 Black Duck Knowledge

[5]

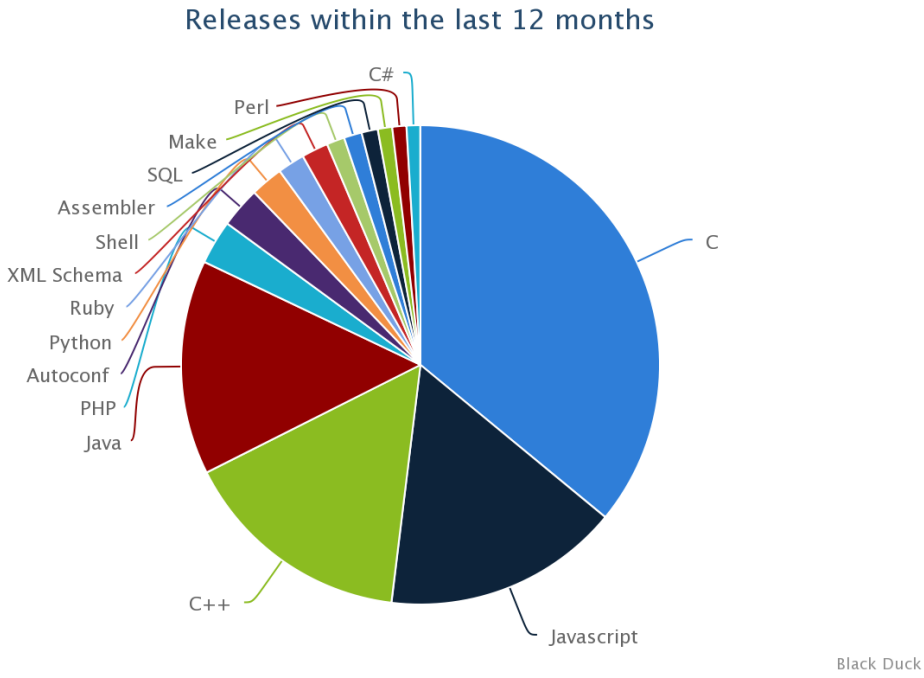
The black-duck, which analyze the usage of language on many forges, and collaborative hosts, rank Javascript number 2, after C, and with about the same usage as C++.

github.com sourceforge.net cpan.org rubyforge7.org planetsourcecode.com ddj.com

[4] http://langpop.corger.nl

[5] https://www.blackducksoftware.com/resources/data/this-years-language-use

Language	%
C	34.80
Javascript	15.45
C++	15.13
Java	14.02
PHP	2.87
Autoconf	2.65
Python	2.15
Ruby	1.77
XML Schema	1.73
Shell	1.18
Assembler	1.16
SQL	1.07
Make	0.94
Perl	0.92
C#	0.90



A.5 Github

http://githut.info/

A.6 HackerNews Poll

https://news.ycombinator.com/item?id=3746692

Language	Count
Python	3335
Ruby	1852
JavaScript	1530
C	1064
C#	907
PHP	719
Java	603
C++	587
Haskell	575
Clojure	480
CoffeeScript	381
Lisp	348
Objective C	341
Perl	341
Scala	255
Scheme	202
Other	195
Erlang	171
Lua	150
Smalltalk	130
Assembly	116
SQL	112
Actionscript	109
OCaml	88
Groovy	83
D	79
Shell	76
ColdFusion	51
Visual Basic	47
Delphi	45
Forth	41
Tcl	34
Ada	29
Pascal	28
Fortran	26
Rexx	13
Cobol	12

Bibliography

[1] D Abadi, D Carney, and U Cetintemel. "Aurora: a data stream management system". In: *Proceedings of the ...* (2003).

[2] DJ Abadi, Y Ahmad, and M Balazinska. "The Design of the Borealis Stream Processing Engine." In: *CIDR* (2005).

[3] DJ Abadi and D Carney. "Aurora: a new model and architecture for data stream management". In: *The VLDB Journal— ...* (2003).

[4] A Adya, J Howell, and M Theimer. "Cooperative Task Management Without Manual Stack Management." In: *USENIX Annual Technical Conference* (2002).

[5] T Akidau and A Balikov. "MillWheel: Fault-Tolerant Stream Processing at Internet Scale". In: *Proceedings of the VLDB Endowment 6.11* (2013).

[6] SP Amarasinghe, JAM Anderson, MS Lam, and CW Tseng. "An Overview of the SUIF Compiler for Scalable Parallel Machines." In: *PPSC* (1995).

[7] GM Amdahl. "Validity of the single processor approach to achieving large scale computing capabilities". In: *Proceedings of the April 18-20, 1967, spring joint ...* (1967).

[8] LO Andersen. "Program analysis and specialization for the C programming language". In: (1994).

[9] H Balakrishnan and M Balazinska. "Retrospective on aurora". In: *The VLDB Journal* (2004).

[10] U Banerjee. *Loop parallelization*. 2013.

[11] JR von Behren, J Condit, and EA Brewer. "Why Events Are a Bad Idea (for High-Concurrency Servers)." In: *HotOS* (2003).

[12] M Bodin and A Charguéraud. "A trusted mechanised JavaSript specification". In: *Proceedings of the 41st ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages* (2014).

[13] S Chandrasekaran and O Cooper. "TelegraphCQ: continuous dataflow processing". In: *Proceedings of the ...* (2003).

[14] J Chen, DJ DeWitt, F Tian, and Y Wang. "NiagaraCQ: A scalable continuous query system for internet databases". In: *ACM SIGMOD Record* (2000).

[15] Austin T. Clements, M. Frans Kaashoek, Nickolai Zeldovich, Robert T. Morris, and Eddie Kohler. "The scalable commutativity rule". In: *Proceedings of the Twenty-Fourth ACM Symposium on Operating Systems Principles - SOSP '13*. New York, New York, USA: ACM Press, Nov. 2013, pp. 1–17. DOI: 10.1145/2517349.2522712.

[16] Melvin E. Conway. "Design of a separable transition-diagram compiler". In: *Communications of the ACM* 6.7 (July 1963), pp. 396–408. DOI: 10.1145/366663.366704.

[17] J Dean and S Ghemawat. "MapReduce: simplified data processing on large clusters". In: *Communications of the ACM* (2008).

[18] Edsger W. Dijkstra. "Guarded commands, nondeterminacy and formal derivation of programs". In: *Communications of the ACM* 18.8 (Aug. 1975), pp. 453–457. DOI: 10.1145/360933.360975.

[19] Edsger W. Dijkstra. "Letters to the editor: go to statement considered harmful". In: *Communications of the ACM* 11.3 (Mar. 1968), pp. 147–148. DOI: 10.1145/362929.362947.

[20] Edsger W. Dijkstra. "The structure of the "THE"-multiprogramming system". In: *Communications of the ACM* 11.5 (May 1968), pp. 341–346. DOI: 10.1145/363095.363143.

[21] Uffe Engberg and Mogens Nielsen. *A Calculus of Communicating Systems with Label Passing*. en. May 1986.

[22] Raul Castro Fernandez, Matteo Migliavacca, Evangelia Kalyvianaki, and Peter Pietzuch. "Making state explicit for imperative big data processing". In: *USENIX ATC* (2014).

[23] D Flanagan. *JavaScript: the definitive guide*. 2006.

[24] P Gardner and G Smith. "JuS: Squeezing the sense out of javascript programs". In: *JSTools@ ECOOP* (2013).

[25] JJ Garrett. "Ajax: A new approach to web applications". In: (2005).

[26] SD Gribble, M Welsh, and R Von Behren. "The Ninja architecture for robust Internet-scale systems and services". In: *Computer Networks* (2001).

[27] NJ Gunther. "A New Interpretation of Amdahl's Law and Geometric Scalability". In: *arXiv preprint cs/0210017* (2002).

[28] NJ Gunther. "A simple capacity model of massively parallel transaction systems". In: *CMG-CONFERENCE-* (1993).

[29] NJ Gunther. "Understanding the MP effect: Multiprocessing in pictures". In: *In other words* (1996).

[30] JL Gustafson. "Reevaluating Amdahl's law". In: *Communications of the ACM* (1988).

[31] Per Brinch Hansen. "Distributed processes: a concurrent programming concept". In: *Communications of the ACM* 21.11 (Nov. 1978), pp. 934–941. DOI: 10.1145/359642.359651.

[32] C Hewitt. "Viewing control structures as patterns of passing messages". In: *Artificial intelligence* (1977).

[33] C Hewitt, P Bishop, and R Steiger. "A universal modular actor formalism for artificial intelligence". In: *Proceedings of the 3rd international joint conference on Artificial intelligence* (1973).

[34] C. A. R. Hoare. "Communicating sequential processes". In: *Communications of the ACM* 21.8 (Aug. 1978), pp. 666–677. DOI: 10.1145/359576.359585.

[35] C. A. R. Hoare. "Monitors: an operating system structuring concept". In: *Communications of the ACM* 17.10 (Oct. 1974), pp. 549–557. DOI: 10.1145/355620.361161.

[36] M Isard, M Budiu, Y Yu, A Birrell, and D Fetterly. "Dryad: distributed data-parallel programs from sequential building blocks". In: *ACM SIGOPS Operating ...* (2007).

[37] Gilles Kahn. "The semantics of a simple language for parallel programming". In: (1974).

[38] Gilles Kahn and David Macqueen. *Coroutines and Networks of Parallel Processes*. en. Tech. rep. 1976, p. 20.

[39] S Krishnamurthy and S Chandrasekaran. "TelegraphCQ: An architectural status report". In: *IEEE Data Eng. ...* (2003).

[40] L Lamport. "Time, clocks, and the ordering of events in a distributed system". In: *Communications of the ACM* (1978).

[41] D Logothetis, C Olston, and B Reed. "Stateful bulk processing for incremental analytics". In: *Proceedings of the 1st ...* (2010).

[42] ND Matsakis. "Parallel closures: a new twist on an old idea". In: *Proceedings of the 4th USENIX conference on Hot ...* (2012).

[43] MD McCool. "Structured parallel programming with deterministic patterns". In: *Proceedings of the 2nd USENIX conference on Hot ...* (2010).

[44] R Milner. "Processes: A mathematical model of computing agents". In: *Studies in Logic and the Foundations of Mathematics* (1975).

[45] R Milner, J Parrow, and D Walker. "A calculus of mobile processes, I". In: *Information and computation* (1992).

[46] R Milner, J Parrow, and D Walker. "A calculus of mobile processes, II". In: *Information and computation* (1992).

[47] Robin Milner. "A calculus of communicating systems". In: *LFCS Report Series* 86.7 (1986), pp. 1–171. DOI: 10.1007/3-540-15670-4_10.

[48] G Moore. "Cramming More Components Onto Integrated Circuits". In: *Electronics* 38 (1965), p. 8.

[49] JP Morrison. *Flow-Based Programming*. 1994, pp. 1–377.

[50] JF Naughton, DJ DeWitt, and D Maier. "The Niagara internet query system". In: *IEEE Data Eng. ...* (2001).

[51] R Nelson. "Including queueing effects in Amdahl's law". In: *Communications of the ACM* (1996).

[52] L Neumeyer and B Robbins. "S4: Distributed stream computing platform". In: *Data Mining Workshops ...* (2010).

[53] VS Pai, P Druschel, and W Zwaenepoel. "Flash: An efficient and portable Web server." In: *USENIX Annual Technical Conference* (1999).

[54] DL Parnas. "On the criteria to be used in decomposing systems into modules". In: *Communications of the ACM* (1972).

[55] Z Qian, Y He, C Su, Z Wu, and H Zhu. “Timestream: Reliable stream computation in the cloud”. In: *Proceedings of the 8th ACM European Conference on Computer Systems (EuroSys ’13)* (2013).

[56] C Radoi, SJ Fink, R Rabbah, and M Sridharan. “Translating imperative code to MapReduce”. In: *Proceedings of the 2014 ...* (2014).

[57] DP Reed. “" Simultaneous" Considered Harmful: Modular Parallelism.” In: *HotPar* (2012).

[58] MC Rinard and PC Diniz. “Commutativity analysis: A new analysis framework for parallelizing compilers”. In: *ACM SIGPLAN Notices* (1996).

[59] W. P. Stevens, G. J. Myers, and L. L. Constantine. “Structured design”. English. In: *IBM Systems Journal* 13.2 (1974), pp. 115–139. DOI: 10.1147/sj.132.0115.

[60] GJ Sussman and GL Steele Jr. “Scheme: A interpreter for extended lambda calculus”. In: *Higher-Order and Symbolic Computation* (1998).

[61] W Thies, M Karczmarek, and S Amarasinghe. “StreamIt: A language for streaming applications”. In: *Compiler Construction* (2002).

[62] A Toshniwal and S Taneja. “Storm@ twitter”. In: *Proceedings of the 2014 ACM SIGMOD international conference on Management of data - SIGMOD ’14* (2014).

[63] S Wei and BG Ryder. “State-sensitive points-to analysis for the dynamic behavior of JavaScript objects”. In: *ECOOP 2014–Object-Oriented Programming* (2014).

[64] M Welsh, D Culler, and E Brewer. “SEDA: an architecture for well-conditioned, scalable internet services”. In: *ACM SIGOPS Operating Systems Review* (2001).

[65] Sunny Wong, Yuanfang Cai, Giuseppe Valetto, Georgi Simeonov, and Kanwarpreet Sethi. “Design Rule Hierarchies and Parallelism in Software Development Tasks”. In: *2009 IEEE/ACM International Conference on Automated Software Engineering*. IEEE, Nov. 2009, pp. 197–208. DOI: 10.1109/ASE.2009.53.

[66] Yuan Yu, Michael Isard, Dennis Fetterly, Mihai Budiu, Ulfar Erlingsson, Pradeep Kumar Gunda, Jon Currey, Frank McSherry, Kannan Achan, and Christophe Poulain. “Some sample programs written in DryadLINQ”. In: *Microsoft Research* (2009).