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.

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Chapter 1

Software Design, State Of The Art

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"A designer is responsible for producing the greatest benefit for any given investment of time, talent, money, and other resources."

— K. Sullivan, W. Griswold, Y. Cai, B. Hallen [130]

With the growth of Software as a Service (SaaS) on the web, the same company carries both development and exploitation of an application at scale of unprecedented size. It revealed the importance of previously unknown economic constraints. To assure the continuous growth and sustainability of an application, it needs to address two contradictory goals : development productivity and performance efficiency. These goals needs to be enforced by the platform supporting the application to build good development habits for the developers. A platform designates any solution that allows to build an application on top of it, including programming languages, compilers, interpreters, frameworks, runtime libraries and so on.

75% of your budget is dedicated to software maintenance.[1] The productivity of a platform is the degree to which developers can quickly produce new and modify existing software. It impacts the maintainability of the applications and relies on the modularity enforced by its platform. Especially, higher order programming is crucial to build and compose modules productively. It relies either on mutable states, or immutable states, but hardly on a combination of both.

However, neither mutable nor immutable states allows performance efficiency. Mutable states leads to synchronization overhead at a coarser-grain level, while immutable states leads to communication overhead at a finer-grain level. Efficiency relies on a combination of synchronization at a fine-grain level, and immutable message passing at a coarse-grain level. This combination breaks the modularity, hence the productivity of an application. A company has no choice but to commit huge development efforts to get efficient performances.

illustration: virtuous circle between community and industry

Moreover, a balance between productivity and efficiency is required for a platform to enter a virtuous circle of adoption. The productivity is required to be appealing to gather a community to support the ecosystem around the platform. This community is appealing for the industry as a hiring pool. Additionally, the efficiency is required to be adopted by the industry to be economically viable. And the industrial relevance provides the reason for this ecosystem to exist and the community to gather.

This chapter presents a broad view of the state of the art in the compromises between productivity and efficiency. It defines software productivity, efficiency, and adoption in section 1.1 and all the underlying concepts, such as higher order programming and state mutability. It then analyzes different platforms according to their focus. platforms focusing on productivity are addressed in section **??**, those

[1] `http://www.castsoftware.com/glossary/software-maintainability`

focusing on efficiency in section **??** and those focusing on a compromise between the two in section 1.4.

1.1 Definitions

The continuous growth and sustainability of a platform relies on three criteria. This section defines these tree criteria, as well as all the underlying concepts.

- Productivity
- Efficiency
- Adoption

1.1.1 Productivity

The productivity of a platform is the degree to which developers can quickly produce new and modify existing software. For a platform to be productive, it needs to enforce modularity directly in the design of applications. Productivity later leads to maintainability.

1.1.1.1 Modularity

Modularity is about encapsulating subproblems and composing them to allow greater design to emerge. It allows to limit the understanding required to contribute to a module [127], which helps developers to repair and enhance the application. Additionally, it reduces development time by allowing several developers to simultaneously implement different modules [147, 20].

The criteria to define modules to improve productivity are high cohesion and low coupling [127]. Cohesion defines how strongly the features inside a module are related. Coupling defines the strength of the interdependences between modules. The encapsulation of modules helps increase their cohesion, and their composition helps decrease coupling. Encapsulation and composition improve productivity.

- Encapsulation $\rightarrow$ High Cohesion
- Composition $\rightarrow$ Low Coupling

1.1.1.2 Encapsulation

illustration: spaghetti programming

Boundary Definition Modular Programming stands upon Structured Programming [39]. It draws clear interfaces around a piece of implementation so that the execution remains enclosed inside. At a fine level, it helps avoid spaghetti code [42], and at a coarser level, it structures the implementation [43] into modules, or layers.

illustration: lasagna programming

Data Protection Modular programming encapsulates a specific design choice in each module, so that it is responsible for one and only one concern. It isolates its evolution from impacting the rest of the implementation [115, 134, 84]. Examples of such separation of concerns are the separation of the form and the content in HTML / CSS, or the OSI model for the network stack.

1.1.1.3 Composition

Higher-Order Programming Higher-order programming introduces lambda expressions, functions manipulable like any other primary value. They can be stored in variables, or be passed as arguments. It replaces the need for most modern object oriented programming design patterns [2] with Inversion of Control [88], the Hollywood Principle [133], and Monads [143]. Higher-order programming help loosen coupling, thus improve productivity [70].

Closures In languages allowing mutable state, lambda expressions are implemented as closure, to preserve the lexical scope [132]. A closure is the association of a function and a reference to 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.

Lazy Evaluation Lazy evaluation allows to defer the execution of an expression when its result is needed. The lazy evaluation of a list is equivalent to a stream with a null-sized buffer [141]. It is a powerful tool for structuring modular programs, as the execution is organized as a concurrent pipeline [1]. The stages process independently each element of the stream. But this concurrency requires the isolation of side-effects to avoid conflicts between stages executions.

The criteria to analyze the productivity of platforms are the following.

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

- Encapsulation → High Cohesion

  Boundary definition

  Data protection

- Composition → Low Coupling

  Higher-order programming, Lambda Expressions

  Lazy evaluation, Stream composition

1.1.2 Efficiency

The efficiency of a software project is the relation between the usage made of available resources and the delivered performance. For an application to perform efficiently, the platform based on needs to enforce scalability directly in its design.

Scalability relies on the parallelism allowed by the commutativity of operations execution [30]. An operation is a sequence of statements. Operations are commutative if the order of their executions is irrelevant for the correctness of their results. Commutativity assures the independence of operations.

1.1.2.1 Independence

illustration: Synchronization vs Message-passing

The independence, and commutativity of an operations depends on its accesses to shared state. If the operations doesn't rely on any shared state, it is independent. The independence of operations allows to execute them in parallel, hence to increase performance proportionally to occupied resources [7, 63]. But if they rely on shared state, they need to coordinate the causal scheduling and atomicity of their executions to avoid conflicting accesses. This scheduling between the operations can be defined in two ways.

Synchronization Operations are scheduled sequentially to have the exclusivity on a shared state, or

Message-passing Operations communicate their local modifications of the state to other operations, in a decentralized fashion.

1.1.2.2 Atomicity

An operation is atomic if it happens in a single bulk. The beginning and end are indistinguishable for an external observer. It assures the developer of the invariance of the memory during the operation. It relies either on the causal scheduling of

operations – synchronization – or exclusivity of their memory accesses – message-passing.

1.1.2.3 Granularity

If the operations access the state too frequently, the communication overhead of message passing exceeds the performance gains of parallelism. And if operations access the state too rarely, the synchronization required for sharing state limits the possible parallelism. These two extremes are inefficient. Operations tend to share state closely at a fine-grain level and less at a coarser-grain level. Therefore, efficiency requires the combination of fine-level state sharing to avoid communication overhead, and coarse-level independence to allow parallelization [65, 64, 109, 62]. The threshold determining frequent or rare access to the state determines the granularity level between synchronization and parallelization of tasks.

The criteria to analyze the performance of platforms are the following.

- Fine-level state sharing

  State mutability → Synchronization

- Coarse-level independence

  State immutability → Message-passing

1.1.3 Adoption

An application is sustainable only if the platform used to build it generates reinforcing interactions between a community of passionate and the industry. A platform needs to present a balance between productivity and efficiency to be adopted by both the community and the industry. The productivity is required for a platform to be appealing to gather a community to support the ecosystem around it. And the efficiency is required to be economically viable and needed by the industry, and to provide the reason for this ecosystem to exist. Additionally, the web acts as a tremendous catalyst fueling these interactions.

The criteria to analyze the adoption of platforms are the following.

- Community Support
- Industrial Need

Adoption requires a balance between efficiency and productivity. This incentive to balance between productivity and efficiency is illustrated in figure 1.1. This figure is used throughout this chapter to graphically represent all the platforms analyzed.

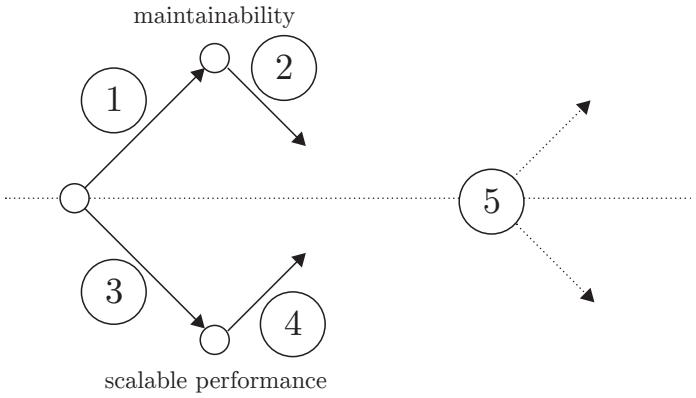


Figure 1.1 – Balance between Efficiency and Productivity

1.2 Productivity Focused Platforms

"It is becoming increasingly important to the data-processing industry to be able to produce [programming systems] at a faster rate, and in a way that modifications can be accomplished easily and quickly."
— W. Stevens, G. Myers, L. Constantine [127].

In order to improve and maintain a software system, it is important to holds in mind a mental representation of its implementation. As the system grows in size, the mental representation becomes more and more difficult to grasp. Therefore, it is crucial to decompose the system into smaller subsystem easier to grasp individually.

"Measuring programming progress by lines of code is like measuring aircraft building progress by weight."
— Bill Gates

Section 1.2.1 presents the modular programming paradigms, and their programming models, oriented toward productivity. Section 1.2.2 presents the adoption of the implementations of modular programming languages. Section 1.2.3 presents the consequences of the modularity on performance. Finally, section 1.2.4 summarizes the three previous sections in a table.

1.2.1 Modular Programming

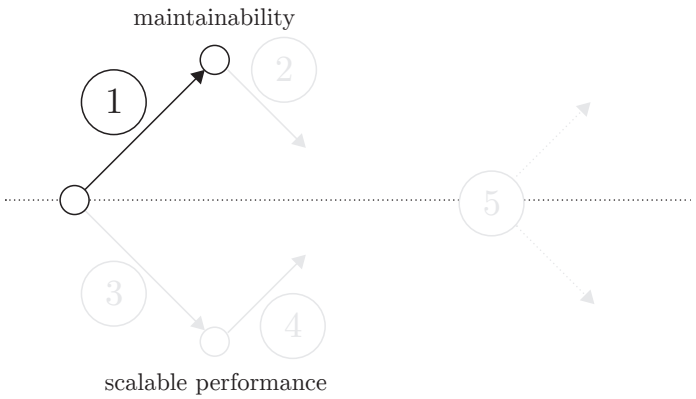


Figure 1.2 – Focus on Maintainability

The next paragraphs presents the different programming model regarding their support to modular programming and productivity.

1.2.1.1 Imperative Programming

Imperative programming is the very first programming paradigm, as it evolves directly from the hardware architectures. It allows to express the suite of operation to carry sequentially on the computing processor. Most imperative languages provide encapsulation with modules but not higher-order programming, nor lazy evaluation. The implementations of Imperative Programming

1.2.1.2 Object Oriented Programming

illustration: multiple cells communicating

The very first Object-Oriented Programming (OOP) language was Smalltalk [56]. It defined the core concepts as message passing and encapsulation [3]. Nowadays, the emblematic figures in the software industry are C++ C++ [129] and Java [58]. They provide encapsulation with Classes, and allows passing mutable structures for performance reasons. They recently introduced higher-order programming with lambda expressions.

[3] http://userpage.fu-berlin.de/~ram/pub/pub_jf47ht81Ht/doc_kay_oop_en

1.2.1.3 Functional Programming

The definition of pure Functional Programming resides in manipulating only expressions and forbidding state mutability, replaced by message passing. The absence of state mutability makes a function side-effect free, hence their execution can be scheduled in parallel. But it implies heavy message passing, which negatively impact performances. The most important pure Functional Programming languages are Scheme [121], Miranda [138], Haskell [82] and Standard ML [106]. They provide encapsulation, higher-order programming and lazy evaluation.

1.2.1.4 Multi-Paradigm

The functional programming concepts are also implemented in other languages along with mutable states and object-oriented concepts. Major recent programming languages, including Java 8 and C++ 11, now commonly present **higher-order functions** and **lazy evaluation**. *In fine*, it helps developers to write applications that are more maintainable, and favorable to evolution [83, 139]. These recent multi-paradigms languages such as Javacript, Python and Ruby combine the different paradigms to help developer building applications faster.

Table 1.1 presents a summary of the analysis of the programming models presented in the previous paragraphs.

Model	Composition	Encapsulation	→	Maintainability
Imperative Programming	3	4		3
Object-Oriented Programming	5	5		5
Functional Programming	5	5		5
Multi Paradigm	5	5		5

Table 1.1 – Maintainability of Modular Programming Platforms

1.2.2 Adoption

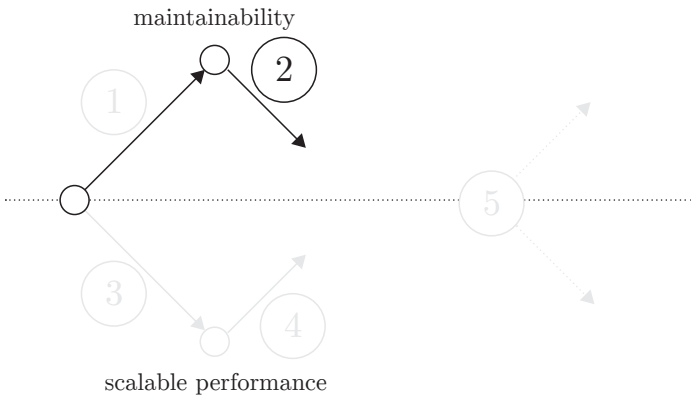


Figure 1.3 – Steering back toward Performence Efficiency

The next paragraphs presents the adoption of Javascript, and the other implementations of the presented programming model.

1.2.2.1 Community

Available Resources As of December 2015, Javascript ranks 8th according to the TIOBE Programming Community index, and 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. And it ranks 7th on the PYPL. The PYPL index is based on Google trends to measure the number of requests on a programming language.

From these indexes, the major programming languages are Java, C++, C, C# and Python. These languages are still widely used by their communities and in the industry.

*

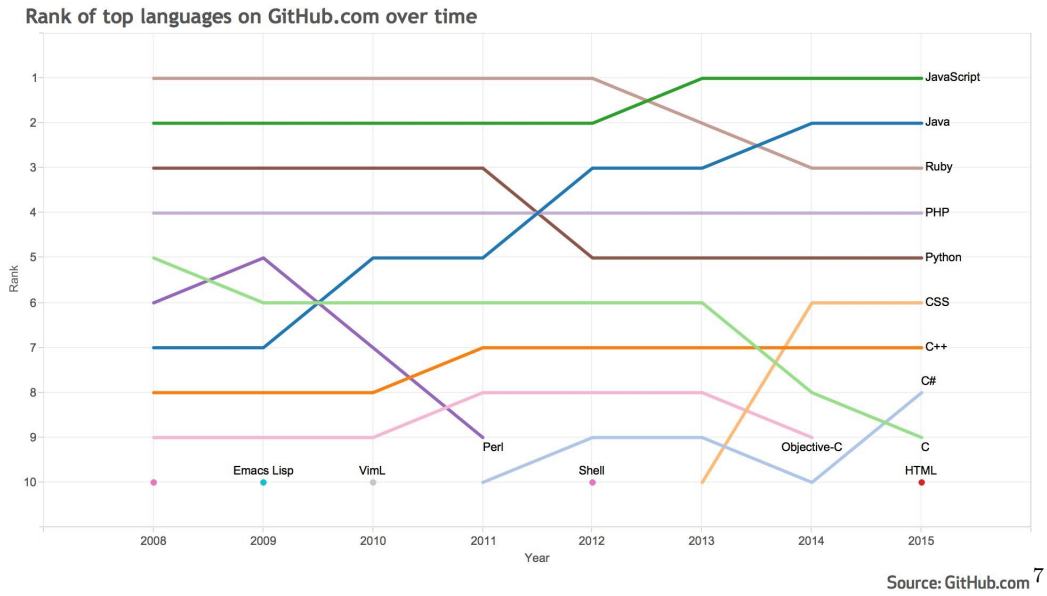
⚠ TODO graphical ranking of TIOBE and PYPL

Developers Collaboration Platforms Online collaboration tools give an indicator of the number of developers and projects using certain languages. Javascript is the most used language on *Github*[4] and the most cited language on *StackOver-*

[4] themostimportantcollaborativedevelopmentplatformgatheringabout9millionsusers.

flow[5]. It represents more than 320,000 repositories on *Github*. The second language is Java with more than 220,000 repositories. It is cited in more than 960,000 questions on *StackOverflow* while the second is Java with around 940,000 questions. And according to a survey by *StackOverflow*, it is currently the language the most popular[6]. Moreover, the Javascript package manager, *npm*, has the most important and impressive package repository growth.

*



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[5] themostimportantQ&Aplatformfordevelopers.

[6] http://stackoverflow.com/research/developer-survey-2015

[7] https://github.com/blog/2047-language-trends-on-github

TODO include so survey graph

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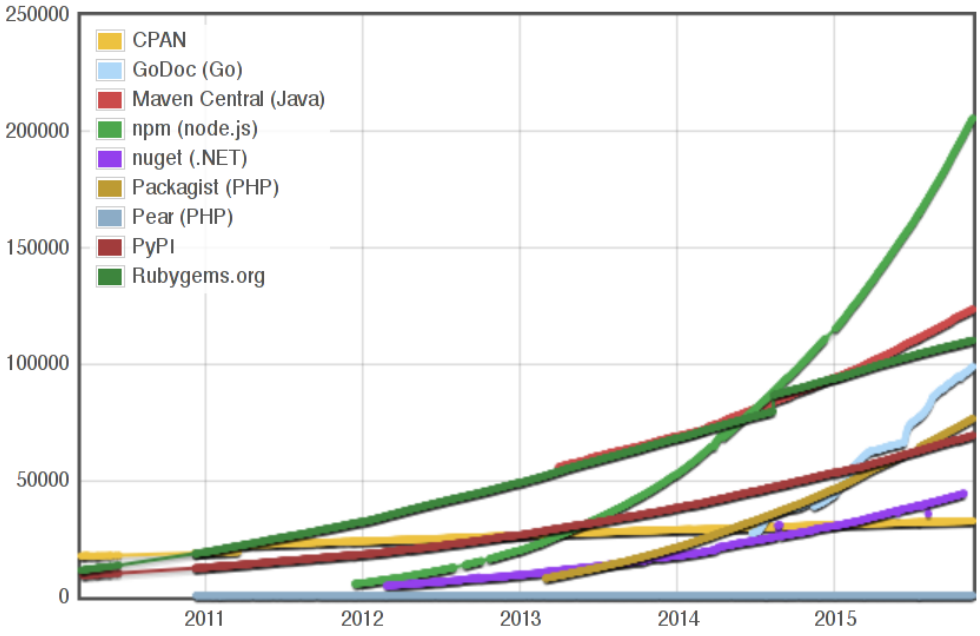
TODO graphical ranking of the tags in StackOverflow



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⚠ TODO redo this graph, it is ugly.

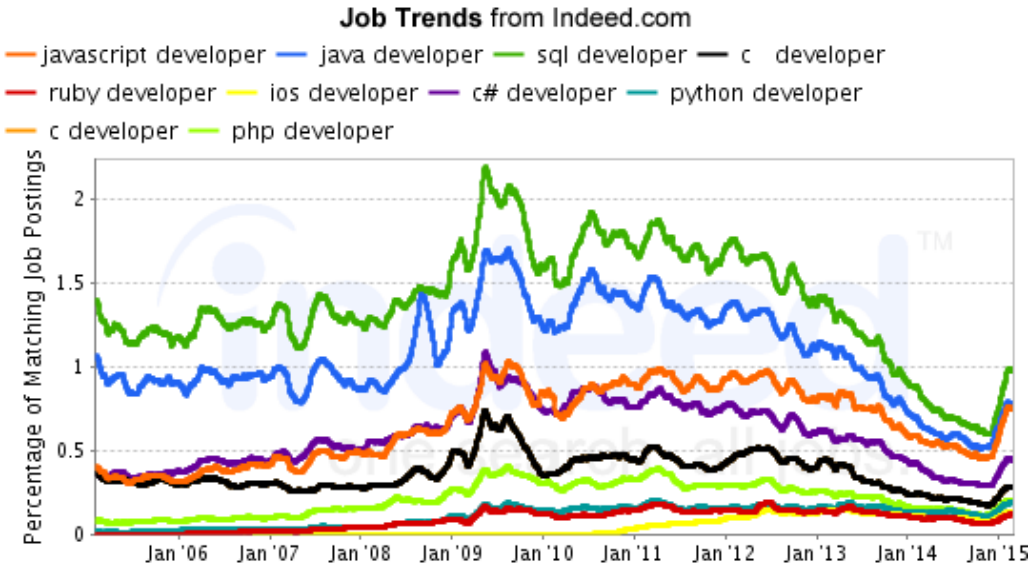
1.2.2.2 Industry

The actors of the software industry tends to hide their activities trying to keep an edge on the competition. The previous metrics represent the visible activity but are barely representative of the software industry. The trends on job opportunities give some additional hints on the situation. Javascript is the third most wanted skill, according to *Indeed*[8], right after SQL and Java.[9] Moreover, according to *breaz.io*[10], Javascript developers get more opportunities than any other developers. Javascript is increasingly adopted in the software industry.

[8] `http://www.indeed.com`

[9] `http://www.indeed.com/jobtrends?q=Javascript%2C+SQL%2C+Java%2C+C%2B%2B%2C+C%2FC%2B%2B%2C+C%23%2C+Python%2C+PHP%2C+Ruby&l=`

[10] `https://breaz.io/`



TODO redo this graph, it is ugly.

Table 1.2 presents a summary of the analysis of the programming models presented in the previous paragraphs.

Model	Community support	Industrial need	→	Adoption
Imperative Programming	3	4		3
Object-Oriented Programming	4	4		4
Functional Programming	0	0		0
Multi Paradigm	5	4		4

Table 1.2 – Adoption of Modular Programming Platforms

1.2.3 Efficiency Limitations

Eventually, the presented languages are hitting a wall on their way to performance.

All the languages presented previously provide either mutable state or immutable state on which to rely to assure encapsulation and composition. Functional programming relies on immutable message-passing. It might impacts performance at a fine-grain level because of heavy memory usage. On the other hand, the synchronization required by mutable state is often hard to develop with [3], or avoid parallelism [114, 94].

The only solution to provide performance efficiency is to combine mutable state at a fine-grain level, with synchronization, and immutable state at a coarse-grain level, with message-passing.

The table 1.3 presents the performance limitations of the languages presented in this section. The platforms extending these languages with concurrent or parallel features to provide performances are addressed in the next section.

Model	Fine-grain level synchronization	Coarse-grain level message passing	→	Performance Efficiency
Imperative Programming	0	0		0
Object-Oriented Programming	0	0		0
Functional Programming	0	0		0
Multi Paradigm	0	0		0

Table 1.3 – Performance Efficiency of Modular Programming Platforms

1.2.4 Summary

Table 1.4 summarizes the characteristics of the solutions presented in this section.

Model	Maintainability	Adoption	Performance Efficiency
Imperative Programming	3	3	0
Object-Oriented Programming	5	4	0
Functional Programming	5	0	0
Multi Paradigm	5	4	0

Table 1.4 – Summary of Modular Programming Platforms

1.3 Efficiency Focused Platforms

Both the academia and the industry proposed solutions with efficiency in mind to cope with the limitations the previous section concludes on. Section 1.3.1 presents the concurrent and parallel programming paradigms, and their programming models. Section 1.3.2 presents the adoption steered by the efficiency of parallel programming. Section 1.3.3 presents the consequences of parallelism on productivity. Finally, section 1.3.4 summarizes the three previous sections in a table.

1.3.1 Concurrency

Web servers need to be able to process huge amount of concurrent operations in a scalable fashion. Concurrency is the ability to make progress on several operations roughly simultaneously. It implies to draw memory boundaries to define independent regions, or to define causality in the execution of tasks. When both boundaries and causality are clearly defined, the tasks are independent and can be scheduled in parallel to make progress strictly simultaneously.

The definition of independent tasks allows the fine level synchronization within a task, and coarse level message passing between the tasks required for performance efficiency. The synchronization of execution at a fine level assures the invariance

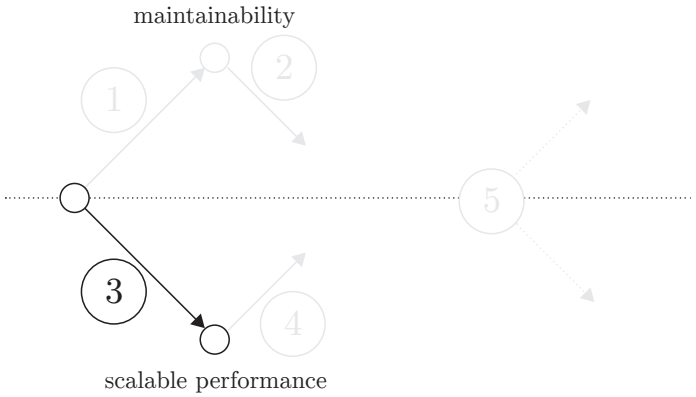


Figure 1.4 – Focus on Performance Efficiency

on the shared state, and avoid communication overhead. The message-passing at a coarser level assures the parallelism. The two are indispensable for efficiency.

1.3.1.1 Concurrent Programming

illustration: feu rouge et rond point

Concurrent programming provides the mechanisms to assure atomicity of concurrent operations. They define the causal scheduling of execution and assure the invariance of the global memory. There are two scheduling strategies to execute concurrent tasks on a single processing unit, cooperative scheduling and preemptive scheduling.

Cooperative Scheduling allows a concurrent execution to run until it yields back to the scheduler. Each concurrent execution has an atomic, exclusive access on the memory.

Preemptive Scheduling allows a limited time of execution for each concurrent execution, before preempting it. It assures fairness between the tasks, such as in a multi-tasking operating system. But the unexpected preemption breaks atomicity, the developer needs to lock the shared state to assure atomicity and exclusivity.

The next paragraphs presents the programming model for these scheduling strategy, the event-driven programing model based on cooperative scheduling, and the multi-threading programming model based on preemptive scheduling. Additionally,

they present two alternatives to these two main programming models, lock-free data-structures and Fibers.

Event-Driven Programming Event-driven execution model queues concurrent tasks needing access to shared resources. The tasks are explicitely defined by the developer. The concurrent tasks are schedule sequentially to assure exclusivity, and cooperatively to assure atomicity. It is very efficient for highly concurrent applications, as it avoids contention due to waiting for shared resources like disks, or network. Several execution model rely on this execution model, like TAME [94], Node.js[11] and Vert.X[12]. As well as some web servers like Flash [114], Ninja [59] thttpd[13] and Nginx[14].

But the event-driven model is limited in performance. The concurrent tasks share the same memory, and cannot be scheduled in parallel. The next paragraph presents work intending to improve performance by reducing the atomic portions of operations to a minimum.

Lock-Free Data-Structures The wait-free and lock-free data-structures use atomic operations small enough so that locking is unnecessary [96, 74, 72, 73, 9]. They are based on instructions provided by transactional memories [68] that combine read and write instructions, They provide concurrent implementations of basic data-structures such as linked list [140, 136], queue [131, 146], tree [118] and stack [71].

However these atomic operations are scheduled sequentially, which limits parallelism. The next paragraphs present multi-threading, which, contrary to the event-driven model, requires the developer to explicitly define atomicity.

Multi-Threading Programming Threads are the small execution containers sharing the same memory execution context within an isolated tasks [43], and scheduled in parallel with fork/join instructions [119, 52, 98]. They execute statements sequentially waiting for completion, and are scheduled preemptively to avoid blocking the global progression. The preemption breaks the atomicity of the execution, and the parallel execution breaks the exclusivity of memory accesses. To restore atomicity and exclusivity, hence assure the invariance, multi-threading programming models provide synchronization mechanisms, such as semaphores [40], guarded commands [41], guarded region [67] and monitors [79].

[11] `https://nodejs.org/en/`
[12] `http://vertx.io/`
[13] `http://acme.com/software/thttpd/`
[14] `https://www.nginx.com/`

Developers tend to use the global memory extensively, and threads require to protect each and every shared memory cell. This heavy need for synchronization leads to bad performances, and is difficult to develop with [3].

Cooperative Threads Cooperative threads, or fibers join the advantage of sequential waiting, with the advantage of cooperative scheduling [3, 16]. It avoids splitting the execution into atomic tasks nor use synchronization mechanisms to assure exclusivity. A fiber yields the execution to another fiber to avoid blocking the execution during a long-waiting operation, and recovers it at the same point when the operation finishes. However, developers need to be aware of these yielding operation to preserve the atomicity[15].

Limitation of Concurrent Programming Concurrent programming provides the synchronization required to assure sequentiality of execution within a task and the causal ordering between tasks. However, multi-threading imposes sequentiality between tasks as well. This global sequentiality is excessive ; it impacts performance, and is difficult to manage efficiently.

The causal ordering between tasks proposed by the event-driven execution model is sufficient to assure correctness of execution [95, 120]. But because of the lack of memory isolation, the concurrent tasks are not scheduled in parallel.

Parallel programming is the only solution for efficiency, at the expense of development efforts to explicitely define the memory isolation of concurrent tasks and their communications by message pasing.

The table 1.5 presents a summary of the analysis of performance of the platforms presented in this section.

[15] `https://glyph.twistedmatrix.com/2014/02/unyielding.html`

Model	Fine-grain level synchronization	Coarse-grain level message passing	→	Performance Efficiency
Event-driven programming	5	0		2
Lock-free Data-Structures	5	0		2
Multi-threading programming	4	0		1
Cooperative Threads	4	0		1

Table 1.5 – Performance Efficiency of Concurrent Programming Platforms

1.3.1.2 Parallel Programming

Concurrent programming allows to define the tasks scheduling causally. Concurrent tasks can be scheduled in parallel only if their memory are isolated.

The Flynn's taxonomy [48] categorizes parallel executions in function of the multiplicity of their flow of instruction and data. Parallel programming models belong to the category Multiple Instruction Multiple Data (MIMD), which is further divided into Single Program Multiple Data (SPMD) [11, 36, 37] and Multiple Program Multiple Data (MPMD) [25, 23]. SPMD defines a single program replicated on many processing units [34, 87, 24] – it is derived from the multi-threading programming model presented in section **??**. While MPMD defines multiple parallel tasks in the implementation [60, 50, 49].

*

⚠ schema of SPMD and MPMD

This section presents MPMD platforms allowing to define isolated tasks. It presents theoretical and programming models on asynchronous communication and isolated execution for parallel programming. It then presents stream processing programming models. And finally, it concludes on the limitations of parallel programming regarding productivity.

Theoretical Models The event-driven programming model used to cope with asynchronous communications allows the causal scheduling of concurrent tasks. This

causal scheduling is sufficient to assure correctness in a distributed system [95, 120]. The Actor model allows to express the causal ordering of computation as a set of parallel actors communicating by asynchronous messages [75, 76, 31]. In reaction to a received message, an actor can create other actors, send messages, and choose how to respond to the next message. Additionally, the communication in reality are too slow compared to execution to be synchronous, and are subject to various faults and attacks [97]. The Actor model takes these physical limitations in account [77].

Similarly, coroutines are autonomous programs which communicate with adjacent modules as if they were input and output subroutines [33]. It defines a pipeline to implement multi-pass algorithms. Similar works include the Communicating Sequential Processes (CSP) [78, 18], and the Kahn Networks [91, 92].

1.3.1.3 Summary of Concurrent and Parallel Programming Models

Table 1.6 presents a summary of the analysis of the paradigm presented in the previous paragraphs.

Model	Fine-grain level synchronization	Coarse-grain level message passing	→	Performance Efficiency
Event-driven programming	5	0		2
Lock-free Data-Structures	5	0		2
Multi-threading programming	4	0		1
Cooperative Threads	4	0		1
Actor Model	5	5		5
Communicating Sequential Processes	5	5		5
Skeleton	4	4		4
Service Oriented Architecture	4	4		4
Microservices	4	4		4

Table 1.6 – Performance Efficiency of Concurrent and Parallel Programming Platforms

1.3.2 Adoption

illustration: mars rover

When the need for efficiency is higher than the need for productivity, the adoption is steered by the industry more than the community. If the industry really needs a platform, it will commit the required development effort despite a low productivity. The platforms for the Mars Rover or the banking systems are 30 years old, yet the industry continues to maintain them. The platform presented in this section emerged from the academia and the industry but are often barely known by the larger community of developers. The more the platform abandons productivity, the less it will be supported by the community.

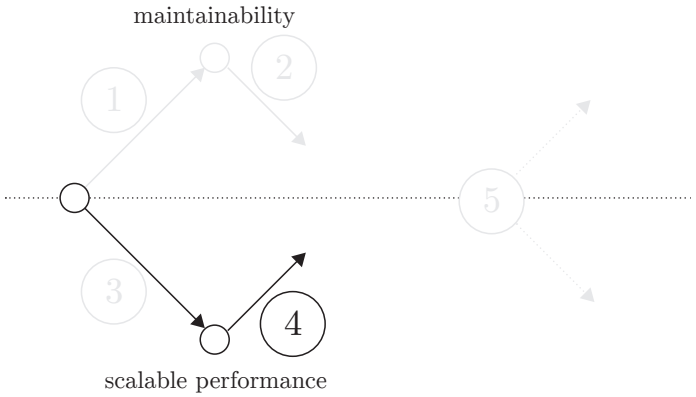


Figure 1.5 – Steering back toward Maintainability

1.3.2.1 Concurrent Programming

Most programming languages implementation supports concurrent programming somehow. Either with multi-threading or event-driven programming. These two are highly adopted by both the industry and the community, as presented in section 1.2.2.

On the other hand, lock-free data structures and cooperative threads comes from the academia, similarly to functionnal programming, and did not encounter significant adoption from the community.

Table 1.7 presents a summary of the adoption of concurrent programming models.

Model	Community support	Industrial need	→	Adoption
Event-driven programming	5	5		5
Lock-free Data-Structures	0	0		0
Multi-threading programming	0	0		0
Cooperative Threads	0	0		0

Table 1.7 – Adoption of Concurrent Programming Platforms

1.3.2.2 Parallel Programming

There exists several platforms directly inspired by the actors model, like Erlang [**JoeArmstrong**], Scala [113], Akka[16] and Play[17]. Scala is a programming language unifying the object model and functional programming. Akka is a framework based on Scala, following the actor model to build highly scalable and resilient applications. Play is a web framework based on top of Akka. And Erlang is a functional language designed by Ericsson to operate networks of telecommunication devices [**Armstrong2014**, 10, 108]

There are as well other platforms inspired by other theoretical model, like , inspired by Coroutines and CSP. Go is an open source language initiated by Google to build highly concurrent services.

These examples of implementation are largely used in the industry, but are almost unknown outside of it. They are backed by strong, but small passionated communities.

However, the organization in independent tasks is hardly compatible with the modular organization presented in the previous section. It is difficult for developers to manage the superposition of these two organizations, tasks and modules. This superposition makes these platforms accessible only to an elite in the industry sup-

[16] `http://akka.io/`
[17] `https://www.playframework.com/`

porting it. The next paragraphs present platforms mitigating the difficulty stemming from the duality between execution decomposition and modularity.

Tasks Organization and Communications To reduce the difficulties of the superposition of tasks and modules, algorithmic skeletons propose predefined patterns of organization to fit certain types of problems [32, 38, 105, 57]. Developers specialize a skeleton and focus on their problem independently of the required communication. These solutions are hardly used by the community, but are crucial in some industrial contexts. A famous example is the map/reduce pattern introduced by Google [38].

Tasks Granularity The Service Oriented Architectures (SOA) allows developers to express an application as an assembly of services connected to each others. Some examples of SOA platforms are OSGi[18], EJB[19] and Spring[20]. It allows to adjust the granularity of tasks to help developers to better fit the tasks organization with the modular organization [2].

More recently, Microservices are tackling the same challenge on the web [47, 51, 107]. Some examples of Microservices are Seneca[21]. They are very recent, and it is difficult to asses their usage in the community nor the industry. But they seems to be increasingly adopted, both in the industry and in the community.

The parallel programming platforms previously presented allow to build generic distributed systems. In the context of the web, a real-time application must process high volumes streams of requests within a certain time. The next paragraphs present platforms focusing on this challenge.

1.3.2.3 Stream Processing Systems

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. Because of this evolution, they are in rupture with MPMD platforms presented until now. They borrows the syntax from SQL to run requests in parallel on continuous data streams. The computation of these requests spread over a distributed architecture.

[18] `https://www.osgi.org/developer/specifications/`
[19] `http://www.oracle.com/technetwork/java/javaee/ejb/index.html`
[20] `http://projects.spring.io/spring-framework/`
[21] `http://senecajs.org/`

Some recent examples are DryadLINQ [85, 150], Apache Hive [135], Timestream [116], Shark [148].

Pipeline Architecture The pipeline architecture introduced by SEDA [145] organizes an application as a network of event-driven stages connected by explicit queues, the output of one feeding the input of the next. The event-driven paradigm of a stage is similar to work like Ninja [59] and Flash [114] previously presented. But the independence of stages allow to spread the execution on a parallel architecture. The academic works and industrial implementations of pipeline architecture are .

Parallel programming is barely supported by the community, but emerges mainly from industrial needs and academic research. The implementations improve efficiency, but prevent their adoption by the community due to a weak productivity. Despite the performance limitation, the event-driven programming model is the best candidate for a concurrent programming model supported by the community, and with concrete needs in the industry. Table 1.8 summarize the adoption of the platform oriented toward performance presented in this section.

Model	Community support	Industrial need	→	Adoption
Event-driven programming	5	5		5
Lock-free Data-Structures	0	0		0
Multi-threading programming	0	0		0
Cooperative Threads	0	0		0
Actor Model	1	5		1
Communicating Sequential Processes	1	5		1
Skeleton	2	5		2
Service Oriented Architecture	3	4		3
Microservices	3	3		3

Table 1.8 – Adoption of Concurrent and Parallel Programming Platforms

1.3.3 Productivity Limitations

Parallel programming requires the organization of execution and memory into independent tasks. It allows the different granularity of state accessibility required for efficiency. At a fine level, the state is shared, while at a coarser level, it is isolated. This difference in state access impacts higher-order programming. It limits the composition of modules, hence impacts productivity.

Without good composition between modules, parallel programming forces to develop two mental representations – one for the module organization and one for the tasks organization – or to abandon the module organization and productivity altogether. It makes parallel programming productive only to an elite of developers that are able to keep the two mental representations.

This thesis focus on platforms allowing developers to be productive, and to pro-

duce efficient web applications to stimulate the economy. To fit the economical context of this thesis, a solution must provide efficiency while avoiding the developers to keep a double mental representation of the implementation. It comes with an abstraction for the tasks and memory organization, for the developer to focus only on the module organization providing productivity. The next section presents some works that provides such an abstraction.

Model	Composition	Encapsulation	→	Maintainability
Event-driven programming	3	3		3
Lock-free Data-Structures	1	1		1
Multi-threading programming	2	2		2
Cooperative Threads	2	2		2
Actor Model	1	1		1
Communicating Sequential Processes	1	1		1
Skeleton	2	2		2
Service Oriented Architecture	3	3		3
Microservices	3	3		3
Data Stream System Management	2	2		2
Pipeline Stream Processing	4	4		4

Table 1.9 – Maintainability of Concurrent, Parallel and Stream Programming Platforms

1.3.4 Summary

Table 1.10 summarizes the characteristics of the platforms presented in this section.

Model	Maintainability	Adoption	Performance Efficiency
Event-driven programming	3	5	2
Lock-free Data-Structures	1	0	2
Multi-threading programming	2	0	1
Cooperative Threads	2	0	1
Actor Model	1	1	5
Communicating Sequential Processes	1	1	5
Skeleton	2	2	4
Service Oriented Architecture	3	3	4
Microservices	3	3	4
Data Stream System Management	2	4	3
Pipeline Stream Processing	4	2	5

Table 1.10 – Summary of Concurrent and Parallel Programming Platforms

1.4 Adoption Focused Platforms

Section 1.2 and section 1.3 present the platforms focusing respectively on productivity and efficiency, and conclude that favoring on one negatively impacts the other.

Moreover, a balance between productivity and efficiency is required to be both supported by the community and needed by the industry, hence trigger a virtuous circle of adoption. This section presents platforms featuring an abstraction of the tasks organization to allow developers to focus on the modular organization to keep both productivity and efficiency. Section **??** presents Compilers, and section **??** presents Runtimes.

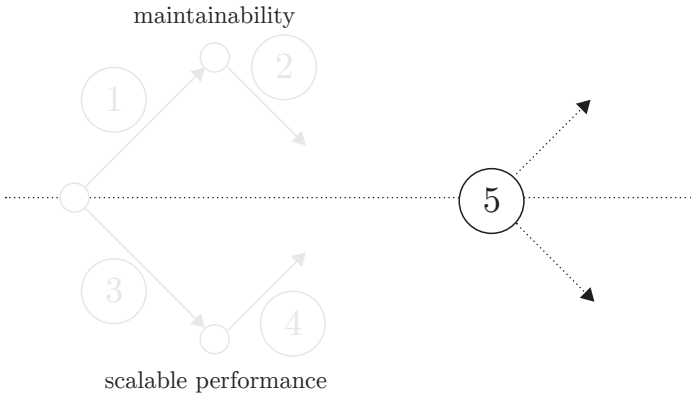


Figure 1.6 – Focus on Adoption

1.4.1 Abstraction of Tasks Organization

1.4.1.1 Compilers

"It is a mistake to attempt high concurrency without help from the compiler"
— R. Behren, J. Condit, E. Brewer [15]

.

As soon as the incompatibility between the modules and the tasks organizations were presented, it was suggested to use a compilation approach to mitigate this incompatibility [115]. This section presents the state of the art to extract parallelization from sequential programs through code transformation and compilation.

*

⚠ read and include [21]

Parallelism Extraction Extracting parallelism from a sequential implementation is a hard problem [89]. A compiler needs to identify the commutative operations to parallelize their executions [122, 30].

An important work was done to parallelize loop iterations [104, 6, 28, 12, 117], particularly using the polyhedral compilation method [151, 61, 137, 13]. To improve performance gains outside of loops, some compilers identify the data-flow parallelism on the whole program [14, 21, 99]. Moreover, the data-flow representation and execution of a program is well suited for modern data processing applications [46], as well as web services [123].

Mutable closures required for higher-order programming remains a challenge to parallelize because of the memory references shared across the program [69, 110, 103]. The next paragraphs present some improvements in compilation applicable for parallelism extraction.

Static analysis Compilers statically analyze the control-flow of a program to detect commutative operations [5]. The point-to analysis identifies side-effects [8, 86, 126, 144] which allows to infer commutativity. However, this analysis is not sufficient to track the dynamic control-flow of higher-order functions [124] like used in Javascript.

Another approach, abstract interpretation, is to interpret the possible path of executions. It allows to statically reason on the behavior of dynamic program [**Raychev2013**, 100, 125, 54, 66, 53, 17]. It is successfully used for security applications [81, 90, 149, 101, 29, 44]*.

Update the citation for Dolby2015

However, these static analysis techniques remains often too imprecise, and expensive for the performance gain to be profitable. Instead, some compilers relies on annotations from the developers.

Annotations Some works proposed to rely on annotations from the developer to identify the shared data structures and infer the commutativity of operations [142, 46]. Such annotations are especially relevant for accelerators such as GPUs or FPGAs, because the development effort yields huge performance improvements [**Tarditi2006**]. Examples of such compilers are OpenMP [35], OpenCL [128], CUDA [112] Cg [102], Brook [19], Liquid Metal [**Huang2008**].

Compilation Limitations For dynamic, higher-level languages like Javascript, the static analysis is not sufficient to correctly infer the independence of operations to parallelize them. And parallel compilers often fall back on relying on annotation

provided by developers. Hence, the burden of detailing the tasks organization falls back to the developer, similarly to the platforms presented in the previous section.

Alternatively, another approach is to rely on the runtime to detect and distribute the commutative operations, and assure the communications. The next paragraphs present runtime allowing this dynamic distribution.

1.4.1.2 Runtimes

Partitioned Global Address Space The Partitioned Global Address Space (PGAS) provides a uniform memory access on a distributed architecture. It attempts to combine the efficiency of distributed memory systems, with the productivity of shared memory systems. Each computing node executes the same program, and provide its local memory to be shared with all the other nodes. The PGAS platform assures the remote accesses and synchronization of memory across nodes. Examples of implementation of the PGAS model are .

Dynamic Distribution of Execution Following SEDA, Leda proposes a model where the independent stages of the pipeline are defined only by their role in the application [**Salmito2014**, 123]. The execution distribution and module organization are different. The actual execution distribution is defined automatically during deployment. This automation manages the execution organizations to help the developer focus on the modular organization. However, it doesn't improve the composition of module with higher-order programming.

Tables 1.11 and 1.13 presents the platforms presented in this section regarding maintainability and performance.

Model	Composition	Encapsulation	→	Maintainability
Partitionned Global Address Space	0	0		0
Dynamic Distribution	0	0		0
Polyhedral Compiler	0	0		0
Annotation Compiler	0	0		0

Table 1.11 – Maintainability of Compilation and Runtime Platforms

Model	Fine-grain level synchronization	Coarse-grain level message passing	→	Performance Efficiency
Partitionned Global Address Space	0	0		0
Dynamic Distribution	0	0		0
Polyhedral Compiler	0	0		0
Annotation Compiler	0	0		0

Table 1.12 – Performance Efficiency of Compilation and Runtime Platforms

1.4.2 Adoption Limitations

All the platforms presented in this section come from the need of the industry to reduce the development commitment required for efficiency. However, these platforms are limited to scientific applications. They respond exclusively to academic or industrial needs, and are barely supported by the community.

The balance between efficiency and productivity is not sufficient for a community of passionate to gather around the platform. The platforms need to answer to needs of small scale for novice to start learning, and to incite the community to experiment and start projects organically. The context of web development is particularly adapted for this requirement.

Model	Community support	Industrial need	→	Adoption
Partitionned Global Address Space	0	0		0
Dynamic Distribution	0	0		0
Polyhedral Compiler	0	0		0
Annotation Compiler	0	0		0

Table 1.13 – Adoption of Compilation and Runtime Platforms

1.4.3 Summary

Table 1.14 summarizes the characteristics of the platforms presented in this section.

Model	Maintainability	Adoption	Performance Efficiency
Partitionned Global Address Space	0	0	0
Dynamic Distribution	0	0	0
Polyhedral Compiler	0	0	0
Annotation Compiler	0	0	0

Table 1.14 – Summary of Compilation and Runtime Platforms

1.5 Analysis

This chapter presented a broad view of platforms and their balance between productivity or efficiency. The platforms favoring one sacrifice the other. The adoption, and usage of these platforms prove that none of these compromises are sustainable.

The productive platforms are highly adopted. Their productivity feed a reinforcing circle of adoption between the community and the industry. However, they lack the efficiency required to strive in the latter stage of a project, where efficiency becomes crucial.

On the other hand, the efficient platforms are not widely adopted by the community. These platforms are unable to respond to the need of the community to prototype and to experiment on small projects to make them evolve into larger ones later on.

Continuous Development It is not possible for a platform to support both productivity and efficiency at the same time. These platforms are oriented toward productivity, efficiency or a compromise between both. As the two are required at different time in the evolution of the project, to follow a project, a platform need to meet the requirements at the good time. They need to supporting productivity to allow the community to experiment, and organically start projects. And then

continuously shift toward efficiency as the project evolve, and requires it.

None of these platforms are able to support productivity then efficiency to follow the evolution of a project. They lack the possibility to make a project evolve from the very early stage until maturation. A project needs to change platform to change the priority. These shifts of platforms have economical consequences.

The table **??** summarizes the analysis of the state of the art presented in this chapter.

Model	Maintainability	Adoption	Performance Efficiency
Imperative Programming	3	3	0
Object-Oriented Programming	5	4	0
Functional Programming	5	0	0
Multi Paradigm	5	4	0
Event-driven programming	3	5	2
Lock-free Data-Structures	1	0	2
Multi-threading programming	2	0	1
Cooperative Threads	2	0	1
Actor Model	1	1	5
Communicating Sequential Processes	1	1	5
Skeleton	2	2	4
Service Oriented Architecture	3	3	4
Microservices	3	3	4

Data Stream System Management	2	4	3
Pipeline Stream Processing	4	2	5
Partitionned Global Address Space	0	0	0
Dynamic Distribution	0	0	0
Polyhedral Compiler	0	0	0
Annotation Compiler	0	0	0

Table 1.15 – Maintainability of Modular Programming Platforms

tab:summary

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