Modelling the Evolution of Programming Languages

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Abstract

Programming languages are engineered languages that allow to instruct a machine and share algorithmic information; they have a great influence on the society since they underlie almost every information technology artefact, and they are at the core of the current explosion of software technology. The history of programming languages is marked by innovations, diversifications, lateral transfers and social influences; moreover, it represents an intermediate case study between the evolution of human languages and the evolution of technology.

In this paper we study the application of the Darwinian explanation to the programming languages evolution by discussing to what extent the evolutionary mechanisms distinctive of biology can be applied to this area. We show that a number of evolutionary building blocks can be recognised in the realm of computer languages, but we also identify critical issues. Far from being crystal clear, this fine-grained study shows to be a useful tool to assess recent results about programming languages phylogenies. Finally, we show that rich evolutionary patterns, such as co-evolution, macro-evolutionary trends, niche construction and exaptation, can be effectively applied to programming languages and provide for interesting explanatory tools.

Keywords: evolutionary theory, programming languages, evolution of technology, cultural evolution.

1 Introduction

The Darwinian theory of evolution has been often applied to cultural systems, both to model the development of specific cultural traits and to provide a general explanatory framework. One main question raised by the literature is about how deep is the analogy between biological and cultural evolution (e.g., [1][3]). Variation, selection and inheritance often operate very differently in the biological and cultural cases, and very different cultural traits, like for instance artefacts in the material cultural world and the cultural propagation of behaviours, arguably require different explanations.

In this paper we focus on the evolution of Programming Languages (PLs), a specific aspect of software systems that represents an interesting case study, lying in the intersection between two notable streams of works in the realm of cultural evolution: the evolution of human languages and the evolution of technology. Programming languages have a great influence on the society, since they underlie almost every information technology artifact. Moreover, the PL arena is very lively, crowded and dynamic: there continuously appear new languages, mainstream languages strongly compete, often pushed by companies that employ
such languages in the technology they sell, and even measuring the success of a PL is a very difficult and debated task [2].

Like human languages, PLs are a means of communication: they allow a programmer to instruct a machine, they allow two or more programs to interoperate, and they also allow programmers to share algorithmic, i.e., formal and precise, information. The first programming languages date back to the 1950s; their history might seem short compared to other cultural systems, but it is very fast and rich, marked by innovations, diversifications, lateral transfers and social influences. Compared to biological systems, variations in both human and programming languages are affected by intentional choices. Intentionality is particularly sharp in the case of PLs, which are carefully designed for a specific goal, and they are the result of a planned combination of elements used in other programming languages, according to the tinkering practice distinctive of the technological evolution. However, even if PLs locally evolve according to a planned design, the macro-history of PLs has been clearly affected by a number of mechanisms distinctive of sociocultural systems; modelling their complex evolution is of critical importance in order to analyse the current explosion of software technology.

We observe that programming languages provide for a well defined and expressive realm, that represents an interesting subject for studying and testing evolutionary patterns, since it shares commonalities with other cultural and technological systems, and at the same time it displays specific features. We then study the application of the Darwinian explanation to the PLs evolution, trying to unveil evolutionary patterns and driving forces that guide, or unfold behind, the development of this rich scientific area. However, we stress the fact that, rather than casting PLs evolution into the Darwinian account, our main goal is to discuss to what extent the evolutionary mechanisms distinctive of biology can be applied to this area, shedding some light on how much the rich Evolutionary Theory’s research program can provide for an explanatory framework, still calling for a pluralism of explanations.

More precisely, we start in Section 2 by describing the aspects that distinguish the evolution of technology and that of human languages from the biological evolution. We then point out that in order to specifically address the case of programming languages, it is important to precisely understand to what extent the building blocks of the evolutionary explanation can be rephrased in this context. Taking inspiration from Pagel’s table detailing the parallels between biological and linguistic evolution [3], we extend in Section 3 such a parallel by discussing how far the basic ingredients of the Darwinian evolution can be rephrased to deal with PLs. Far from being crystal clear, the rough identification of the building blocks of the PLs evolution shows to be a useful tool to assess the results obtained by R. Solé and S. Valverde [4], who applied systematic phylogenetic methods to infer evolutionary trees of programming languages starting from a network of influence. Finally, we show in Section 4 that richer evolutionary patterns, such as co-evolution, macro-evolutionary trends, niche construction and exaptation, can be effectively applied to programming languages, and provide for interesting and useful explanatory tools.

## 2 Programming languages: an intermediate case between the evolution of technology and that of human languages

The evolution of technology. The comparative study of technological development and biological evolution is a very rich and lively topic: the analogies and differences are so profound that delving into this comparison is still a source of insightful thoughts. Like biological
evolution, the technological development displays a process of descent with variation and selection, which includes convergence, contingency and extinction. Even an elaborate evolution pattern like punctuated equilibria applies also to the technological progress: see [5] for a detailed discussion about the existence of punctuated equilibria in technology diffusion. At the same time, differently from biological systems, technological innovations are examples of planned design, ranging from short-term goals (e.g. a safer car) up to long-term expectations (e.g. ubiquitous computing initially achieved by means of laptops, then by means of smartphones, now by the Internet of Things scenario). In particular, the leading role of planned design is here especially magnified by the fact that technology often offers a clear notion of measurable progress to be reached, in terms of efficiency, correctness, safety, cost or speed.

It is also well known that tinkering, that is the widespread reuse and combination of available elements, is a typical feature of the evolution process. New technologies often emerge as a recombination of preexisting technologies, in a similar way as new biological structures reuse available elements. However, as observed in [6], the impact of introducing new simple technological elements can be very high, and completely reset the path of future technologies, whereas in biology established solutions are seldom replaced. On the other hand, a crucial point is that the study of technological innovations, and in particular that of information technology, must significantly take into account the interactions with social and economic factors. Nowadays information technology, economy and social systems are deeply interconnected and interdependent, each one being able to transform the development landscape of the others. We claim that it is not just a matter of mutually affecting, co-evolving, domains, but these days information technology, economy and social systems can be better interpreted as a proper ecosystem. For instance, in the case of information technology, issues of retro-compatibility, but also market dominance or trends, often limit or make impossible the spreading of better solutions, while the dominant technology keeps stuck to suboptimal products. As an example, Web-based solutions for software applications are sometimes dictated by a trend, whereas classical client-server architectures avoiding browsers would have been best suited. Moreover, technological innovations like the Internet, Cloud computing and Big Data, have been so impactful on the society, that they are no more just scientific words, but they are also economical and social keywords.

One of the pivotal components of information technology artefacts is represented by software systems, which essentially aim at controlling the behaviour of physical components. Interestingly, software provides a particularly well preserved fossil record, hence it is a good candidate to re-apply quantitative analysis methods, such as phylogenetic relationships reconstruction, which are well established in evolutionary biology. However, the applicability of these methods for the reconstruction and the analysis of software evolution raises a number of issues. First of all, as observed by R. Solé et al. in [6], software systems offer multiple levels of detail: the code written in a given programming language, the architecture of interacting pieces of code and data, the social network of engineers that designed the software system and those that maintain it over its life-cycle. In this setting even appropriate definitions of what would correspond to mappings between genotype and phenotype is far from being trivial. The second issue comes from the observation that the phylogeny of technology is not hierarchical: the combinatorial effect of tinkering, the rapid and large information exchange, the ageing process of technologies, entail reticulate phylogenies similar to that of bacteria. Then reticulate networks, instead of trees, appear to be more appropriate when dealing with technological innovations. The study of patent networks provides a clear example of this phenomenon: it shows instances of different patterns like gradual evolution, stasis followed by
punctuation, extinction, selection and even resurrection ([6, 7]). Moreover, the multi-parental
genealogy of patented inventions calls for highly multi-parental, possibly multilevel, lineages
of evolution ([8]).

The evolution of human languages. Human languages are well recognised culturally trans-
mitted replicators. They put forward multiple ways in which individuals learn from one
another, and give evidence of how cultural traits get distributed through the different chan-
nels of social transmission. The study of their complex evolution provides insights about
the interplay between biological and cultural evolution, and highlights the role of different
evolutionary mechanisms. The recent debate (e.g. [1, 9, 10, 11]) emphasizes the dis-
analogies between the way variation, selection and inheritance operate in the biological and
cultural cases and calls for a generalisation of the classical Darwinian selectional and replica-
tive models. Indeed, cultural transmission displays both preservative and constructive trans-
mission aspects; for instance, while propagating the word sound can only rely on copying,
propagating the word meaning triggers constructive, re-productive, processes [1]. Moreover,
phenotypic plasticity, developmental constraints, niche construction and inclusive inheritance
have been pointed out as major factors that, together with selection, shaped the complex traits
of the human language [9].

In the next section we will argue that programming languages similarly entail peculiar
mechanisms of transmission, and they also possibly require a generalisation of the Darwinian
replicator model. Moreover, in this context the variation and selection processes are not
causally independent; it is often the case that the very same people have a role both in the
design of new languages (i.e., in variation) and in determining a language success or failure
(i.e., in selection). This is just an example of the sociocultural effects on the PLs development,
and it is reminiscent of Lane et al.’s reciprocity principle: “the generation of new artefact
types is mediated by the transformation of relationships among agents/organisations; and new
artefact types mediate the transformation of relationships among agents/organisations” [13].

An interesting setting for comparing the evolutions of human languages and program-
miring languages is the study of their phylogenetic history. By systematically applying well
developed techniques of phylogeny reconstruction, and cautiously assessing their results, rich
and nontrivial dynamics may be identified. However, this approach is full of methodological
and epistemological issues. When comparing human languages and PLs, a first important
remark is about the topology of language phylogenies. In [14] the authors observe that the
phylogenetic analyses of human languages show that trees are well suited models for de-
scribing language histories, even if they evolve both vertically and horizontally. This can be
explained by observing that human language phylogenies have been constructed on top of a
fundamental vocabulary, that is a data set made of 200 words (Swadesh list) corresponding
to conservative, cross-culturally universal meanings, such as ‘mother’ or ‘sun’. These words
tend to evolve slowly and resist to lateral influences, they can be seen as adaptive cultural
traits, that hence more likely have a phylogenetic (vertical) signature. Moreover, families of
human languages, such as Indo-European and Bantu languages do not hybridise so much,
which also explains why human language phylogeny is shaped like a tree with monophyletic
groups.

The case of programming languages is different and particularly subtle. First of all, the
methods applied to the study of human languages cannot be directly applied to PLs: defining
a sort of Swadesh list for PLs would be very controversial, if not meaningless. In [4] sys-
tematic phylogenetic methods have been applied to infer evolutionary trees of PLs starting
from a network of influences. However, the nature of technological innovations described above suggests that the results in [4] might underestimate the reticulated nature of PLs phylogeny. We will more precisely discuss the approach of [4] in the next section, but we point up that prior to phylogeny reconstruction, lay unsolved questions like what should a PL phylogeny account for? and what is the “adaptive core” of a programming language? We think that the first step to answer these questions is to precisely study the basic characteristics of programming languages so to understand to what extent they can be effectively cast into the evolutionary framework.

3 The basic ingredients of PLs evolution

In [3] Mark Pagel gathers into a table a detailed parallel between biological and linguistic evolution. The same table is adapted and extended in [14] to deal with cultural systems. In this section we virtually add a column to such a table, extending the parallel to encompass the case of programming languages.

As observed by Pagel, the key among these parallels is that both biology and human languages are digital systems of replicators, that is they both include discrete heritable units, respectively the genes and the words or phonemes, that assure transmission fidelity. In the case of PLs, discrete units correspond to language primitives, such as loops, conditional commands, functions, but also objects or threads in richer languages. Another crucial aspect is the identification of the replication mechanisms: in biology inheritance comes essentially with parent-offspring, while human language is replicated by means of teaching, learning and imitation. For programming languages there is no filiation mechanism, programmers learn a coding language and assess their knowledge by checking the execution of the programs they write. It is important to observe that in the learning phase the language cannot be modified, in particular there is no pragmatic semantics for PLs: a program will not be executed unless it fully respects the required syntax. For instance, even missing a simple symbol like a curly bracket can cause a C++ program to be rejected by the machine. Replication and inheritance processes can also characterise the life-cycle of a given piece of software, but this aspect is rather related to the software engineering practice, that corresponds to a different observation level, that is orthogonal to our focus on the coding language.

In order to give a precise account of inheritance and a number of related concepts, we cannot avoid trying to clearly delineate our observation level by addressing the pivotal issue of defining what is a programming language species.

What is a PL species? In analogy with human languages, it is rather natural to say that a species corresponds to a distinct programming language, such as Fortran, Java or C++. The analog of people talking the same language is instead less clear: individuals belonging to the same species, say, “the Java species”, might correspond to the programs written in Java or to the Java programmers. We claim that “populating” a programming language with people that code in that language shades the distinctive features of computer languages. For instance, programmers are usually polyglot, but they do not mix programming languages: multi-language software systems are precisely defined in terms of separate mono-language modules that interoperate according to a precise algorithm, that is in turn implemented in another formal language. On the other hand, letting the individuals correspond to the programs brings in a number of deep consequences.
First of all, we remark that each programming language comes with a language specification that precisely defines which program phrases belong to that language: different Java programs may behave differently or use different subsets of Java primitives, but it is impossible for a program to use an altered version of a Java construct or a new piece of syntax, since the machine would recognise it as an error, that is an ill-defined, non-executable program. As a consequence, a language specification provides for a clear definition of the species boundaries, but at the same time in this view we have that PL species provide no individual variability, therefore the very 'population thinking'\(^1\), which is the essence of the evolutionary framework, seems to fade.

To be precise, the language specification is not always so sharp and accurate: for instance, the syntax of the C language has a standard definition in terms of a formal grammar \([15]\), while the Java specification language is given as a written English document \([16]\). In some case it is difficult to trace the boundaries between a language and its libraries (e.g. Python) or there might be just a reference implementation with extensive test suites instead of a language specification, as for Perl. Nevertheless, for any programming language, in order to execute a program written in that language, the computer has first to translate that program into machine instructions. Therefore each PL requires an automatic translator (a compiler or an interpreter) that must be designed according to some parsing rules that recognise syntactically well-defined programs. Hence the specific syntax definition instructing the language parser happens to determine the species boundaries. In particular, programming languages do not hybridise: a program mixing Java commands and C++ commands is rejected by the compiler. Hybrid languages might still be defined, they are often called dialects; however their definition must encompass the dialect’s parser with a precise specification of which program is recognised to belong to the dialect and which is not. Henceforth the dialect is not an hybrid but it is another species itself.

Therefore we have that, on the one hand, even if the language specification may be blurred in some case, the definition of PL species seems to be sharper than that, still very controversial, of human languages species and biological species. On the other hand, by losing individual variability the populational explanatory framework can hardly be applied. Nevertheless, despite this crucial difficulty, which we highlight as an open problem, we think that a number of evolutionary building blocks can still be recognised in the realm of computer languages.

**Diversification processes.** Even if the sharp notion of species given above entails no individual variability, we can recognise a language mutation when an updated language specification is released. For instance, the Python 3.4.0 language would hardly be considered a different language from Python 3.3.3. Moreover, issues of backward-compatibility impose that the programs written according to the old specification must be correctly interpreted also by the new parser. In addition, whenever a program construct is abandoned in the new release, the new language specification labels such a construct as a “deprecated feature”, that is a primitive that can still be correctly parsed (for backward-compatibility) but that must not be used anymore. Interestingly, deprecated features could be assimilated to vestigial traits in biology.

Whenever the language specification undergoes a major update, a speciation event occurs. For instance Java 8 is in many sense a different language from Java 7 because it provides new

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\(^1\) “Population thinking involves looking at a system as a population of relatively autonomous items of different types with the frequency of types changing over time” ([11]).
## Biological Evolution

| Discrete heritable units | Human Languages Evolution | PLs Evolution |
|--------------------------|---------------------------|---------------|
| nucleotides, aminoacids, genes | words, phonemes, syntax | primitives, syntax |

## Mechanisms of inheritance

|   |   |   |
|---|---|---|
| reproduction, occasionally clone | teaching, learning, imitation | fixed specification |

## Hybridisation

|   |   |   |
|---|---|---|
| species mixes | language Creoles | no: hybrid code does not execute |

## Mutation

|   |   |   |
|---|---|---|
| genetic alteration | new words, mistakes, sound changes | specification/version update |

## Speciation

|   |   |   |
|---|---|---|
| allopatric, sympatric, ... | lineage splits (e.g. geographic, social, ethnic -separation) | major language update |

## Anagenesis

|   |   |   |
|---|---|---|
| evolution without splitting | linguistic change without split | just minor updates |

## Horizontal transfer

|   |   |   |
|---|---|---|
| horizontal gene transfer | borrowing | lateral influence but no hybrids |

## Clines

|   |   |   |
|---|---|---|
| geographic clines | dialects and dialect chains | dialects are different languages |

## Drift

|   |   |   |
|---|---|---|
| genetic drift | language drift | no random sampling effect |

| Table 1: Some analogies between biological, human languages and programming languages evolution. |

Language constructs that deeply modify the programming style\(^2\). Moreover, a parallel can be established by biological allopatric speciation, that is, speciation by means of geographic separation and diversification, and domain specific languages (DSLs), that is, PLs specialised to particular application domains. For instance, Csound is an audio programming language used by composers and musicians derived from the C language. On the other hand, biological anagenesis, that is, species evolution without splitting events, can be recognised for PostScript, the language used by laser printers, whose specification underwent only minor updates.

The final three rows in Table 1 are direct consequences of the sharp definition of PLs species and the fact that PLs are explicitly/intentionally designed. Lateral gene transfer and new words acquisition by borrowing have no parallel in programming languages. There are certainly lateral influences in the design (and update) of a language specification, i.e., at speciation events, but not between individuals. Similarly, geographic clines and dialects...\(^2\) Significant efforts have been made to guarantee backward-compatibility.
chains can be only superficially compared with PL dialects: for instance a program written in a dialect of Java is in general not recognised by the Java compiler, thus it can directly interoperate with standard Java software only if it just relies on the common language core. Finally, genetic and language drift have no parallel in the context of programming languages, because there is no random sampling effect in the replication mechanism.

**External processes.** We complete our analogies in Table 2 starting with the description of the selection processes. In the case of programming languages, as well as in general for technology, the natural selection distinctive of biology can be compared to the inherent concept of scientific progress. A PL that allows a more efficient implementation, or that is safer of less error-prone, or that is targeted to a more advanced hardware, will survive other languages. On the other hand, social selection and trends operate on PLs similarly to other cultural systems. As discussed in the previous section, strong selection pressures also come from economic factors, that might overcome “natural” selection and determine the dominance of sub-optimal solutions.

Language extinction happens also in computer science, for instance in the case of low-level languages explicitly targeted to obsolete hardware. The case of the Cobol language is curious: it is definitely an obsolete language but most of the financial software systems consist of stable Cobol programs and porting such systems to a different language opens the way to the introduction of errors, maintenance and compatibility issues that might be not sustainable. The adopted solution is to keep the core software written in Cobol and wrap it with a front-end written in a modern language. This solution reminds of the canalisation processes found in biology. Finally, as an example of announced extinction, we mention the Objective-C language. It is variant of the C language that has been designed in the 1980s but that became mainstream only in 2000 when Apple imposed its usage to develop applications for its mobile devices. In 2014 Apple released Swift, a modern programming language that makes programming easier, safer and faster, thus actually condemning Objective-C to extinction. Clearly, Objective-C will still be necessary to maintain the applications written in Objective-C, but mobile applications become obsolete very quickly, thus the language will probably fade away.

| Biological Evolution | Human Languages Evolution | PLs Evolution |
|----------------------|---------------------------|---------------|
| **Selection**        |                           |               |
| natural selection    | social selection and trends| progress, social selection, trends |
| **Extinction**       |                           |               |
| species (mass) extinction | language death       | language death |
| **Fossils**          |                           |               |
| fragmented fossil records | ancient texts          | dead languages, deprecated features |
| **Evolution rate and awareness** |                     |               |
| slow, not planned    | fast or slow, partially intentional | fast, fully designed |

Table 2: Further analogies between biological, human languages and programming languages evolution.
The final row in Table 2 illustrates the difference in the evolution rates: biological species evolve very slowly, while PLs evolution is extremely fast. Moreover, there is no intelligent design guiding biological evolution, whereas every choice in the specification of a programming language is intentional. It is important to observe that even if local choices are carefully designed, the global evolutionary process for PLs is not completely planned: long-term effects might have not been planned, and reactions to social, economical or contingent factors can hardly be anticipated. Some of these non completely intentional effects will be discussed in the next section.

3.1 The programming paradigms as a multilevel issue

Recently S. Valverde and R. Solé [4] put forward a quantitative study of the evolutionary dynamics displayed by programming languages. They consider a dataset of 347 PLs, appeared between 1952 and 2010; an influence graph is then reconstructed by extracting from Wikipedia the list of PLs that influenced the design of each PL. From such a graph, which is a quite tangled and complex network, the authors extract a phylogenetic tree following the approach of [17] developed in the context of networks of citation in scientific publications. More precisely, the method generates a backbone based on identifying the most influential parent for each language, and an additional graph that keeps all the horizontal exchanges among languages.

The proposed method is ingenious since other quantitative approaches rely on syntactic similarity measures that can hardly be defined for PLs. The method finds two, disjoint and highly imbalanced, major clades corresponding to the imperative and the functional programming families, together with several smaller classes, thus accurately mapping the known historic development of PLs. Moreover, the bundle of links observed in the horizontal transfer graphs supports the combinatorial rule of technological evolution mentioned above. On the other hand, we think that one major authors’ remark about the obtained results deserves a deeper examination.

The authors observe that in many of the lineages obtained by their method there are examples of languages displaying object-oriented (OO) traits. They claim that the historical separation of imperative and functional programming transitions to a convergent evolution towards object orientation. Indeed, OO-programming’s strengths in abstraction, modularity, dependency management and code reuse made this paradigm a de facto standard for the development of reliable large-scale software. However, we think that explaining the emergence of OO-programming in terms of convergence is not fully satisfactory and biased, essentially coming as a consequence of choosing trees, rather than networks, as a working model. As we discussed in the previous section, trees might underestimate the reticulated nature of technological phylogenies. We then propose a different explanation, based on a precise account of the notion of programming paradigms.

Given a PL, a program must be written according to the precise language syntax, however there is some freedom about the adopted style, which marks the program’s paradigm. A programming paradigm (e.g., imperative, functional, object-oriented, declarative, logic) is a set of programming patterns that characterise the structure of programs and entail a fundamental style of computer programming. In computer science paradigms are also used to classify PLs into taxonomies. Using the biological talk, we can say that if a PL is a species, a paradigm is a family or a class. However, differently from biology, there is no unique, generally accepted, classification (see e.g. [18]) because paradigms cannot be formally defined as the language
syntax, and more importantly because there are aspects of languages that do not neatly divide up into paradigms. Indeed, PLs are designed to support one or many paradigms, and recent PLs are often explicitly designed to take the best from an ingenious mix of paradigms. On the other hand, while there is no individual variability at the level of species, the situation is very different at the level of paradigms: new paradigms emerge (speciation), they compete (selection) and they often merge (hybridise). Moreover, for some multi-paradigm language the different paradigms are somehow orthogonal, such as in Scala; therefore the mix of paradigms is not just a matter of hybridisation, but an actual overlapping of classes.

Interestingly, a biological counterpart to this scenario is represented by the so called multilevel genealogical discordance, that is, when the pattern of phylogeny at one level of the biological hierarchy fails to map onto patterns at other levels. Not surprisingly, such a discordance is especially notable for microbial organisms, where the extensive presence of lateral gene transfer, hybridisation, and recombination lead to reticulate phylogenies. Multilevel lineages have been advocated by Matt Haber [19] to let phylogeny reconstructions take into account that biological gradients also apply over levels of the hierarchy. Moreover, as observed by Haber, multilevel discordance is related to the lineages multiple decomposability problem, that is reminiscent of the problem of partitioning PLs into programming paradigms mentioned above.

We leave the case of paradigms as a further open problem. We argue that object-orientation is just an instance of this problem, that can be better addressed in a multilevel evolution framework rather than resorting to convergent evolution. In this view, we conclude pointing out an intriguing conjecture, that might shed light on the multilevel explanation. At the level of species the evolution of PLs is powerfully driven by syntactic traits, whereas at the level of programming paradigms the evolution might be driven by “semantics/behavioural traits” corresponding to different ways to encode a behaviour. In the functional paradigm a behaviour is encoded as a function, in the imperative paradigm it is represented as a sequence of steps, in the declarative paradigm a behaviour is a property to be satisfied and in the OO paradigm it is encoded as an abstract data type. Syntactic and semantic traits are clearly related but the study of their interplay might give insights about the hierarchical relationship between PLs and programming paradigms.

4 Rich evolutionary patterns as explanatory tools

The Darwinian Theory of Evolution is much more than random variation and natural selection, it offers a number of sophisticated evolutionary patterns that provide for interesting and useful explanatory tools. While in the previous section we discussed the basic building blocks of the evolutionary framework, in this section we show that richer patterns in the evolutionary research program can be recognised also in the context of programming languages.

Co-evolution. By analogy with the co-evolution of human language and brain, PLs have clearly co-evolved with hardware technology. Besides the two radiation events described in \[4\] corresponding to the birth of structured programming in the 1950s-60s and the personal computer revolution in the 1980s, we can identify a number of recent technological innovations that determined major evolutionary leaps in mainstream programming languages \[20\]. The first one is the advent of the Internet, and especially its appeal to the market, which shifted the PL goals from efficiency to portability and security an also promoted scripting PLs, such as JavaScript and PHP, to write programs to be embedded into web pages and web
servers. Moreover, the fact that nowadays efficient hardware can only be parallel (by means of multicores and GPU processors but also clusters of machines), boosted PLs that support parallel and distributed programming, up to Cloud computing. Finally, the smart technologies provided by the Internet of Things increase the huge amount of data that can be collected, and ask for PLs that support the so-called High Performance Computing needed to deal with the Big Data era.

Interestingly, in the case of programming languages we can devise another important co-evolving lineage, that has no biological counterpart: the advances of theoretical research. Indeed, mainstream programming and theoretical research on PLs have been mutually influenced: Robin Milner’s Turing lecture [21] recalls that suitable programming abstractions come from a dialectic between the experimental tests conducted by practical programming and the deep mathematical tests conducted by the theoretical approach. The formal languages studied by theoreticians are well suited to test new programming primitives and new mix of “language traits” in a concise and expressive model. In other terms, they allow for experimentation in a controlled environment, thus testing and promoting language mutations that are not necessarily driven by the actual environment or the short-term future. Even if also in biology mutations are not (always) driven by adaptation, such a designed testing and experimentation has no equal both in biology and human language evolution. Experimental manipulations can be conducted in some cultural systems, especially in the technological systems, but the possibility of a direct and strict interaction between the theoretical research and the programming practice is distinctive of PLs.

**Macro-evolutionary trends.** A macro-evolutionary trend is a transversal development that encompasses different species. In the realm of PLs we can recognise a macro-trend increasing the abstraction level provided by languages. Indeed, new languages provide support for more declarative programming, focusing on “what to do” rather than on “how to do it” [20]. The details of the implementation of “how to do it” are progressively moved under the hood by increasing the complexity of the language runtime; for instance consider Java’s automatic garbage collector as opposed to C++’s fine-grained, powerful but error-prone, control over the memory.

This evolutionary trend is explained by the fact that higher level programming abstractions enhance program correctness and productivity, but it is important to observe that it is achievable because of the underlying (co-evolving) trend that provides for increasingly efficient hardware which supports stratification of virtual machines and increasingly complex runtime systems.

**Niche construction.** We have already observed that modern PLs are designed as a mix of programming paradigms. Moreover, modern software systems, such as those distinctive of innovative Internet-driven companies such as Google, Facebook, LinkedIn, are written using a mix of languages, actually a mix of software layers provided by different language frameworks, that interoperate at different abstraction levels.

On the other hand, we can identify a specific ecosystem of languages for the Web development. Rich and dynamic websites, like Twitter’s, Amazon’s or eBay’s websites, involve the development of a back-end, connected to a database, and a front-end for user’s interactions. In particular, the languages involved in the front-end development, that is, HTML5 to deal with the page content, CSS to deal with the page appearance and JavaScript to deal with the page behaviour, establish a real niche-construction effect: they are different languages but
they mutually affect their evolution.

**Exaptation.** An interesting example of functional shift can be identified observing that after fifty years of functional programming languages, the distinctive traits of those languages, that is functions, shine in new languages essentially because they leverage effective concurrent programming. Indeed, for a long time functional programming techniques had been confined to languages that have never become mainstream. But looking at a function as an abstraction that represents a behaviour, which can be passed around and composed, allows for a smooth integration with the design of the concurrent execution of different tasks. Moreover, the spatial thinking supported by functional programming smoothly fits object-oriented programming’s ability of structuring software systems. Therefore well-established mainstream imperative (an object-oriented) languages such as C++ and Java recently embarked on a deep change to introduce higher-order functions (in C++11 and Java8) that leverage efficient parallel programming over large data structures.

## 5 Conclusions

The programming languages development represents a well structured case study to investigate how deep is the analogy between biological and cultural evolution. It is supported by a rich and complete fossil record and lays in the intersection between two notable streams of work in the realm of cultural evolution: the evolution of human languages and the evolution of technology.

In this paper we argued that in order to understand how much the Evolutionary Theory can provide for an explanatory framework in this realm, it is important to carry out a precise assessment of how far the basic ingredients of the Darwinian evolution can be rephrased to deal with PLs. We showed that many evolutionary mechanisms, such as diversification processes and external pressures have an actual correspondent. However, we raised a number of critical issues, such as the identification of replication mechanisms and the lack of populational thinking entailed by the species definition. The analysis of PLs phylogenies put forward hierarchical considerations, and we suggested the use of a multilevel evolution framework to encompass the case of programming paradigms. Finally, we showed that richer evolutionary patterns, such as co-evolution, macro-evolutionary trends, niche construction and exaptation, can be effectively applied to describe and interpret the complex evolution of programming languages.

This paper fits in the recent debate emphasising the disanalogies between the way variation, selection and inheritance operate in the biological and cultural cases. We have seen PLs as a bridge between the evolution of technology and that of human languages; an interesting future step will be comparing the PLs case with the study of patented inventions, which share with PLs the highly multi-parental genealogy and the complex and reticulated, possibly multilevel, lineages. Finally, a distinctive feature also worthy of further investigation is the impact of theoretical research on the evolution of PLs as a source of experimental manipulation.
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