Do Fewer Tiers Mean Fewer Tears? Eliminating Web Stack Components to Improve Interoperability

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Abstract

Web applications are structured as multi-tier stacks of components. Each component may be written in a different language and interoperate using a variety of protocols. Such interoperation increases developer effort, can introduce security vulnerabilities, may reduce performance and require additional resources. A range of approaches have been explored to minimise web stack interoperation.

This paper explores a pragmatic approach to reducing web stack interoperation, namely eliminating a tier/component. That is, we explore the implications of eliminating the Apache web server in a JAPyL web stack: Jupyter Notebook, Apache, Python, Linux, and replacing it with PHP libraries. We conduct a systematic study to investigate the implications for web stack performance, resource consumption, security, and programming effort.

1 Introduction

The architecture of a modern web application comprises a multi-tier stack of components. The classic example is the 4-tier Linux, Apache, MySQL, and PHP (LAMP) stack [12], cf. Figure 1. The components are written in different languages and interoperate using standard protocols like HTTP or SQL.

A diverse set of components and languages raises a number of challenges. (1) Interoperation increases developer effort: the developer must be fluent in all of the languages, components and their interactions, i.e. be a full stack developer. (2) Interoperation can introduce security vulnerabilities like SQL injection. (3) Interoperation reduces performance as requests must be handled by multiple components, and data must be marshalled between them. (4) Interoperating multiple components consumes additional resources as memory and compute time is required for each component.

A range of approaches have been used to improve interoperation in web stacks. Some stacks focus on a single language, e.g. MEAN focuses on Javascript [6]. Other stacks use a common VM to minimise the interoperation overheads between languages, e.g. the .NET framework uses the Common Language Runtime [9]. Sometimes web stack languages are combined, e.g. PyHyp combines Python and PHP [2]. The most radical approach is to combine all web stack languages into a single tierless language, such as Links [5] or Hop [20].

We take a less radical but more pragmatic approach to simplifying web stacks. We investigate the implications of replacing a tier or component, with code libraries. That is, we explore the implications of eliminating the Apache web server in a Jupyter Notebook web stack called JAPyL (Jupyter, Apache, Python, Linux), replacing it with a PHP threaded library.

This paper explores the following hypotheses for web stack tiers. (1) Does reducing the number of tiers improve web stack performance i.e. latency, throughput. (Section 4.2)? (2) Does reducing the number of tiers reduce resource consumption, i.e. core utilization and memory us-
Interoperating multiple components increases the attack surface of the application, e.g. in LAMP, interoperating Apache with PHP can leave the stack vulnerable to Cross Site Scripting (XSS) if security headers are not implemented or web forms are not properly sanitized.  Security Vulnerabilities. Interoperating multiple components increases the attack surface of the application, e.g. in LAMP, interoperating Apache with PHP can leave the stack vulnerable to Cross Site Scripting (XSS) if security headers are not implemented or web forms are not properly sanitized.

Performance Overheads can be introduced by interoperation, e.g. data must be marshalled between components, and memory and compute resources must be available for each component.

2.2 Reducing Webstack Interoperation

Some approaches to reducing interoperation in modern multi-tier web stacks are as follows.

Interoperation is reduced by consistently using a single language as far as possible throughout the stack. For example, the MEAN web stack uses JavaScript as the primary programming language and composes MongoDB, ExpressJS, AngularJS & NodeJS. MEAN typically outperforms LAMP by 2.5x or more due to the computational inefficiencies of PHP and the inefficiency of Apache in handling I/O operations.

2.3 Hosting Jupyter Notebooks

The Jupyter Platform has gained in popularity especially in the realm of data science because it allows users to process, analyse & manipulate data; and create analytical and statistical models with just a few lines of code that can be tested straight from a browser user interface. In addition, Jupyter Notebooks allows for the interoperation of different languages, such as the popular R-Python combination used by data scientists, through custom techniques such as subkernels and magics.

Generally, the standard way to make Jupyter Notebooks web accessible is to use the Jupyter, Apache, Python, Linux (JAPyL) web stack (Figure 2), and embed the Notebook into a webpage or site with an Apache Web Server as a Reverse Proxy. Here, Apache is usually interposed.
between the client and the Jupyter Server, taking requests from clients and forwarding them to Jupyter. This is done in order to create an extra layer of security to protect the Jupyter Server \[16\]. Appendix B \[1\] provides an example of the configurations a developer has to implement in both Apache and the Jupyter Server to allow for communication between the two components.

3 Case Studies

We explore the implications of eliminating a tier in a web stack, focusing on how the interoperation changes. Specifically we compare two Jupyter notebook stacks: JAPyL that composes Jupyter, Apache, Python and Linux in 4 tiers (Figure 2); and JPL that replaces Apache with a PHP thread library and composes Jupyter, PHP and Linux (Figure 4) in 3 tiers.

3.1 JAPyL

JAPyL is a conventional 4-tier architecture composing Jupyter, Apache, Python and Linux (Figure 2).

3.1.1 Security Configurations

In addition to the Reverse Proxy JAPyL also utilises a Defense-in-Depth multi-layered security approach (Figure 3). That is, various security mechanisms are deployed throughout the stack. The intention is that if an attacker targets the Jupyter Notebook online and is able to penetrate one layer, another layer may thwart the attack.

The JAPyL Defense-in-Depth model comprises: (1) Security Headers (2) SSL Encryption (3) URL Port Spoofing (4) IP Whitelisting / Blacklisting (5) Read Only Notebook Cells (6) Password Authentication (7) Password Encryption (8) Port Spoofing.

3.2 JPL

JPL (Jupyter, PHP, Linux) is a 3-tier architecture that carefully replicates the web service and security mechanisms of JAPyL (Figure 4). The Apache tier is replaced by the ReactPHP thread library, and some hand-coded PHP security code.

3.2.1 Imperative Configuration and Security

In contrast to JAPyL’s declarative specification of configuration and security much of the implementation is imperative. That is, only PHP was written to perform the necessary configurations as demonstrated by the examples in Appendix E \[1\].

Using an imperative paradigm means that the level of abstraction has decreased compared with JAPyL. However the developer has the expressiveness to implement the neces-
sary functionalities, and can potentially implement features not supported by the JAPyL DSLs [8].

Figure 4. 3-Tier JPL Architecture

3.2.2 Why PHP?

The rationale for using PHP to eliminate a web component is twofold. Not only is it one of the most popular and mature web programming technologies, but also offers a range of technical benefits [13], as follows. PHP provides simple parsing and marshalling, e.g. parsing JSON and XML with a single line of code. PHP supports multiple major databases including MySQL, dBase, IBM DB2, InterBase, FrontBase, ODBC, PostgreSQL, SQLite, etc. PHP is a mature technology, and supported by a range of frameworks like CakePHP, CodeIgniter, Zend, Larvarel that not only make development faster but also provide flexible coding styles and interfaces for programmers.

For our interoperability study, the most significant benefit of PHP is that it follows the familiar object oriented paradigm. Hence developers can, for example, create custom classes, and interoperate relatively smoothly with other object oriented languages in the stack like Java and, crucially for our study, Python.

Languages that are very similar interoperate with less semantic friction. Python and PHP are indeed similar, and have even been combined into PyHyp [2]. That is both languages support class creation, encapsulation, functions, immutable data, inheritance, object creation, polymorphism, and shared state and shared memory.

4 Evaluation

4.1 Experiment Design

We evaluate the performance and programmability of JPL by comparing it to JAPyL stacks on two platforms: Docker & native Raspberry Pi 3. While Jupyter Stacks are mostly deployed in virtualized environments like Docker [21], it is far easier to obtain accurate core and memory resource measurements on the Raspberry Pi. Where possible, the components used in the JAPyL and JPL stacks are identical, and as follows: Docker 18.09, Raspbian Stretch, Jupyter Server 5.7.8, Ubuntu 16.04. JAPyL uses Apache Server 2.4.34, and JPL ReactPHP 0.8.4. Experiments for the Docker platforms is conducted on an Intel Core i3 system, Windows 10 Operating System with 2.23GHz and 8GB of RAM.

Two existing Jupyter Notebooks not written by the authors are downloaded from GitHub. They are selected to be well designed [19], i.e. to have a notebook title & introduction, descriptions of the model parameters, and of the data parameters, and to import packages. The notebooks are simply loaded by the JAPyL and JPL stacks.

To minimise variability, the reported results are the median of three consecutive benchmark executions.

4.2 Performance: Latency and Throughput

Given the reduced number of tiers in JPL compared with JAPyL and that PHP is similar to Python, it is reasonable to expect JPL to outperform JAPyL.

Figure 5 shows the request latencies of JAPyL and JPL as the number of concurrent connections varies from 50 to 1000 on all platforms. Contrary to our expectations it shows that JPL latency is two or three times greater than JAPyL. The results are almost similar for the RaspberryPi as shown in Figure 6.

Figure 5. JAPyL vs JPL Latencies (Docker)

Figure 7 shows the request throughput of JAPyL and JPL as the number of connections varies. It also confounds our expectation by revealing that JPL throughput is two orders of magnitude lower than for JAPyL. We attribute
this to relatively poor thread management in the PHP React library [13], compared with Apache that is designed for high degrees of parallelism and to effectively utilise multicore systems [12].

As the JPL stack eliminates Apache and runs fewer components it is reasonable to expect JPL to consume less resource than JAPyL.

A possible explanation for this is memory leaks. This refers to a long running PHP request where the amount of memory utilised will slowly increase over time. There is some memory in PHP which just cannot be freed up on a regular basis due to its reliance on reference counting to manage memory [13].

4.3 Resource Usage: Core Utilization, Memory Overhead

As the JPL stack eliminates Apache and runs fewer components it is reasonable to expect JPL to consume less resource than JAPyL.

Figure 9 shows the CPU utilisation of JAPyL and JPL as they process https requests with 100 concurrent connections on the Raspberry Pi platform. Again, contrary to expectation JPL utilisation is typically 20% greater than JAPyL.
components in JPL, overall size might be expected to be smaller, but it is 135MB greater. Table 2 reveals why: PHP is much larger than Apache.

| Table 1. Memory Residencies |
|-----------------------------|
| Stack | Size(MB) |
| JAPyL  | 645      |
| JPL    | 860      |

| Table 2. Component Size |
|-------------------------|
| Object  | Size(MB) |
| Apache  | 165      |
| PHP     | 390      |

4.4 Security

Table 3 shows that the JAPyL Defense-in-Depth security model can be replicated in JPL, but requires key functions to be hand coded. In some cases, such as the security header feature, JPL was able to surpass JAPyL as the implementation could be automated with just a few lines of code as demonstrated in Appendix E [1]. That is, hand coding enables greater security than relying on Apache’s declarative security options.

| Table 3. JAPyL vs JPL Security Implementations |
|-----------------------------------------------|
| Read Only Cells | JSON Coding | JSON Coding |
| Password Encryption | Command Line | Command Line |
| Port Spoofing | Hand Coded  | Hand Coded  |
| SSL Encryption | Apache Configs | Hand Coded  |
| IP Whitelisting | Hand Coded  | Hand Coded  |
| IP Blacklisting | Hand Coded  | Hand Coded  |
| Security Headers | Hand Coded  | Automated  |

4.5 Programmability

4.5.1 Code Size

Code size is widely recognised as a measure of developer effort and of maintainability. Table 4 enumerates the lines of code required to implement the functionalities of the JAPyL and JPL stacks. Implementing the JPL web stack requires 267 fewer lines of code, or 42% less code. This is to be expected because there are fewer languages and paradigms to be implemented as shown in Table 3. JAPyL utilises 3 programming languages compared to 2 in JPL.

| Table 4. Lines of Code (LOC) |
|-----------------------------|
| Functionality | JAPyL | JPL |
| Embed Notebook | 10    | 36  |
| Host Webpage   | 29    | 26  |
| Reverse Proxy  | 33    | 23  |
| Security Configs| 21     | 31  |
| Language Processing | 527  | 63  |
| Messaging      | 11    | 85  |
| Total          | 631   | 364 |

4.5.2 Code Complexity

Language Implementation Code complexity is dependent on how many paradigms the programmer must use and how many control flows must be managed [3]. Our expectation is that since JPL uses fewer programming languages and paradigms than JAPyL in implementation, the code complexity will be less.

However, our experiments reveal that the structural code complexity needed to interoperate the components and PHP language in JPL is slightly higher when compared to JAPyL based on Cyclomatic Complexity. Table 6 shows that JAPyL has a rating of 19 when compared to 21 in JPL. This means that the code in JPL has more control flows that have to be managed.

This is crucial because despite having fewer lines of codes, a higher complexity number means that the programmer may have to deal with more control paths in the JPL code which could lead to more unexpected results and defects such as poor performance and higher resource consumption due to interoperation. Casti et al. state that just because a system or application has fewer components or layers does not usually make it simpler or less complex. You still have to take into account the processes and behaviour interactions which may be impacted as well as the compatibility factor between system components and languages [3].

5 Conclusion

Summary We have explored whether reducing the number of tiers/components eases the construction of web applications by reducing interoperability. We did so by systematically comparing the 4-tier JAPyL and 3-tier JPL web stacks (Section 3). The key findings from our case study are as follows.

Performance Eliminating the Apache component, and associated interoperation, in JPL and replacing it with a PHP threaded library increases latency (Figure 5) and reduces throughput (Figure 7). We believe this reflects that the Apache thread management is far superior to that provided by the PHP React library (Section 4.2).
**Table 5. Implementation Languages and Paradigm Comparison.**

| Functionality      | JAPyL | JPL   | JAPyL | JPL   |
|--------------------|-------|-------|-------|-------|
| Embed Notebook     | HTML  | HTML  | Declarative | Declarative |
| Host Webpage       | Apache Configs | PHP | Declarative | Imperative |
| Reverse Proxy      | Apache Configs | PHP | Declarative | Imperative |
| Security Settings  | Apache Configs | PHP | Declarative | Imperative |
| Language Processing| Python | PHP | Object-Oriented | Object-Oriented |
| Messaging          | JSON  | PHP | Data Serialization | Imperative |
| **Total**          | 4     | 2    | 3     | 2     |

**Table 6. Cyclomatic Complexity (cc)**

| Functionality      | JAPyL | JPL |
|--------------------|-------|-----|
| Embed Notebook     | 1     | 1   |
| Host Webpage       | 1     | 1   |
| Reverse Proxy      | 1     | 1   |
| Security Configs   | 1     | 5   |
| Language Processing| 13    | 1   |
| Messaging          | 2     | 12  |
| **Total**          | 19    | 21  |

**Resource Consumption** Despite replacing Apache, JPL consumes more resources. JPL uses 30% more core cycles, and (Figure 9), and we believe that this is due to Apache being better at thread management. JPL uses 33% more memory (Table 1) as PHP is much larger (390Mb) than Apache (165Mb) (Section 4.3).

**Security** provided by JPL and JAPyL is almost identical, although hand-written PHP in JPL can provide additional capabilities, e.g. automating the handling of security headers. This is a benefit of the lower-level imperative security coding (Section 4.4).

**Programmability** Eliminating the Apache tier/component results in the following. There is a reduction in number of programming languages and paradigms utilised (Table 3) and a smaller code size (Table 4) when compared to JAPyL. This means less developer effort for stack implementation and reduced chances of semantic friction.

**Reflection.** We anticipated that eliminating a tier/ component would simplify the stack. By reducing interoperability we hoped to improve performance and security, and to reduce resource consumption and programming effort. Our JAPyL/JPL study confounded these expectations. It is possible that substituting Apache with PHP was a poor decision, and that using a language with better memory management and support for multi-threading, like Erlang or Go, would meet these expectations.

**Future work** will further investigate replacing monolithic stack components with programming language technologies for a variety of stacks, domains, and programming languages. We intend that tier elimination has minimal impact on an application stack’s function, but seek to explore potential non-functional benefits. To this end we are currently comparing a conventional, and a tierless Clean iTask/mTask, implementation of a smart campus IoT stack.

**References**

[1] R. Adrian, S. Jeremy, and P. Trinder. Online appendix: Do fewer tiers mean fewer tears?, 2020. [http://www.dcs.gla.ac.uk/~ramsad/papers/FewerTiersAppendix.pdf](http://www.dcs.gla.ac.uk/~ramsad/papers/FewerTiersAppendix.pdf).

[2] E. Barrett, C. F. Bolz, L. Diekmann, and L. Pratt. Fine-grained language composition: A case study. *arXiv preprint arXiv:1503.08623*, 2015.

[3] J. L. Casti. On system complexity: Identification, measurement, and management. In *Complexity, language, and life: Mathematical approaches*, pages 146–173. Springer, 1986.

[4] I. K. Chaniotis, K.-I. D. Kyriakou, and N. D. Tselikas. Is node.js a viable option for building modern web applications? a performance evaluation study. *Computing*, 97(10):1023–1044, 2015.

[5] E. Cooper, S. Lindley, P. Wadler, and J. Yallop. Links: Web programming without tiers. In *International Symposium on Formal Methods for Components and Objects*, pages 266–296. Springer, 2006.

[6] B. Dayley. *Node.js, MongoDB, and AngularJS web development*. Addison-Wesley Professional, 2014.

[7] D. Endler. The evolution of cross site scripting attacks. Technical report, Technical report, iDEFENSE Labs, 2002.

[8] B. N. Freeman-Benson. Kaleidoscope: mixing objects, constraints, and imperative programming. In
[9] J. J. Gough and K. J. Gough. Compiling for the Net Common Language Runtime. Prentice Hall PTR, 2001.

[10] M. Grimmer, R. Schatz, C. Seaton, T. Würthinger, M. Luján, and H. Mössenböck. Cross-language interoperability in a multi-language runtime. ACM Transactions on Programming Languages and Systems (TOPLAS), 40(2):8, 2018.

[11] C. Ireland, D. Bowers, M. Newton, and K. Waugh. A classification of object-relational impedance mismatch. In 2009 First International Conference on Advances in Databases, Knowledge, and Data Applications, pages 36–43. IEEE, 2009.

[12] J. Lee and B. Ware. Open Source Web Development with LAMP: Using Linux, Apache, MySQL, Perl, and PHP. Addison-Wesley Professional, 2003.

[13] R. Lerdorf, K. Tatroe, B. Kaehms, and R. McGredy. Programming Php. " O'Reilly Media, Inc.," 2002.

[14] W. H. Li, D. R. White, and J. Singer.Jvm-hosted languages: they talk the talk, but do they walk the walk? In Proceedings of the 2013 International Conference on Principles and Practices of Programming on the Java Platform: Virtual Machines, Languages, and Tools, pages 101–112. ACM, 2013.

[15] J. W. Lloyd. Practical advtanges of declarative programming. In GULP-PRODE (1), pages 18–30, 1994.

[16] M. Milligan. Interactive hpc gateways with jupyter and jupyterhub. In Proceedings of the Practice and Experience in Advanced Research Computing 2017 on Sustainability, Success and Impact, page 63. ACM, 2017.

[17] C. Northwood. The Full Stack Developer: Your Essential Guide to the Everyday Skills Expected of a Modern Full Stack Web Developer. Springer, 2018.

[18] I. Ristic. Apache security. O’Reilly Media, 2005.

[19] A. Rule, A. Tabard, and J. D. Hollan. Exploration and explanation in computational notebooks. In Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems, page 32. ACM, 2018.

[20] M. Serrano, E. Gallesio, and F. Loitsch. Hop: a language for programming the web 2. 0. In OOPSLA Companion, pages 975–985, 2006.