Garbage Collection in JyNI – How to bridge Mark/Sweep and Reference Counting GC

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Abstract—Jython is a Java-based Python implementation and the most seamless way to integrate Python and Java. It achieves high efficiency by compiling Python code to Java bytecode and thus letting Java’s JIT optimize it—an approach that enables Python code to call Java functions or to subclass Java classes. It enables Python code to leverage Java’s multithreading features and utilizes Java’s built-in garbage collection (GC). However, it currently does not support CPython’s C-API and thus does not support native extensions like NumPy and SciPy. Since most scientific code depends on such extensions, it is not runnable with Jython.

Jython Native Interface (JyNI) is a compatibility layer that aims to provide CPython’s native C extension API on top of Jython. JyNI is implemented using the Java Native Interface (JNI) and its native part is designed to be binary compatible with existing extension builds. This means Jython can import the original C extensions, i.e., the same .dll- or .so-files that CPython would use.

For various reasons, implementing CPython’s C-API is not an easy task. Just to name a few issues—it offers macros to access CPython internals, uses a global interpreter lock (GIL) in contrast to Jython and lets extensions perform reference-counting-based GC, which is incompatible with Java’s GC approach. For each of the arising issues, JyNI proposes a feasible solution; most remarkably it emulates CPython’s reference-counting GC on top of Java’s mark-and-sweep-based approach (taking care of adjacent concepts like finalizers and weak references and their interference with Jython). (Note that there are vague considerations around to switch to mark-and-sweep-based GC in a future CPython too; cf. [PY3.PL15]. So this algorithm might one day be even relevant to CPython in terms of running legacy modules.)

This work’s main purpose is to describe the algorithm JyNI uses to support GC in detail, also covering weak references and testing native memory management. Beside this we give a comprehension of JyNI’s general design and briefly describe how it deals with CPython’s GIL. Finally we provide runnable code examples, e.g., a demonstration of JyNI’s support for the ctypes extension and a first experimental import of NumPy.

Index Terms—Jython, Java, Python, CPython, extensions, integration, JNI, native, NumPy, C-API, SciPy, GC

1 INTRODUCTION

As interpreter-based languages, Python and Java both depend on native language bindings/extensions in many scenarios. Especially scientific code mostly relies on NumPy or native interfaces to some computation- or control-framework that connects Python to problem-specific hardware or libraries—a fact that usually ties this kind of code to CPython. Developing and maintaining such bindings is usually a difficult and error-prone task. One major goal of the JyNI-project is to let Python and Java—with the help of [JYTHON]—share their pools of language bindings, vastly enriching both ecosystems.

While Jython already enables Python code to access Java frameworks and also native JNI-based (Java Native Interface) C extensions, it currently locks out all extensions that use CPython’s native API [C-API]. Remember that this does not only affect the actual C extensions, but also all Python frameworks that have a—maybe single, subtle—dependency on such an extension. Dependencies can include:

- Libraries like NumPy that are written directly in terms of the C-API. These libraries, which in turn link native libraries like BLAS, are widely used in the Python ecosystem, especially in scientific code.
- [CYTHON] is a popular tool to build optimized C code from Python source that has been annotated with types and other declaration, using the C-API to link.
- The [CTYPES] and [CFFI] modules, comparable to [JNA] and [JNI] in the Java-world respectively, are other popular means of providing support for C bindings, also all written to use the C-API.
- [SWIG], [PYREX] (from which Cython was derived), Boost.Python ([BOOSTPY]) and [SIP] are further tools that create extensions using the C-API.

[JyNI] (Jython Native Interface) is going to improve this situation. It is a compatibility layer that implements CPython’s C-API on top of JNI and Jython. This way it enables Jython to load native CPython extensions and use them the same way as one would do in CPython. To leverage this functionality, no modification to Python code or C extension source code is required—one just needs to add JyNI.jar to Jython’s classpath (along with its binary libraries). That means JyNI is binary compatible with existing builds of CPython extensions.

Developing JyNI is no trivial task, neither is it completed yet. Main reason for this is Python’s rather complex C-API that allows to access internal structures, methods and memory positions directly or via C preprocessor macros (in some sense CPython simply exposes its own internal API via a set of public headers). Existing extensions frequently do make use of this, so it is not a purely academical concern. Concepts like Python’s global interpreter lock (GIL), exception handling and
None of the named approaches reached a sufficient level of functionality/compatibility, at least not for current language versions (some of them used to work to some extent, but became unmaintained). In the Python ecosystem the C extension API has been an ongoing issue since its beginning. PyPy famously has been encouraging developers to favor CFFI over C extension API, as it is the only existing approach that has been designed to be well portable to other Python implementations. However, even if this effort would work out, there would be so many legacy extensions around that a serious move to CFFI won’t be done in foreseeable future.

For some of these projects JyNI’s GC-approach might be a relevant inspiration, as they face the same problem if it comes to native extensions. There are even vague considerations for CPython to switch to mark-and-sweep-based GC one day to enable a GIL-free version (c.f. [PY3_PL15]). Background here is the fact that reference-counting-based garbage collection is the main reason why CPython needs a GIL: Current reference counters are not atomic and switching to atomic reference counters yields insufficient performance. In context of a mark-and-sweep-based garbage collection in a future CPython the JyNI GC-approach could potentially be adopted to support legacy extensions and provide a smooth migration path.

### 2 Implementation

In order to bridge Jython’s and CPython’s concepts of PyObject, we apply three different techniques, depending on the PyObject’s implementation details.

![Diagram of Approaches to bridge PyObjs](image)

**Fig. 1: Approaches to bridge PyObjects.** Left: Native PyObject wraps Java. Center: Java-PyObject wraps native one. Right: Objects are mirrored.

The basic approach is to back the C-API of PyObject by a Java-PyObject via JNI. This would avoid data synchronization issues, but is only feasible if there are matching counterparts of the PyObject type in Jython and CPython (fig. 1, left). For CPython-specific types we can do it the other way round (fig. 1, center). Another problem is that CPython API defines macros in public headers that access PyObjects’ internal data. To deal with these, we sometimes have to mirror the object (fig. 1, right). This might involve data synchronization issues, but luckily macros mostly exist for immutable types, so initial synchronization is sufficient. [JyNI_EP13] describes this in more detail.

- Our plan is to support the CPython-variant of CFFI in JyNI as an alternative to the ideal approach of a direct port. Creating a true Jython version of CFFI would be a distinct project and was partly done based on [JNR]/JFFI.

1. This yields advantages and disadvantages compared to JyNI; discussing these is out of scope for this work.
2.1 Global interpreter lock

As mentioned before, CPython needs a GIL, because its reference-counting-based GC uses non-atomic reference counters. That means that CPython is entirely single-threaded in its usual operation mode. A native extension can explicitly release the GIL by inserting the macros \texttt{Py\_BEGIN\_ALLOW\_THREADS} and \texttt{Py\_END\_ALLOW\_THREADS} to deal with multiple threads and related things like input events (e.g. Tkinter needs this). In the potentially multithreaded code between these macros it is the extension’s own responsibility to refrain from non-thread-safe operations like incrementing or decrementing reference counters. This can be error-prone and challenging as the extension must ensure this also for eventually called external methods.

Jython on the other hand has no GIL and is fully multithreaded based on Java’s threading architecture. This does not mean multithreading would be trivial – one still has to care for concurrency issues and thread synchronization, but the whole machinery Java came up with for this topic is available to deal with it.

From JyNI’s perspective this is a difficult situation. On one hand we want to avoid regressions on Jython-site, especially regarding an important feature like GIL-freeness. On the other hand, native C extensions might rely on CPython’s GIL. So as a compromise JyNI provides a GIL for native site that is acquired by any thread that enters native code. On returning to Java code, i.e. finishing the native method call, the JyNI-GIL is released. Note that re-entering Java-site by doing a Java call from a native method would not release the GIL. In case it is desired to release the GIL for such a re-entering of Java-site or in some other situation, JyNI also supports \texttt{Py\_BEGIN\_ALLOW\_THREADS} and \texttt{Py\_END\_ALLOW\_THREADS} from CPython. This architecture implies that multiple threads can exist on Java-site, while only one thread can exist on native site at the same time (unless allow-threads macros are used). When combining multithreaded Jython code with JyNI it is the developer’s responsibility to avoid issues that might arise from this design.

3 Garbage Collection

While there are standard approaches for memory management in context of JNI, none of these is applicable to JyNI. In this section we sketch the default approaches, illustrate why they fail and finally provide a feasible solution.

3.1 Why is Garbage Collection an issue?

Consider a typical JNI-scenario where a native object is accessed from Java. Usually one would have a Java-object (a “peer”) that stores the native memory address of the C-object (i.e. a pointer to it) in a \texttt{long\_field}. The naive approach to do memory management would be a \texttt{finalize\textunderscore method} in the peer-class. This finalizer would then trigger a native \texttt{free\_call} on the stored memory-handle. However, finalizers are considered bad style in Java as they impact GC-efficiency. The recommended approach for this scenario is based on weak references and a reference-queue (c.f. [JREF]).

![Ordinary JNI memory management](image1)

**Fig. 2:** Ordinary JNI memory management

![A native peer backed by a Java-object](image2)

**Fig. 3:** A native peer backed by a Java-object

To prevent Java-GC from destroying the Java-backend while it is in use, JNI offers the concept of global references – JNI-\texttt{GlobalRef}\_objects. However, native code must explicitly create and release such global references. During the lifetime of a native global reference the Java-site referent is immortal. Now consider the referent would hold further references to other Java-objects. The reference chain could at some point include an object that is a peer like shown in figure 2. This peer would keep alive a native object by holding a reference-increment on it. If the native object also holds reference-increments of other native objects this can create a pathological reference cycle like illustrated in figure 4.

This kind of cycle cannot be cleared by Java-GC as the \texttt{GlobalRef} prevents it. Native reference cycle search like known from CPython could not resolve the cycle either, because it cannot be traced through Java-site. For debugging purposes we actually added a traverseproc-mechanism to Jython that would allow to trace references through Java-site, but to clear such a cycle in general just tracing Java-site references is not sufficient; Java-site reference counting would...
be required. This in turn would Jython require to have a GIL, which would be an unacceptable regression.

3.2 How JyNI solves it (basic approach)

To solve this issue, JyNI explores the native reference graph using CPython’s traverseproc mechanism. This is a mechanism PyObjects must implement in order to be traceable by CPython’s garbage collector, i.e. by the code that searches for reference cycles. Basically a PyObject exposes its references to other objects this way. While JyNI explores the native reference graph, it mirrors it on Java-site using some minimalistic head-objects (JyNIGCHead): see figure 5. Note that with this design, also Java-objects, especially Jython-PyObjects can participate in the reference graph and keep parts of it alive. The kind of object that needed a JNI-GlobalRef in figure 4, can now be tracked by a JNI-WeakGlobalRef while it is kept alive by the mirrored reference graph on Java-site as figure 5 illustrates.

If a part of the (native) reference-graph becomes unreachable (figure 6), this is reflected (asynchronously) on Java-site. On its next run, Java-GC will collect this subgraph, causing weak references to detect deleted objects and then release native references.

3.3 How JyNI solves it (hard case)

The fact that the reference-graph is mirrored asynchronously can lead to bad situations. While JyNI features API that allows C code to report changes of the graph, we cannot enforce third-party-written native extensions to report such changes. However, we made sure that all built-in types instantaneously send updates to Java-site on modification.

Now consider that a native extension changes the reference graph silently (e.g. using macro access to a PyObject) and Java’s GC runs before this change was mirrored to Java-site. In that case two types of errors could normally happen:

1) Objects might be deleted that are still in use
2) Objects that are not in use any more persist

The design applied in JyNI makes sure that only the second type of error can happen and this only temporarily, i.e. objects might persist for an additional GC-cycle or two, but not forever. To make sure that the first kind of error cannot happen, we check a to-be-deleted native reference subgraph for inner consistency before actually deleting it.

If not all native reference counts are explainable within this subgraph (c.f. figure 7), we redo the exploration of participating PyObjects and update the mirrored graph on Java-site.

While we can easily recreate the GC-heads, there might be PyObjects that were weakly reachable from native site and were swept by Java-GC. In order to restore such objects, we must perform a resurrection (c.f. figure 9).
The term “object-resurrection” refers to a situation where an object was garbage-collected, but has a finalizer that restores a strong reference to it. Note that while resurrection is not recommended – actually the possibility of a resurrection is the main reason why finalizers are not recommended – it is a legal operation. So certain GC-heads need to be able to resurrect an underlying Jython-PyObject and thus must have a finalizer. Since only certain objects can be subject to a silent reference-graph modification, it is sufficient to let only GC-heads attached to these objects implement finalizers – we use finalizers only where really needed.

3.4 Testing native garbage collection

Since the proposed garbage collection algorithm is rather involved, it is crucial to have a good way to test it. To achieve this we developed a monitoring concept that is capable of tracking native allocations, finalizations, re- and deallocations. The class JyNI.JyReferenceMonitor can – if native monitoring is enabled – list at any time all natively allocated objects, their reference counts, timestamps for allocation, finalization, re- and deallocations and the corresponding code positions (file and line-number) that performed the memory operations. Unless explicitly cleared, it can also provide history of these actions. The method listLeaks() lists all currently allocated native objects (actually these are not necessarily leaks, if the method is not called at the end of a program or test). While listLeaks() is useful for debugging, getCurrentNativeLeaks() provides a list that is ideal for unit testing. E.g. one can assert that no objects are leaked:

```python
from JyNI import JyReferenceMonitor as monitor
...
self.assertEqual(
    len(monitor.getCurrentNativeLeaks()), 0)
```

The native counterpart of JyNI.JyReferenceMonitor is JyRefMonitor.c. Its header defines the JyNIDebug macro family, which we insert into C code wherever memory operations occur (mainly in obmalloc.c and various inlined allocations in stringobject.c, inobject.c etc.).

Consider the following demonstration code:

```python
demoExtension.argCountToString(lst)
def _print_monitor_monitor.listLeaks()
system.gc()
time.sleep(2)
print "Leaks after GC:"
monitor.listLeaks()
```

It creates a reference cycle, passes it to a native function and deletes it afterwards. By passing it to native code, a native counterpart of lst was created, which cannot be cleared without some garbage collection (also in CPython it would need the reference cycle searching GC). We list the leaks before calling Java’s GC and after running it. The output is as follows:

```
Leaks before GC:
Current native leaks:
1406405747208_GC (list) #2:
  "((...), ', 'test'),"_j #3 *38
14064057457768_GC (tuple) #1:
  "((...), ', 'test'),"_j #3 *38
14064057461832 (str) #2: "test"_j #3 *38
14064057457856_GC (tuple) #3:
  "((...), ', 'test'),"_j #3 *38
Leaks after GC: no leaks recorded
```

We can see that it lists some leaks before running Java’s GC. Each line consists of the native memory position, the type (in parentheses), the current native reference count indicated by #, a string representation and the creation time indicated by * in milliseconds after initialization of the JyReferenceMonitor class. The postfix _GC means that the object is subject to garbage collection, i.e. it can hold references to other objects and thus participate in cycles. Objects without _GC will be directly freed when the reference counter drops to zero. The postfix _j of the string representation means that it was generated by Jython rather than by native code. We close this section by discussing the observed reference counts:

- The list-object has one reference increment from its JyGCHead and the other from the tuple at the bottom of the output.
- The first-listed tuple is the argument-tuple and only referenced by its JyGCHead.
- The string is referenced by its JyGCHead and the list.
- The tuple at the bottom is referenced by its JyGCHead, by the list and by the argument-tuple.

4 Weak References

Supporting the PyWeakRef built-in type in JyNI is not as complicated as garbage collection, but still a notably involved task. This is mainly due to consistency requirements that are not trivial to fulfill.

- If a Jython weakref-object is handed to native site, this shall convert to a CPython weakref-object and vice versa.
- If native code evaluates a native weakref, it shall return exactly the same referent-PyObject that would have been created if the Java-pendant (if one exists) was evaluated and the result was handed to native site; also vice versa.
If a Jython weak reference is cleared, its native pendant shall be cleared either. Still, none of them shall be cleared as long as its referent is still alive.

This implies that even if a Jython referent-PyObject was deleted (can happen in mirror-case) Jython weakref-objects stay alive as long as the native pendant of the referent is alive. If evaluated, such a Jython weakref-object retrieves the Jython referent by converting the native referent.

An obvious requirement is that this shall of course work without keeping the referents alive or creating some kind of memory leak. JyNI’s delicate GC mechanism must be taken into account to fulfill the named requirements in this context.

In the following, we explain JyNI’s solution to this issue. We start by explaining the weakref-concepts of Jython and CPython, completing this section by describing how JyNI combines them to a consistent solution. Note that CPython’s weakref-module actually introduces three built-in types:

• 
  _PyWeakref_RefType (“weakref”)
• 
  _PyWeakref_ProxyType (“weakproxy”)
• 
  _PyWeakref_CallableProxyType (“weakcallableproxy”)

4.1 Weak References in Jython

In Jython the package org.python.modules._weakref contains the classes that implement weak reference support.

• ReferenceType implements the “weakref”-built-in
• ProxyType implements the “weakproxy”-built-in
• CallableProxyType implements the “weakcallableproxy”-built-in

All of them extend AbstractReference, which in turn extends PyObject.

4.2 Weak References in CPython

In CPython, each weakref-type simply contains a reference to its referent without increasing reference count.

4.3 Weak References in JyNI

JyNI’s weak reference support is grounded on CPython’s approach on native site and Jython’s approach on Java-site. However, the actual effort is to bridge these approaches in a consistent way. To fulfill the requirement for consistent clear-status, we establish a “Java-referent dies first”-policy. Instead of an ordinary GlobalRef, JyNI uses a subclass called NativeGlobalRef. This subclass holds a reference-increment for the native counterpart of its referent. This ensures that the native referent cannot die as long as Jython weak references exist (see figure 12). Otherwise, native weak references might be cleared earlier than their Jython-pendants. Note that the native ref-increment held by NativeGlobalRef cannot create a reference-cycle, because it is not reflected by a JyNIGCHead as seen in figure 5. Also, the consistency-check shown in figure 7 takes this ref-increment into account, i.e. tracks ref-increments coming from NativeGlobalRef’s separately.

Fig. 11: CPython’s concept for weak references

Figure 11 shows that – like in Jython – referents track weak references pointing to them; in this case references are stored in a double-linked list, allowing to iterate them for callback-processing.

Fig. 12: JyNI’s concept for weak references

As figure 10 illustrates, Jython creates only one Java-style weak reference per referent. This is created in form of a GlobalRef-object, which extends java.lang.ref.WeakReference. It stores all Jython weak references pointing to it in a static, weak-referencing map. This is needed to process potential callbacks when the reference is cleared. Once created, a GlobalRef is tied to its referent, kept alive by it and is reused throughout the referent’s lifetime. Finally, AbstractReference-subclasses refer to the GlobalRef corresponding to their actual referent.

Fig. 13: JyNI weak reference after Java-referent was collected

If the Jython-referent and its native pendant are handled in mirror-mode, it can happen that the Java-referent is garbage-
collected while the native one persists. As soon as the Jython-referent is collected, its NativeGlobalRef releases the native reference-increment (see figure 13). Still, it will not be cleared and process callbacks, before also the native referent dies. Until then, NativeGlobalRef continues to be valid – it implements its get-method such that if the Jython-referent is not available, it is recreated from the native referent. As long as such a retrieved referent is alive on Java-site, the situation in figure 12 is restored.

5 EXAMPLES
The code-samples in this section are runnable with Jython 2.7.1 and JyNI 2.7-alpha.3 or newer (alpha.4 for NumPy-import).

5.1 Using Tkinter from Java
In [JyNI_EP13] we demonstrated a minimalistic Tkinter example program that used the original Tkinter binary bundled with CPython. Here we demonstrate how the same functionality can be achieved from Java code. This confirms the usability of Python libraries from Java via Jython and JyNI. While the main magic happens in Jython, it is not completely self-evident that this is also possible through JyNI and required some internal improvements to work. Remember the Tkinter-program from [JyNI_EP13]:

```python
import sys
# Include native Tkinter:
sys.path.append('/usr/lib/python2.7/lib-dynload')
sys.path.append('/usr/lib/python2.7/lib-tk')
from Tkinter import *
root = Tk()
txt = StringVar()
txt.set("Hello World!")
def print_text():
    print txt.get()

def print_time_stamp():
    from java.lang import System
    print "System.currentTimeMillis: "+str(System.currentTimeMillis())

Label(root,
    text="Welcome to JyNI Tkinter-Demo!").pack()
Entry(root, textvariable=txt).pack()
Button(root, text="print text",
    command=print_text).pack()
Button(root, text="print timestamp",
    command=print_time_stamp).pack()
Button(root, text="Quit",
    command=root.destroy).pack()
root.mainloop()
```

To translate the program to Java, we must provide type-information via interfaces:

```java
import org.python.core.*;

public static interface Entry {
    public void pack();
}

public static interface Tk {
    public void mainloop();
    public void destroy();
}

public static interface StringVar {
    public String get();
    public void set(String text);
}

public static interface Label {
    public void pack();
}

public static interface Button {
    public void pack();
}
```

We define the methods backing the button-actions as static methods with a special Python-compliant signature:

```java
public static void printText(PyObject[] args, String[] kws) {
    System.out.println(txt.get());
}

public static void printTimeStamp(PyObject[] args, String[] kws) {
    System.out.println("System.currentTimeMillis: "+
                      System.currentTimeMillis());
}

public static void destroyRoot(PyObject[] args, String[] kws) {
    root.destroy();
}
```

On top of this a rather Java-like main-method can be implemented. Note that constructing objects is still somewhat unhandy, as keywords must be declared in a string-array and explicitly passed to Jython. Calling methods on objects then works like ordinary Java code and is even type-safe based on the declared interfaces.

```java
public static void main(String[] args) {
    PySystemState pystate = Py.getSystemState();
    pystate.path.add("/usr/lib/python2.7/lib-dynload");
    pystate.path.add("/usr/lib/python2.7/lib-tk");
    PyModule tkModule = (PyModule)imp.importName("Tkinter", true);
    root = tkModule.newJ(Tk.class);
    txt = tkModule.newJ(StringVar.class);
    txt.set("Hello World!");
    Label lab = tkModule.newJ(Label.class,
        new String[]{"text"}, root,
        "Welcome to JyNI Tkinter-Demo!");
    lab.pack();
}
```
5.2 Using native ctypes

As of version alpha.3 JyNI has experimental support for [CTYPES]. The following code provides a minimalist example that uses Java- and C-API. Via an std-lib C-call we obtain system time and print it using Java console.

```python
import sys
sys.path.append('/usr/lib/python2.7/lib-dynload')
import ctypes
from java.lang import System
libc = ctypes.CDLL('libc.so.6')
print libc
print libc.time
System.out.println('Timestamp: ' + str(libc.time(0)))
```

The output is as follows:

```
<CDLL 'libc.so.6', handle 83214548 at 2>
<_FuncPtr object at 0x7f897c7165d8>
Timestamp: 1446170809
```

Note that Jython already features an incomplete ctypes-module based on JFFI (which is part of [JNI]). Without JyNI the output would look as follows:

```
<ctypes.CDLL instance at 0x2>
(FuncPtr object at 0x7f897c7165d8>
Timestamp: 1446170809
```

E.g. operations involving floating point numbers fail as of this writing, so a usable support is still in some distance. Considering its vast complexity, mastering NumPy’s importscript `numpy/__init__.py` is yet a crucial milestone on this front.

Major challenges here were dependencies on several other extensions. E.g. NumPy depends on ctypes and datetime (i.e. on datetime’s C-API, rendering the Jython-variant of datetime insufficient) – see ctypes example in 5.2 and datetime example in [JyNI_EP13].

NumPy also contains Cython-generated code, which results in huge and hard to read C source-files. E.g. `mtrand.c` from NumPy’s random module contains more than 40,000 lines of code, making it a true challenge to debug. In this sense the feasible NumPy-import also demonstrates a basic Cython-capability of JyNI alpha.4.

6 Roadmap

While NumPy- and SciPy-support is the driving motivation for the JyNI-project (since these extensions are of most scientific importance), it is very hard to assess how much work will be needed to actually reach this goal. Determining even the feasibility of full NumPy support beforehand would be a project for itself, so we focus on taking one hurdle by another, converging to full NumPy support as far as possible.

Another important goal is better cross-platform support. Currently JyNI works (i.e. is tested) with Linux and OSX and hypothetically (i.e. untested) with other POSIX systems.

The planned main features for the next release (alpha.5) are support for the buffer protocol and improved NumPy-support. More testing with Cython and improved support will be addressed after JyNI alpha.5.

References

[JyNI] Stefan Richthofer, Jython Native Interface (JyNI) Homepage, http://www.JyNI.org, 2015-08-17, Web. 2016-07-01
