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(54) **SCALABLE AND SEAMLESS EXECUTION OF PYTHON NOTEBOOK PARAGRAPHS ON LARGE-SCALE VMS THROUGH SNAPSHOTTING OF STATE**

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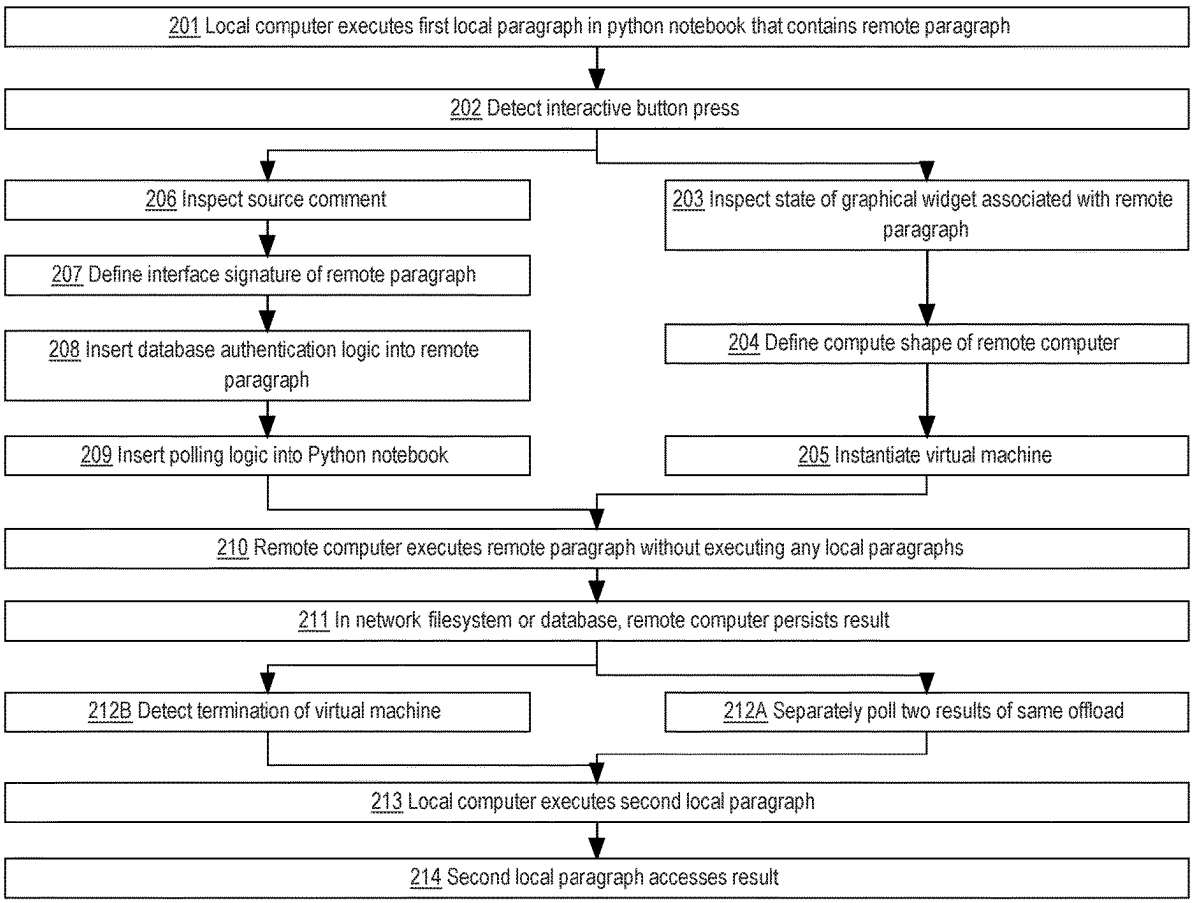
(57) **ABSTRACT**

Here is acceleration of Python based on novel notebook instrumentation that offloads a computationally intensive paragraph for remote execution. Python notebook paragraphs may be offloaded to custom virtual machines (VMs) by seamless snapshotting of notebook state. This enables the user to selectively execute paragraph(s) locally or on different VMs that cater to the specific computational requirements of each notebook paragraph. Diverse paragraphs may demand varying levels of computational resources. A notebook may run in the usual manner on a chosen VM shape (i.e. configuration of capabilities and capacities) and offload the execution of the most computationally intensive paragraphs to VMs with more powerful shapes when desired, while being able to resume execution in the starting VM in a seamless manner. In this elastic way, the user is able to vertically scale the execution and, for reliability, obtain an isolated (i.e. dedicated, not multitenant) environment.



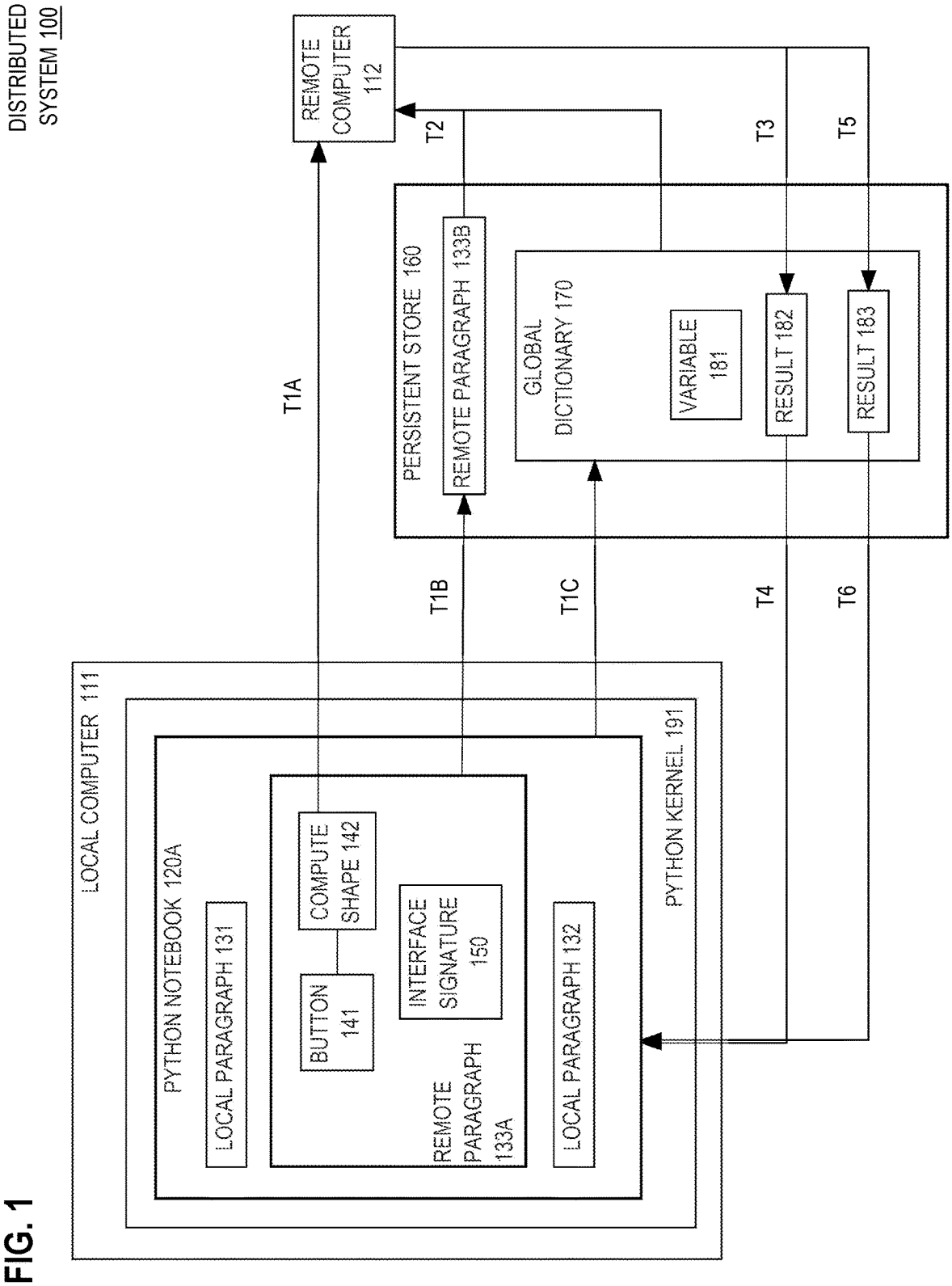
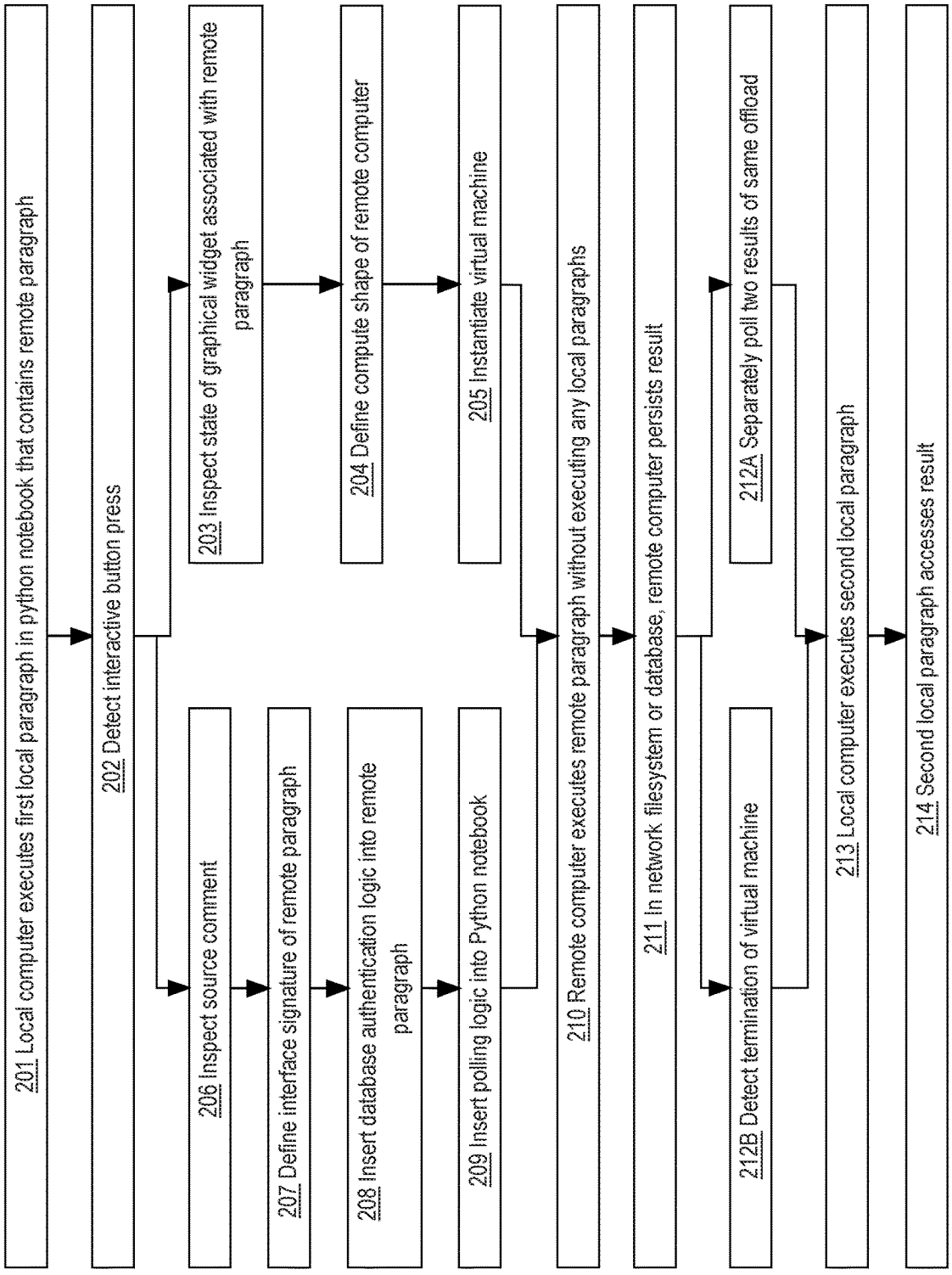

DISTRIBUTED SYSTEM 100
REMOTE COMPUTER 112
T1A
T2
T3
T5
PERSISTENT STORE 160
REMOTE PARAGRAPH 133B
GLOBAL DICTIONARY 170
VARIABLE 181
RESULT 182
RESULT 183
T1B
T1C
T4
T6
LOCAL COMPUTER 111
PYTHON NOTEBOOK 120A
LOCAL PARAGRAPH 131
COMPUTE SHAPE 142
BUTTON 141
INTERFACE SIGNATURE 150
REMOTE PARAGRAPH 133A
LOCAL PARAGRAPH 132
PYTHON KERNEL 191

FIG. 1

FIG. 2


201 Local computer executes first local paragraph in python notebook that contains remote paragraph
202 Detect interactive button press
206 Inspect source comment
207 Define interface signature of remote paragraph
208 Insert database authentication logic into remote paragraph
209 Insert polling logic into Python notebook
203 Inspect state of graphical widget associated with remote paragraph
204 Define compute shape of remote computer
205 Instantiate virtual machine
210 Remote computer executes remote paragraph without executing any local paragraphs
211 In network filesystem or database, remote computer persists result
212B Detect termination of virtual machine
212A Separately poll two results of same offload
213 Local computer executes second local paragraph
214 Second local paragraph accesses result

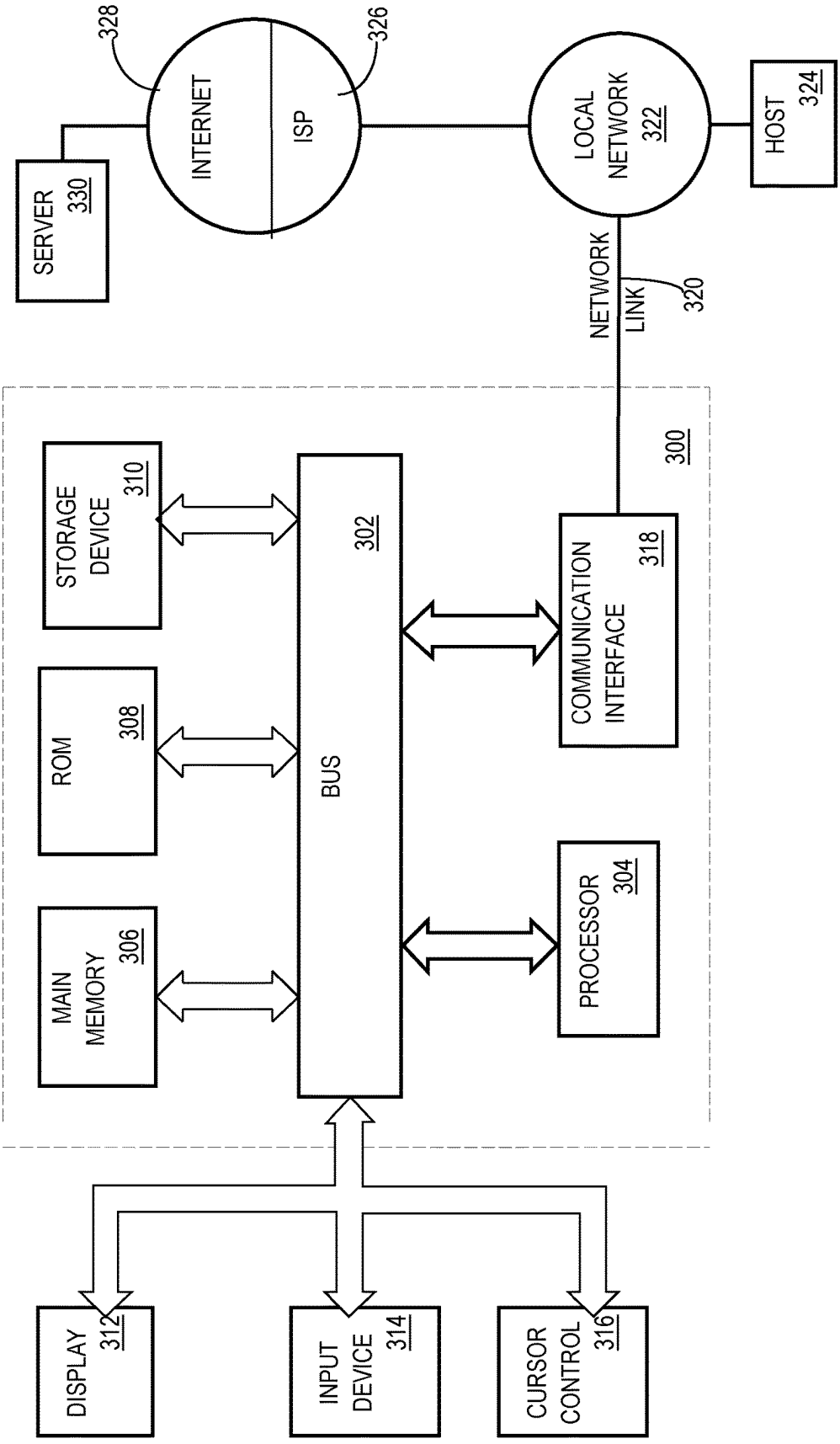

328
INTERNET
ISP
326
SERVER 330
LOCAL NETWORK 322
HOST 324
NETWORK LINK 320
300
STORAGE DEVICE 310
BUS 302
COMMUNICATION INTERFACE 318
ROM 308
MAIN MEMORY 306
PROCESSOR 304
DISPLAY 312
INPUT DEVICE 314
CURSOR CONTROL 316

FIG. 3

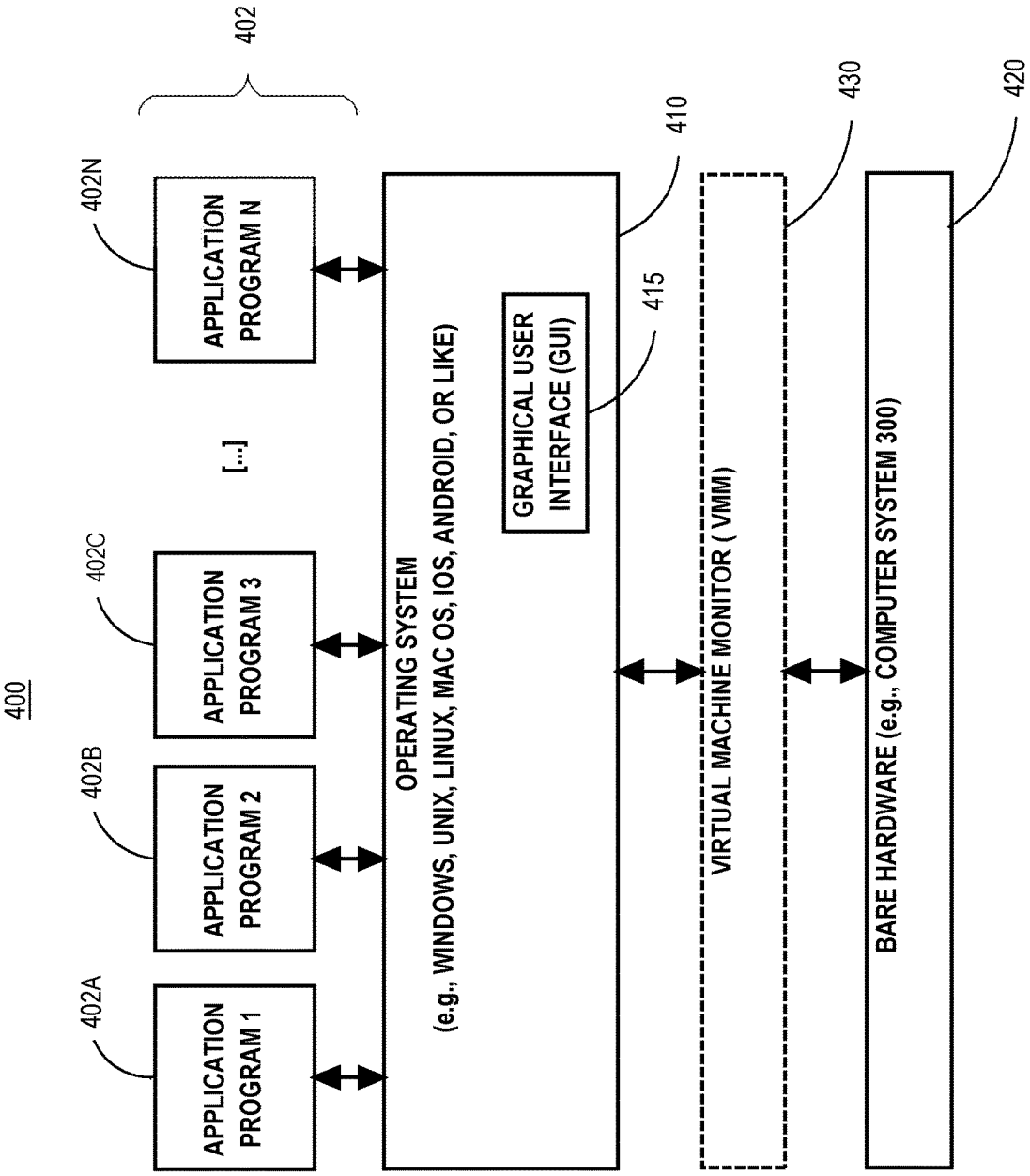

400
402
402A
APPLICATION PROGRAM 1
402B
APPLICATION PROGRAM 2
402C
APPLICATION PROGRAM 3
[...]
402N
APPLICATION PROGRAM N
OPERATING SYSTEM
(e.g., WINDOWS, UNIX, LINUX, MAC OS, IOS, ANDROID, OR LIKE)
GRAPHICAL USER INTERFACE (GUI)
415
410
VIRTUAL MACHINE MONITOR (VMM)
430
BARE HARDWARE (e.g., COMPUTER SYSTEM 300)
420

FIG. 4

SCALABLE AND SEAMLESS EXECUTION OF PYTHON NOTEBOOK PARAGRAPHS ON LARGE-SCALE VMS THROUGH SNAPSHOTTING OF STATE

FIELD OF THE DISCLOSURE

[0001] This disclosure relates to acceleration of interactive Python for data science. Novel notebook instrumentation offloads a computationally intensive paragraph for remote execution.

BACKGROUND

[0002] The current landscape of Python notebooks has a latency problem due to an absence of a user-friendly and low-overhead way to capture and resume a notebook's state in different execution environments. This deficiency becomes particularly evident in data science where computational demands often vary between distinct paragraphs in a same notebook. For example, a machine learning training paragraph often needs significantly more computational power than preliminary data analysis and preprocessing paragraphs.

[0003] An ordinary examples of intensive resource allocation for data science is XGBoost model preparation that typically imposes the following demands.

[0004] Large datasets: XGBoost needs large datasets to learn complex relationships and achieve high accuracy. Dataset processing may include cleaning, scaling, and feature engineering such as transformations and aggregations.

[0005] Model Training: Multiple decision trees are built sequentially, each splitting data based on an information gain criterion. Finding the optimal split at each node involves evaluating numerous possible splits.

[0006] Regularization and boosting: Many weak learners are combined into an ensemble.

[0007] Memory bottleneck: XGBoost algorithms heavily rely on random access to data during training. Large datasets might not fit entirely in random access memory (RAM), causing frequent and high-latency disk accesses.

[0008] Hyperparameter tuning: Finding the optimal combination of hyperparameters values involves numerous training runs.

[0009] In cloud environments, the problem is exacerbated. Computer resources are consumed by a powerful virtual or physical computer that is unnecessarily allocated for an entire session, and there is no mechanism to adaptively change the VM configuration during notebook execution. This not only results in excessive resource consumption but, in a multitenant environment such as a public cloud, may also cause starvation (i.e. interference by resource exhaustion) for one tenant by another tenant that share a same resource pool. Even modest concurrent machine learning tasks can strain powerful machines and lead to overallocation (i.e. inefficient resource utilization). For example, as many as nine tenants may concurrently share a virtual or physical computer.

[0010] Overallocation is a waste of time and space of computers. If a solution could avoid overallocation, space and time would be saved inside a computer.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] In the drawings:

[0012] FIG. **1** is a block diagram that depicts an example distributed system that accelerates interactive Python execution for data science based on novel notebook instrumentation by a local computer that offloads a computationally intensive paragraph for remote execution on a remote computer;

[0013] FIG. **2** is a flow diagram that depicts an example process that a local computer and a remote computer may cooperatively perform to accelerate interactive Python execution for data science based on novel notebook instrumentation for the local computer to offload a computationally intensive paragraph for remote execution on the remote computer;

[0014] FIG. **3** is a block diagram that illustrates a computer system upon which an embodiment of the invention may be implemented;

[0015] FIG. **4** is a block diagram that illustrates a basic software system that may be employed for controlling the operation of a computing system.

DETAILED DESCRIPTION

[0016] In the following description, for the purposes of explanation, numerous specific details are set forth in order to provide a thorough understanding of the present invention. It will be apparent, however, that the present invention may be practiced without these specific details. In other instances, well-known structures and devices are shown in block diagram form in order to avoid unnecessarily obscuring the present invention.

General Overview

[0017] Here is acceleration of interactive Python for data science based on novel notebook instrumentation that offloads a computationally intensive paragraph for remote execution. This is a technical solution for efficiently offloading the execution of Python notebook paragraphs to, for example, custom virtual machines (VMs) by seamless snapshotting of notebook state. This innovative approach enables the user to selectively execute paragraph(s) locally or on different VMs that cater to the specific computational requirements of each notebook paragraph. This technology is especially useful in data science and computational workloads, where diverse paragraphs demand varying levels of computational resources. By addressing this challenge, this approach not only optimizes computational resource utilization but also enhances user flexibility and resource efficiency in a cloud environment.

[0018] This technical solution solves the problem of resource overallocation, as discussed in the above Background, by allowing the user to run a notebook in the usual manner on a chosen VM shape (i.e. configuration of capabilities and capacities), and offload the execution of the most computationally intensive paragraphs to VMs with more powerful shapes when desired, while being able to resume execution in the starting VM in a seamless manner without the need for specific actions on the part of the user. In this elastic way, the user is able to vertically scale the execution and, for reliability, obtain an isolated (i.e. dedicated, not multitenant) environment. For the cloud provider and cloud tenants, this avoidance of overallocation prevents waste of computer resources.

[0019] This approach harnesses Python's globals dictionary to achieve reflective access to the dynamic state within a Python notebook. This novel approach facilitates capture, serialization, and persistence of a snapshot of the notebook's state for seamless resumption of execution in a different environment, which achieves vertical scaling on demand and at a per-paragraph granularity. This innovative functionality relies on the following important components.

[0020] Frontend Interaction: A user-friendly frontend element, potentially realized through an ipywidget or a similar graphical interface, serves as an interactive trigger for executing instrumentation responsible for implementing this functionality.

[0021] Intermediate Storage: An intermediary persistent storage system, which can be implemented using technologies such as a relational database or a (e.g. JavaScript object notation, JSON) document store, facilitates the exchange of notebook state between the local and remote VMs.

1.0 Example Distributed System

[0022] FIG. **1** is a block diagram that depicts example distributed system **100** that accelerates interactive Python execution for data science. Novel notebook instrumentation by local computer **111** offloads a computationally intensive paragraph for remote execution on remote computer **112**. Computers **111-112** may be one or more instances of a rack server such as a blade, a mainframe, or a virtual machine (VM).

[0023] Herein, a VM may contain its own operating system (OS) and/or simulated central processing unit (CPU) that are independent of the physical computer that hosts the VM. For example, the VM and the host computer may or may not have different instruction set architectures (ISA) and may or may not have different kinds or versions of OS's. Although not shown, computers **111-112** are interconnected by a communication network. Computers **111-112** may have same or different ISAs.

[0024] Herein, a program container directly uses and exposes the CPU and OS of the host computer. In an extreme example, either or both of computers **111-112** is a program container that is hosted in a VM that is hosted by a physical computer. Docker containerization is an example of a program container.

1.1 Python Paragraphs in Notebooks

[0025] Python is a high-level general-purpose scripting (i.e. interpreted) language with dynamic datatypes and garbage collection. Python natively supports important programing paradigms such as structured, object oriented, imperative, and functional. Herein, Python has two distinct source code formats, which are a script and a notebook. A Python script is a sequence of Python statements whose execution is monolithic such that most or all of the script executes to completion. A Python script may persist as a .py text file that has execute permission.

[0026] In contrast, a Python notebook is a sequence of Python paragraphs that can be executed individually or as a subset of adjacent paragraphs, such as by interactive selection in an integrated development environment (IDE). A Python paragraph, also referred to herein as a code cell, is a sequence of Python statements. A Python notebook may persist as a .ipynb JavaScript object notation (JSON) text file.

[0027] Because a paragraph and a script each is a sequence of statements, operation of a paragraph or script may be somewhat similar. Herein, execution of a script is heavyweight because the execution is independent. For example, an executing script may have its own address space and OS process.

[0028] Herein, executions of paragraphs in a notebook is lightweight because the executions occur in a Python kernel that is shared by all Python paragraphs in the notebook. For example, a Python kernel may provide a memory heap that is shared by all Python paragraphs in the notebook. Even if an object in the shared heap is no longer referenced by the paragraph that allocated the object, the Python kernel will not garbage collect the object if another paragraph still references the object. Thus, paragraphs may share data and state such as Python variables. For example, two paragraphs may access a same variable. Herein, all variables are presumed to be global variables, which means that they are accessible anywhere in a notebook and may, for example, be retained in the Python kernel until the kernel is terminated.

[0029] In an embodiment, a notebook may contain a mix of Python paragraphs and non-Python paragraphs that may contain source logic of other programming languages such as an interpreted language such as R or JavaScript, or a compiled language such as Java or C++. A paragraph may be repeatedly executed. For example, a first execution of a compiled-language paragraph may automatically entail compilation of the source logic of the paragraph to generate object code of the paragraph, which consists of bytecode or machine instructions that a central processing unit (CPU) can directly execute. A second execution of the already compiled paragraph does not entail compilation because the paragraph's object code is retained and reused, unless the paragraph is edited (i.e. revised) before the second execution, in which case recompilation occurs.

1.2 Offload of Remote Paragraph

[0030] In the shown example, python notebook **120**A is an original and un-instrumented notebook that local computer **111**: a) loads and partially executes locally (i.e. within local computer **111**) and b) instruments (i.e. inserts instrumentation) to generate remote paragraph **133**B to offload to remote computer **112** for remote execution. Local paragraphs **131-132** are optional and demonstrate various scenarios later herein. For example, a notebook may contain only remote paragraph(s).

[0031] Herein, execution of any local paragraph occurs in local computer **111**, and execution of any remote paragraph occurs in a computer other than local computer **111**. For example, separate executions of two remote paragraphs may occur on same or different remote computers such as remote computer **112**. Even though the two remote paragraphs may have discrepant resource requirements, the discrepant remote paragraphs may execute together in a same VM that is configured to satisfy the union of both paragraph's resource requirements. For example for a first execution, a first selection may include only the first remote paragraph, and the first execution occurs on a first VM. For a second execution that instead includes both remote paragraphs, a different VM with more resources may instead be used. In other words, different executions of the first paragraph may

occur on different VMs depending on which additional remote paragraphs should execute with the first paragraph. Resource-based assignment of remote paragraphs to remote computers is discussed later herein.

[0032] For example as discussed later herein, a space intensive remote paragraph may execute on a first remote computer that contains much memory, and a compute intensive remote paragraph may execute on a second remote computer that contains many processing cores. As discussed later herein, a remote computer may be a virtual machine (VM) that is dynamically created and configured with capabilities and capacities to suit particular remote paragraph(s). In a just-in-time (i.e. on demand) example, the VM is not created until the remote paragraph should execute. If the subset of notebook paragraph(s) selected for execution do not include a remote paragraph, no VM is created and no remote execution occurs even if the notebook contains an unselected remote paragraph.

[0033] In the shown example, remote paragraph **133**A is an original and un-instrumented paragraph that local computer **111** instruments to generate remote paragraph **133**B to offload to remote computer **112** for remote execution. Remote paragraph offloading may occur as discussed later herein and as follows. For example, offloading mechanisms may depend on the embodiment. The following is an example Python remote paragraph **133**A that begins with two line comments that define interface signature **150** as discussed later herein.

[0034] #inputs: depth, dataset_url, preprocessor, load_dataset

[0035] #outputs: model

[0036] model=RandomForestClassifier (max_depth=depth)

[0037] dataset=load_dataset (dataset_url)

[0038] dataset=dataset.transform (preprocessor)

[0039] model.fit (dataset)

1.3 Intermediate Persistent Store

[0040] Computers **111-112** are distinct network elements of a communication network. Depending on the embodiment, persistent store **160** may be a distinct network element or may be contained in one of computers **111-112**. Persistent store **160** provides more or less temporary storage of data and metadata exchanged between computers **111-112** as discussed below. In alternative embodiments, a) persistent store **160** is absent and replaced by a volatile store or b) persistent store **160** is absent and all data and metadata exchanged between computers **111-112** is directly transferred between computers **111-112**.

[0041] An advantage of persistent store **160** is that decoupling between computers **111-112** is increased, which increases the reliability of distributed system **100**. For example if remote computer **112** is a dynamically created VM, local computer **111** can stage data and metadata in persistent store **160** before remote computer **112** is created. For example: a) persistent store **160** may be a backlog queue for multiple pending offloads by multiple local computers and b) distributed system **100** may be a cloud that contains a central dispatcher that c) dequeues and dispatches one pending offload at a time when a physical computer becomes idle or reclaims sufficient unused resources, and d) the central dispatcher does not decide which physical computer in the cloud should host a VM for an offload until the offload is dequeued. In an embodiment, the cloud is a Simple Linux Utility for Resource Management (SLURM) data science cluster.

[0042] If remote computer **112** crashes while executing remote paragraph **133**B, the central dispatcher can repeat the same offload to a different remote computer without impacting Python kernel **191**. In various embodiments, local computer **111** never communicates directly with remote computer **112** or does not know that remote computer **112** exists. Indirect cooperation of computers **111-112** may occur in the following sequence of times T**1**-T**6**.

1.4 Example Interactive Offload Lifecycle

[0043] Times T**1**A-T**1**C may occur in any ordering or concurrently. In the following interactive embodiment, pressing button **141** in a Python IDE causes the sequence of times T**1**-T**6**. In various ways, the Python IDE may associate Python components **141-142** with remote paragraph **133**A. In an embodiment, Python components **141-142** are custom or proprietary graphical user interface (GUI) widgets at the beginning of remote paragraph **133**A that can be preloaded or scraped by Python components **120**A and **191** as discussed later herein.

[0044] For example, compute shape **142** may specify capabilities and/or resource capacities of remote computer **112**. In an embodiment, compute shape **142** specifies discrete capabilities and capacities. In another embodiment, compute shape **142** instead selects one predefined shape from a variety of predefined shapes.

[0045] For example, remote computer **112** may be an uncreated VM, and pressing button **141** may cause creation and configuration of remote computer **112** as specified by compute shape **142**. If dynamic creation of remote computer **112** is slow, pressing button **141** may, concurrent to time T**1**A, cause storing of Python components **133**B and **170** in persistent store **160** at times T**1**B-T**1**C.

[0046] Pressing button **141** may cause Python kernel **191** to generate remote paragraph **133**B from remote paragraph **133**A. Remote paragraphs **133**A-B may be identical except that: a) remote paragraph **133**B does not contain widgets **141-142**, and b) only remote paragraph **133**B may contain instrumentation.

1.5 Python Dictionary of Global Variables

[0047] At time T**1**C, Python component **120**A or **191** stores an exact copy (or an incomplete copy as discussed below) of global dictionary **170** into persistent store **160**. Although not shown, an original and identical global dictionary **170** is contained in Python kernel **191**.

[0048] Global dictionary **170** may be a predefined Python "globals" dictionary that is a hash table of the global variables of Python components **120**A and **191**. Global dictionary **170** and its global variables may be read or written by Python kernel **191** and by any shown Python component within Python kernel **191**. For example, one paragraph may write a global variable, and another paragraph may read the global variable. Thus through global dictionary **170**, multiple paragraphs may exchange data, metadata, and state as needed to cooperate. For example, a sequence of paragraphs may operate as respective stages of a Python pipeline through which data, metadata, and state flows from stage to stage.

[0049] Time T1A creates remote computer **112** and, at time T2, remote computer **112** creates a Python kernel (not shown) and Python notebook **120**B (not shown) that is not a copy of Python notebook **120**A. At time T2, those two newly created Python components begin executing in remote computer **112**, and they retrieve Python components **133**B and **170** from persistent store **160**. In other words, time T2 causes Python components **133**B and **170** to be loaded and operable in remote computer **112**.

1.6 Interface Signature

[0050] In an embodiment, global dictionary **170** in persistent store **160** is an incomplete copy of the global dictionary in Python kernel **191**. For example, interface signature **150** may specify (e.g. by name) a subset of global variables that remote paragraph **133**B can read and a subset of global variables that remote paragraph **133**B can write. That is, interface signature **150** may specify inputs and outputs of remote paragraph **133**B. In that case, global dictionary **170** consists of only a portion of the global dictionary in Python kernel **191**. In that case at time T1C, global dictionary **170** in persistent store **160** contains only the subset of global variables that will be inputs that will be read by remote paragraph **133**B as specified by interface signature **150**.

[0051] In an embodiment, interface signature **150** is annotation(s) in a comment at the beginning of remote paragraphs **133**A-B, and Python components in computers **111**-**112** may analyze interface signature **150** by analyzing the annotations in the comment. For example at time T1C, Python kernel **191** may inspect interface signature **150** in remote paragraph **133**A to detect which global variables are inputs that should be initially included in global dictionary **170**. For example, global variable **181** may be an input that local computer **111** writes and remote computer **112** reads.

[0052] In an embodiment, interface signature **150** is not part of a comment and instead is automatically generated based on dataflow analysis by a Python compiler. In that case, interface signature **150** specifies inputs and outputs that are automatically inferred by liveness analysis that statically detects which Python variables should be operated as inputs and outputs.

[0053] At time T2, the Python kernel in remote computer **112** copies global dictionary **170** from persistent store **160**. Thus at time T2, the more or less initially empty global dictionary in the Python kernel in remote computer **112** is replaced by global dictionary **170**, or the contents of global dictionary **170** supplement (i.e. are added to) that initial global dictionary. Between times T2-T3, remote paragraph **133**B executes in the Python kernel in remote computer **112**, which is faster than executing remote paragraph **133**A in local computer **111**. In other words, offloading remote paragraph(s) provides acceleration.

1.7 Return and use of Offload Results

[0054] As remote paragraph **133**B executes in remote computer **112**, partial results **182**-**183** are incrementally generated. Partial results **182**-**183** are global variables that are identified by name as outputs in interface signature **150**. At time T1C, global dictionary **170** in persistent store **160** does not contain results **182**-**183**, even though interface signature **150** names results **182**-**183** as outputs that remote paragraph **133**B will eventually generate.

[0055] In the following embodiment, asynchronous polling is used to detect completion of execution of remote paragraph **133**B. In an alternative embodiment, synchronous remote procedure call (RPC) is instead used to cause execution of remote paragraph **133**B and/or detect completion of execution of remote paragraph **133**B. Polling operates as follows.

[0056] Python notebook **120**A may periodically poll global dictionary **170** in persistent store **160** to detect the availability of one or both of results **182**-**183** in global dictionary **170** in persistent store **160**. For example at time T2, Python notebook **120**A may begin polling first for only result **182**, but result **182** is not yet available. At time T3, remote paragraph **133**B in remote computer **112** generates result **182** and inserts result **182** into global dictionary **170** in persistent store **160**.

[0057] In an embodiment at time T3, the Python kernel in remote computer **112** detects (e.g. by instrumentation in remote paragraph **133**B) that remote paragraph **133**B has generated result **182** in the global dictionary in the Python kernel in remote computer **112**. At time T3, that detection may cause the Python kernel in remote computer **112** to either: a) insert result **182** into global dictionary **170** in persistent store **160** or b) copy some or all of the global dictionary in the Python kernel in remote computer **112** to overwrite (i.e. replace) global dictionary **170** in persistent store **160**.

[0058] At time T4, Python notebook **120**A again polls and detects that result **182** is available in global dictionary **170** in persistent store **160**. At time T4, that detection may cause Python notebook **120**A to poll for result **183**, but result **183** is not yet available in global dictionary **170** in persistent store **160**.

[0059] At time T5: a) remote paragraph **133**B in remote computer **112** generates result **183** in remote computer **112** and b) stores result **183** into global dictionary **170** in persistent store **160**. At time T6, Python notebook **120**A again polls and detects that result **183** is available in global dictionary **170** in persistent store **160**. Thus at time T6, Python notebook **120**A has cumulatively retrieved all of results **182**-**183**. Upon completion of time T5, remote computer **112** may be discarded without waiting for time T6.

[0060] In the shown embodiment and scenario, local paragraph **131** executes in local computer **111**. Then, local computer **111** offloads remote paragraph **133**A to remote computer **112** that executes it as remote paragraph **133**B that may read input variable **181** and write output results **182**-**183**. Then, local computer **111** retrieves results **182**-**183** and executes local paragraph **132** that may read results **182**-**183**. For example, times T4 and T6 may insert results **182**-**183** as global variables into the global dictionary in Python kernel **191**.

[0061] In that scenario, paragraphs **131**, **133**B, and **132** execute sequentially in that ordering. For example: a) local paragraph **131** may be unaware of being followed by a remote paragraph, b) local paragraph **132** may be unaware of being preceded by a remote paragraph, and c) remote paragraph **133**B may be unaware of being preceded or followed by local paragraphs **131**-**132**. That is, all paragraphs **131**-**133** use a global dictionary in whichever Python kernel is executing, and persistent store **160** is used to exchange global variables between computers **111**-**112**. In that way, Python notebook **120**A may contain any mix of local and remote (i.e. accelerated) paragraphs for sequential

execution or interactively selected execution. For example, interactivity may cause remote paragraph **133**B to execute before local paragraph **131** executes or after local paragraph **132** executes. Likewise, interactive selection may entirely avoid execution of any of paragraphs **131**-**133**.

1.8 Example Offload Activities

[0062] As discussed earlier and later herein, offloading remote paragraph **133**B for execution may entail one or more of the following activities:

[0063] serialization, over a communication network, of a global dictionary of a Python kernel,

[0064] persistence, into a network file system or a database, of a global dictionary of a Python kernel,

[0065] serialization, over a communication network, of the remote paragraph without the Python notebook,

[0066] persistence, into a network file system or a database, of the remote paragraph without the Python notebook,

[0067] detection of an interactive button press,

[0068] insertion of database authentication logic into the remote paragraph,

[0069] insertion of polling logic into the Python notebook, and

[0070] instantiation of a remote computer.

[0071] In an embodiment with a public cloud such as Oracle, Amazon, or Google, a cloud storage bucket may be used for file persistence instead of a network file system. In an Azure cloud embodiment, a bucket of files may be referred to as a storage blob. Seamless temporary delegation of storage security credentials from local computer **111** to remote computer **112** is an advantage of a cloud bucket.

2.0 Example Offload Process

[0072] FIG. **2** is a flow diagram that depicts an example process that computers **111**-**112** may perform to accelerate interactive Python execution for data science. In this process, novel notebook instrumentation by local computer **111** offloads a computationally intensive paragraph for remote execution on remote computer **112**. As discussed earlier herein, execution may, for example by interactive selection, include only remote paragraph **133**B. For example, Python notebook **120**A may lack local paragraphs or contain only unselected local paragraphs.

[0073] If no local paragraphs should execute, then local paragraph steps **201** and **213**-**214** do not occur. For example if no local paragraph should execute before remote paragraph **133**B, then the process of FIG. **2** begins at step **202** instead of step **201**. Likewise if no local paragraph should execute after remote paragraph **133**B, then the process of FIG. **2** ends at step **212** instead of step **214**. Python notebook **120**A may contain additional local or remote paragraphs. For example, multiple remote paragraphs may be offloaded together for execution together on remote computer **112**.

[0074] The process of FIG. **2** entails cooperation of computers **111**-**112** that may be disintermediated (i.e. decoupled) by use of persistent store **160**. Local computer **111** performs steps **201**-**209** and **212**-**214**. Remote computer **112** performs steps **210**-**211**. Herein, performance of an activity by local computer **111** may be implemented as performance of the activity by either of Python component **120**A or **191**. Likewise, performance of an activity by remote computer **112** may be implemented as performance of the activity by similar Python components.

[0075] In one example in step **201** before times T**1**A-C, local computer **111** executes local paragraph **131** as discussed earlier herein. For example, local paragraph **131** may set the value of variable **131** in local computer **111**.

[0076] In step **202** more or less immediately before times T**1**A-C, local computer **111** detects an interactive press of button **141**, which causes times T**1**A-C as discussed earlier herein. In particular, time T**1**A obtains remote computer **112** and times T**1**B-C initialize persistent store **160**. As discussed earlier herein, that obtaining may precede or follow that initializing, or they may be concurrent.

[0077] In particular, in the shown right branch, steps **203**-**205** perform obtaining remote computer **112** and, in the shown left branch, steps **206**-**209** perform initializing persistent store **160**. That is, the left and right branches may or may not concurrently occur. In particular, the right branch performs time T**1**A, and the left branch performs times T**1**B-C, and both branches are performed by local computer **111**.

[0078] As discussed earlier herein, compute shape **142** may be exposed as a graphical widget that is associated with remote paragraph **133**A. Step **203** scrapes (i.e. inspects the state of) the graphical widget. Data scraped by step **203** may be used by step **204** to define compute shape **142** as a data structure that can be used to obtain remote computer **112**.

[0079] Various embodiments of compute shape **142** may specify any of:

[0080] an amount of graphical processing unit (GPU) memory of the second computer exceeding 500 gigabytes,

[0081] an amount of byte-addressable nonvolatile memory of the second computer exceeding twenty terabytes,

[0082] a count of virtual network interface cards (VNIC) or processor cores of the second computer exceeding a hundred, and/or

[0083] an identifier of a predefined compute shape.

[0084] In an embodiment or scenario, remote computer **112** already exists and already is sufficiently provisioned to satisfy compute shape **142**. In another embodiment or scenario, remote computer **112** does not yet exist, and step **205** instantiates remote computer **112** as a virtual machine as discussed earlier herein. If step the right branch (i.e. time T**1**A) finishes before the left branch (i.e. times T**1**B-C), remote computer **112** waits for the left branch to finish.

[0085] In the left branch, step **206** inspects an annotation in a source comment in remote paragraph **133**A. Data provided by that inspection is used by step **207** to define interface signature **150** as a data structure as discussed earlier herein.

2.1 Example Instrumentation of Remote Paragraph

[0086] Persistent store **160** may be implemented as a database or a network file system. Only if a database is used, instrumentation step **208** inserts database authentication logic into remote paragraph **133**B, which may include open database connectivity (ODBC) details such as any part or parameter of a Java ODBC (JDBC) connection uniform resource locator (URL) such as a database hostname or internet protocol (IP) address, the database's network socket

port number, the name of the database or schema, the user account name of the database client account, and the password of that account.

[0087] For example, the inserted authentication logic may contain a partial or complete JDBC connection string (i.e. URL). After instrumenting remote paragraph **133**B, step **208** stores instrumented remote paragraph **133**B into persistent store **160**. Step **208** performs time T**1**B. The following is an example instrumented Python remote paragraph **133**B.

[0088] #authenticate onto DB class DBClient:

[0089] def init (self, connection_string):

[0090] def download (self, variable_name):
return variable

[0091] def upload (self, variable_name, variable):

[0092] db_client=DBClient (os.environ["CONN_STRING"]) #Load inputs #Starting from input methods def load_dataset (url):
#Then input variables

[0093] depth=5 #primitives can be copied straight from notebook code

[0094] dataset_url="www.datasets.net/example"

[0095] preprocessor=db_client.download ("preprocessor")
#Actual paragraph code

[0096] model=RandomForestClassifier (max_depth=depth)

[0097] dataset=load_dataset (dataset_url)

[0098] dataset=dataset.transform (preprocessor) model.fit (dataset)
#Upload outputs db_client.upload ("model", model)

[0099] In an enhanced security embodiment, step **208** does not involve a database password. For example in an Oracle Cloud Infrastructure (OCI) embodiment, step **208** instead instruments use of a wallet that is a secure container that stores authentication and signing credentials used for accessing the database as a cloud service. In an embodiment, wallet usage is audited and restricted by an OCI vault.

2.2 Example Polling Instrumentation

[0100] Instrumentation step **209** inserts results polling logic into Python notebook **120**A as discussed earlier herein. In the following example Python polling logic: a) output_names contains the variable names of results **182-183**, b) check_existence is a poll, and c) globals is the built in Python dictionary of global variables.

[0101] start=time ( )

[0102] while not numpy.all ([db_client.check_existence (o) for o in output_names]) and

[0103] timeout<500000: sleep (5)

[0104] timeout=(time ( )−start)

[0105] globals.update ({output_name:db_client.download (output_name) for output_name in output_names})

2.3 Example Persistence Instrumentation

[0106] Although time T**1**C is performed by the left branch, FIG. **2** does not show a step for time T**1**C that stores global dictionary **170** into persistent store **160** as discussed earlier herein. It is harmless for the left branch to finish before the right branch finishes. For example, an embodiment may require that the left branch finishes before the right branch starts. The following example global dictionary persistence Python logic implements time T**1**C.

[0107] #authenticate onto DB class DBClient:

[0108] def_init_ (self, connection_string):

[0109] def download (self, variable_name):
return variable

[0110] def upload (self, variable_name, variable):

[0111] def check_existence (self, variable_name):

[0112] db_client=DBClient (os.environ["CONN_STRING"])

[0113] #Load inputs

[0114] db_client.upload ("preprocessor", globals["preprocessor"]) #preprocessor is in the notebook kernel and can be accessed with globals

2.4 Offload Execution and Results

[0115] Although time T**2** is performed immediately before step **210**, FIG. **2** does not show a step for time T**2** that generates, instruments, and populates Python notebook **120**B (not shown in FIG. **1**) in the Python kernel in remote computer **112**, including copying Python components **133**B and **170** from persistent store **160** into Python notebook **120**B or the Python kernel in remote computer **112**.

[0116] Between times T**2**-T**3** in step **210**, remote computer **112** executes remote paragraph **133**B without executing any local paragraphs. A local paragraph is never contained in a remote computer nor in persistent store **160**. For example, Python notebook **120**A may be inaccessible by remote computer **112**.

[0117] As discussed earlier herein, remote computer **112** performs times T**3** and T**5**, and local computer **111** performs times T**4** and T**6**. Thus for times T**3**-T**6**, computers **111-112** may concurrently operate. Also as discussed earlier herein, an embodiment may: a) persist each of results **182-183** individually at respective times T**3** and T**5** and b) poll for each of results **182-183** individually at respective times T**4** and T**6**. Thus, step **211**: a) may be repeated to perform each of times T**3** and T**5** or b) may persist both of results **182-183** together such as when times T**3** and T**5** are a same single time. If (a), then both of persistence step **211** and polling step **212**A may be repeated and interleaved.

[0118] Steps **212**A-B are mutually exclusive ways for local computer **111** to wait for remote paragraph **133**B to finish executing. That is, an embodiment of local computer **111** implements step **212**A or **212**B but not both.

[0119] In an embodiment, step **212**A separately (i.e. individually) polls multiple results **182-183** of a same offload (i.e. offloaded execution of remote paragraph **133**B) as discussed earlier herein, such as with the above example Python polling logic from instrumentation step **209**.

[0120] In an embodiment, remote computer **112** is a virtual machine that was created by step **205**, and step **212**B detects termination of the virtual machine.

[0121] After execution of remote paragraph **133**B finishes, local computer **111**: a) performs times T**4** and T**6**, b) finishes waiting, and c) may or may not automatically or interactively execute local paragraph **132** in step **213** that may occur without re-executing local paragraph **131**. For example, local paragraph **132** may read none, one, or both of results **182-183** in step **214**.

[0122] The process of FIG. **2** may be repeated to execute same or different remote paragraph(s) on a same or different remote computer as discussed earlier herein. For example, a first offloading of remote paragraph **133**B may or may not

entail instantiating a virtual machine that may or may not be retained for reuse by a second offloading of a same or different remote paragraph.

Hardware Overview

[0123] According to one embodiment, the techniques described herein are implemented by one or more special-purpose computing devices. The special-purpose computing devices may be hard-wired to perform the techniques, or may include digital electronic devices such as one or more application-specific integrated circuits (ASICs) or field programmable gate arrays (FPGAs) that are persistently programmed to perform the techniques, or may include one or more general purpose hardware processors programmed to perform the techniques pursuant to program instructions in firmware, memory, other storage, or a combination. Such special-purpose computing devices may also combine custom hard-wired logic, ASICs, or FPGAs with custom programming to accomplish the techniques. The special-purpose computing devices may be desktop computer systems, portable computer systems, handheld devices, networking devices or any other device that incorporates hard-wired and/or program logic to implement the techniques.

[0124] For example, FIG. **3** is a block diagram that illustrates a computer system **300** upon which an embodiment of the invention may be implemented. Computer system **300** includes a bus **302** or other communication mechanism for communicating information, and a hardware processor **304** coupled with bus **302** for processing information. Hardware processor **304** may be, for example, a general purpose microprocessor.

[0125] Computer system **300** also includes a main memory **306**, such as a random access memory (RAM) or other dynamic storage device, coupled to bus **302** for storing information and instructions to be executed by processor **304**. Main memory **306** also may be used for storing temporary variables or other intermediate information during execution of instructions to be executed by processor **304**. Such instructions, when stored in non-transitory storage media accessible to processor **304**, render computer system **300** into a special-purpose machine that is customized to perform the operations specified in the instructions.

[0126] Computer system **300** further includes a read only memory (ROM) **308** or other static storage device coupled to bus **302** for storing static information and instructions for processor **304**. A storage device **310**, such as a magnetic disk or optical disk, is provided and coupled to bus **302** for storing information and instructions.

[0127] Computer system **300** may be coupled via bus **302** to a display **312**, such as a cathode ray tube (CRT), for displaying information to a computer user. An input device **314**, including alphanumeric and other keys, is coupled to bus **302** for communicating information and command selections to processor **304**. Another type of user input device is cursor control **316**, such as a mouse, a trackball, or cursor direction keys for communicating direction information and command selections to processor **304** and for controlling cursor movement on display **312**. This input device typically has two degrees of freedom in two axes, a first axis (e.g., x) and a second axis (e.g., y), that allows the device to specify positions in a plane.

[0128] Computer system **300** may implement the techniques described herein using customized hard-wired logic, one or more ASICs or FPGAs, firmware and/or program logic which in combination with the computer system causes or programs computer system **300** to be a special-purpose machine. According to one embodiment, the techniques herein are performed by computer system **300** in response to processor **304** executing one or more sequences of one or more instructions contained in main memory **306**. Such instructions may be read into main memory **306** from another storage medium, such as storage device **310**. Execution of the sequences of instructions contained in main memory **306** causes processor **304** to perform the process steps described herein. In alternative embodiments, hard-wired circuitry may be used in place of or in combination with software instructions.

[0129] The term "storage media" as used herein refers to any non-transitory media that store data and/or instructions that cause a machine to operation in a specific fashion. Such storage media may comprise non-volatile media and/or volatile media. Non-volatile media includes, for example, optical or magnetic disks, such as storage device **310**. Volatile media includes dynamic memory, such as main memory **306**. Common forms of storage media include, for example, a floppy disk, a flexible disk, hard disk, solid state drive, magnetic tape, or any other magnetic data storage medium, a CD-ROM, any other optical data storage medium, any physical medium with patterns of holes, a RAM, a PROM, and EPROM, a FLASH-EPROM, NVRAM, any other memory chip or cartridge.

[0130] Storage media is distinct from but may be used in conjunction with transmission media. Transmission media participates in transferring information between storage media. For example, transmission media includes coaxial cables, copper wire and fiber optics, including the wires that comprise bus **302**. Transmission media can also take the form of acoustic or light waves, such as those generated during radio-wave and infra-red data communications.

[0131] Various forms of media may be involved in carrying one or more sequences of one or more instructions to processor **304** for execution. For example, the instructions may initially be carried on a magnetic disk or solid state drive of a remote computer. The remote computer can load the instructions into its dynamic memory and send the instructions over a telephone line using a modem. A modem local to computer system **300** can receive the data on the telephone line and use an infra-red transmitter to convert the data to an infra-red signal. An infra-red detector can receive the data carried in the infra-red signal and appropriate circuitry can place the data on bus **302**. Bus **302** carries the data to main memory **306**, from which processor **304** retrieves and executes the instructions. The instructions received by main memory **306** may optionally be stored on storage device **310** either before or after execution by processor **304**.

[0132] Computer system **300** also includes a communication interface **318** coupled to bus **302**. Communication interface **318** provides a two-way data communication coupling to a network link **320** that is connected to a local network **322**. For example, communication interface **318** may be an integrated services digital network (ISDN) card, cable modem, satellite modem, or a modem to provide a data communication connection to a corresponding type of telephone line. As another example, communication interface **318** may be a local area network (LAN) card to provide a data communication connection to a compatible LAN. Wireless links may also be implemented. In any such implemen-

tation, communication interface **318** sends and receives electrical, electromagnetic or optical signals that carry digital data streams representing various types of information.

[0133] Network link **320** typically provides data communication through one or more networks to other data devices. For example, network link **320** may provide a connection through local network **322** to a host computer **324** or to data equipment operated by an Internet Service Provider (ISP) **326**. ISP **326** in turn provides data communication services through the world wide packet data communication network now commonly referred to as the "Internet" **328**. Local network **322** and Internet **328** both use electrical, electromagnetic or optical signals that carry digital data streams. The signals through the various networks and the signals on network link **320** and through communication interface **318**, which carry the digital data to and from computer system **300**, are example forms of transmission media.

[0134] Computer system **300** can send messages and receive data, including program code, through the network (s), network link **320** and communication interface **318**. In the Internet example, a server **330** might transmit a requested code for an application program through Internet **328**, ISP **326**, local network **322** and communication interface **318**.

[0135] The received code may be executed by processor **304** as it is received, and/or stored in storage device **310**, or other non-volatile storage for later execution.

Software Overview

[0136] FIG. **4** is a block diagram of a basic software system **400** that may be employed for controlling the operation of computing system **300**. Software system **400** and its components, including their connections, relationships, and functions, is meant to be exemplary only, and not meant to limit implementations of the example embodiment(s). Other software systems suitable for implementing the example embodiment(s) may have different components, including components with different connections, relationships, and functions.

[0137] Software system **400** is provided for directing the operation of computing system **300**. Software system **400**, which may be stored in system memory (RAM) **306** and on fixed storage (e.g., hard disk or flash memory) **310**, includes a kernel or operating system (OS) **410**.

[0138] The OS **410** manages low-level aspects of computer operation, including managing execution of processes, memory allocation, file input and output (I/O), and device I/O. One or more application programs, represented as **402**A, **402**B, **402**C . . . **402**N, may be "loaded" (e.g., transferred from fixed storage **310** into memory **306**) for execution by the system **400**. The applications or other software intended for use on computer system **300** may also be stored as a set of downloadable computer-executable instructions, for example, for downloading and installation from an Internet location (e.g., a Web server, an app store, or other online service).

[0139] Software system **400** includes a graphical user interface (GUI) **415**, for receiving user commands and data in a graphical (e.g., "point-and-click" or "touch gesture") fashion. These inputs, in turn, may be acted upon by the system **400** in accordance with instructions from operating system **410** and/or application(s) **402**. The GUI **415** also serves to display the results of operation from the OS **410** and application(s) **402**, whereupon the user may supply additional inputs or terminate the session (e.g., log off).

[0140] OS **410** can execute directly on the bare hardware **420** (e.g., processor(s) **304**) of computer system **300**. Alternatively, a hypervisor or virtual machine monitor (VMM) **430** may be interposed between the bare hardware **420** and the OS **410**. In this configuration, VMM **430** acts as a software "cushion" or virtualization layer between the OS **410** and the bare hardware **420** of the computer system **300**.

[0141] VMM **430** instantiates and runs one or more virtual machine instances ("guest machines"). Each guest machine comprises a "guest" operating system, such as OS **410**, and one or more applications, such as application(s) **402**, designed to execute on the guest operating system. The VMM **430** presents the guest operating systems with a virtual operating platform and manages the execution of the guest operating systems.

[0142] In some instances, the VMM **430** may allow a guest operating system to run as if it is running on the bare hardware **420** of computer system **400** directly. In these instances, the same version of the guest operating system configured to execute on the bare hardware **420** directly may also execute on VMM **430** without modification or reconfiguration. In other words, VMM **430** may provide full hardware and CPU virtualization to a guest operating system in some instances.

[0143] In other instances, a guest operating system may be specially designed or configured to execute on VMM **430** for efficiency. In these instances, the guest operating system is "aware" that it executes on a virtual machine monitor. In other words, VMM **430** may provide para-virtualization to a guest operating system in some instances.

[0144] A computer system process comprises an allotment of hardware processor time, and an allotment of memory (physical and/or virtual), the allotment of memory being for storing instructions executed by the hardware processor, for storing data generated by the hardware processor executing the instructions, and/or for storing the hardware processor state (e.g. content of registers) between allotments of the hardware processor time when the computer system process is not running. Computer system processes run under the control of an operating system, and may run under the control of other programs being executed on the computer system.

Cloud Computing

[0145] The term "cloud computing" is generally used herein to describe a computing model which enables on-demand access to a shared pool of computing resources, such as computer networks, servers, software applications, and services, and which allows for rapid provisioning and release of resources with minimal management effort or service provider interaction.

[0146] A cloud computing environment (sometimes referred to as a cloud environment, or a cloud) can be implemented in a variety of different ways to best suit different requirements. For example, in a public cloud environment, the underlying computing infrastructure is owned by an organization that makes its cloud services available to other organizations or to the general public. In contrast, a private cloud environment is generally intended solely for use by, or within, a single organization. A community cloud is intended to be shared by several organizations within a community; while a hybrid cloud comprise

two or more types of cloud (e.g., private, community, or public) that are bound together by data and application portability.

[0147] Generally, a cloud computing model enables some of those responsibilities which previously may have been provided by an organization's own information technology department, to instead be delivered as service layers within a cloud environment, for use by consumers (either within or external to the organization, according to the cloud's public/private nature). Depending on the particular implementation, the precise definition of components or features provided by or within each cloud service layer can vary, but common examples include: Software as a Service (SaaS), in which consumers use software applications that are running upon a cloud infrastructure, while a SaaS provider manages or controls the underlying cloud infrastructure and applications. Platform as a Service (PaaS), in which consumers can use software programming languages and development tools supported by a PaaS provider to develop, deploy, and otherwise control their own applications, while the PaaS provider manages or controls other aspects of the cloud environment (i.e., everything below the run-time execution environment). Infrastructure as a Service (IaaS), in which consumers can deploy and run arbitrary software applications, and/or provision processing, storage, networks, and other fundamental computing resources, while an IaaS provider manages or controls the underlying physical cloud infrastructure (i.e., everything below the operating system layer). Database as a Service (DBaaS) in which consumers use a database server or Database Management System that is running upon a cloud infrastructure, while a DbaaS provider manages or controls the underlying cloud infrastructure and applications.

[0148] The above-described basic computer hardware and software and cloud computing environment presented for purpose of illustrating the basic underlying computer components that may be employed for implementing the example embodiment(s). The example embodiment(s), however, are not necessarily limited to any particular computing environment or computing device configuration. Instead, the example embodiment(s) may be implemented in any type of system architecture or processing environment that one skilled in the art, in light of this disclosure, would understand as capable of supporting the features and functions of the example embodiment(s) presented herein.

[0149] In the foregoing specification, embodiments of the invention have been described with reference to numerous specific details that may vary from implementation to implementation. The specification and drawings are, accordingly, to be regarded in an illustrative rather than a restrictive sense. The sole and exclusive indicator of the scope of the invention, and what is intended by the applicants to be the scope of the invention, is the literal and equivalent scope of the set of claims that issue from this application, in the specific form in which such claims issue, including any subsequent correction.

What is claimed is:

1. A method comprising:

executing, by a first computer, a local paragraph in a Python notebook that contains a remote paragraph; and

executing, by a second computer, the remote paragraph without executing the local paragraph in the second computer.

2. The method of claim **1** wherein:

said local paragraph is a first local paragraph;

the method further comprises executing, by the first computer, after said executing the first local paragraph and said executing the remote paragraph, a second local paragraph in the Python notebook;

said executing the first local paragraph occurs exactly once.

3. The method of claim **2** wherein:

said executing the first local paragraph and said executing the second local paragraph occur in a first Python kernel;

said executing the remote paragraph occurs in a second Python kernel.

4. The method of claim **2** wherein:

the second computer is a virtual machine;

the method further comprises the Python notebook detecting, before said executing the second local paragraph, termination of the virtual machine.

5. The method of claim **2** wherein:

said executing the remote paragraph comprises the second computer persisting, in a network file system or a database, a result;

said executing the second local paragraph comprises accessing the result.

6. The method of claim **5** wherein:

the result contains a first result and a second result;

the method further comprises separately polling the first result and the second result.

7. The method of claim **1** further comprising the Python notebook defining an interface signature of the remote paragraph.

8. The method of claim **7** wherein said defining the interface signature of the remote paragraph comprises the Python notebook inspecting a source comment.

9. The method of claim **8** wherein the remote paragraph contains the source comment.

10. The method of claim **8** wherein the source comment specifies a variable that the remote paragraph will read or write.

11. The method of claim **1** further comprising the Python notebook defining a compute shape of the second computer.

12. The method of claim **11** wherein the compute shape specifies at least one setting selected from a group consisting of:

an amount of graphical processing unit (GPU) memory of the second computer exceeding 500gigabytes,

an amount of byte-addressable nonvolatile memory of the second computer exceeding twenty terabytes,

a count of virtual network interface cards (VNIC) or processor cores of the second computer exceeding a hundred, and

an identifier of a predefined compute shape.

13. The method of claim **11** wherein said defining the compute shape comprises the Python notebook inspecting a state of a graphical widget associated with the remote paragraph.

14. The method of claim **1** further comprising the Python notebook offloading the remote paragraph to the second computer.

15. The method of claim **14** wherein said offloading comprises the Python notebook performing an action selected from a group consisting of:

serialization, over a communication network, of a global dictionary of a Python kernel, persistence, into a network file system or a database, of a global dictionary of a Python kernel, serialization, over a communication network, of the remote paragraph without the Python notebook,

persistence, into a network file system or a database, of the remote paragraph without the Python notebook,

detection of an interactive button press,

insertion of database authentication logic into the remote paragraph,

insertion of polling logic into the Python notebook, and

instantiation of the second computer.

16. The method of claim **1** wherein the first computer and the second computer have different instruction set architectures.

17. One or more non-transitory computer-readable media storing instructions that, when executed by one or more processors, cause:

executing, by a first computer, a local paragraph in a Python notebook that contains a remote paragraph; and

executing, by a second computer, the remote paragraph without executing the local paragraph in the second computer.

18. The one or more non-transitory computer-readable media of claim **17** wherein:

said local paragraph is a first local paragraph;

the instructions further cause executing, by the first computer, after said executing the first local paragraph and said executing the remote paragraph, a second local paragraph in the Python notebook;

said executing the first local paragraph occurs exactly once.

19. The one or more non-transitory computer-readable media of claim **18** wherein:

said executing the remote paragraph comprises the second computer persisting, in a network file system or a database, a result;

said executing the second local paragraph comprises accessing the result.

20. The one or more non-transitory computer-readable media of claim **17** wherein the instructions further cause the Python notebook defining an interface signature of the remote paragraph.

21. The one or more non-transitory computer-readable media of claim **20** wherein said defining the interface signature of the remote paragraph comprises the Python notebook inspecting a source comment.

22. The one or more non-transitory computer-readable media of claim **17** wherein the instructions further cause the Python notebook defining a compute shape of the second computer.

23. The one or more non-transitory computer-readable media of claim **17** wherein the instructions further cause the Python notebook offloading the remote paragraph to the second computer.

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