Intentional Forgetting

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Abstract. Many damaging cybersecurity attacks are enabled when an attacker can access residual sensitive information (e.g. cryptographic keys, personal identifiers) left behind from earlier computation. Attackers can sometimes use residual information to take control of a system, impersonate a user, or manipulate data. Current approaches to addressing access to residual sensitive information aim to patch individual software or hardware vulnerabilities. While such patching approaches are necessary to mitigate sometimes serious security vulnerabilities in the near term, they cannot address the underlying issue: explicit requirements for adequately eliminating residual information and explicit representations of the erasure capabilities of systems are necessary to ensure that sensitive information is handled as expected.

This position paper introduces the concept of intentional forgetting and the capabilities that are needed to achieve it. Intentional forgetting enables software and hardware system designers at every level of abstraction to clearly specify and rigorously reason about the forgetting capabilities required of and provided by a system. We identify related work that may help to illuminate challenges or contribute to solutions and consider conceptual and engineering tradeoffs in implementations of forgetting capabilities. We discuss approaches to modeling intentional forgetting and then modeling the strength of a system’s forgetting capability by its resistance to disclosing information to different types of detectors. Research is needed in a variety of domains to advance the theory, specification techniques, system foundations, implementation tools, and methodologies for effective, practical forgetting. We highlight research challenges in several domains and encourage cross-disciplinary collaboration to one day create a robust theory and practice of intentional forgetting.

1 Introduction

Many damaging cybersecurity attacks occur when the attacker accesses residual evidence of sensitive information (e.g. cryptographic keys, personal identifiers) left behind on a system from earlier computation. Access to such information can enable attackers to take control of a system, impersonate a user, or manipulate data. Often, that information persists unexpectedly: at one semantic layer, the information disappears (e.g., the variable goes out of scope, the file is deleted), but the layer below contains some remaining evidence of that information (e.g., the last value of the variable still resides in memory, the bits representing the data from the file are still stored together on the drive). At the higher level of
abstraction, the system behaves as expected (e.g., the compiler indicates that
the variable does not exist, the operating system indicates that the file does not
exist), but at the lower level, a curious observer would likely find considerable
evidence of the information.

Computer systems are designed to work this way for good reason: Multi-
ple layers of abstraction enable the creation of logically complex behavior from
the simplest of electronic hardware operations. It seems irrational to demand
that system implementations hide messy details and provide logically consistent
abstractions except when we suddenly (and without warning) want the oppo-
site – high assurance that those messy details have very specific and previously
unspecified properties.

Current approaches to addressing access to residual sensitive information aim
to patch individual software vulnerabilities or implement a software mitigation
to fix an individual hardware vulnerability. Clever cybersecurity researchers have
found alternative vulnerabilities [17,16] even after the fixes have been applied,
challenging the system defenders to the next round of cat-and-mouse. While
such patching approaches are necessary to mitigate sometimes serious security
vulnerabilities in the near term, they cannot address the underlying issue: with-
out explicit requirements for adequately eliminating residual information, system
designers must guess the capabilities architects of the next layer of abstraction
might need.

This position paper argues for an intentional forgetting capability. Applica-
tion software developers require an intentional forgetting capability in the oper-
ating system software. System software designers require that capability in the
hardware. Integrating hardware to create a system requires specific intentional
forgetting capabilities of the various hardware components, such as memories,
processors, storage devices, or network hardware. Intentional forgetting capabil-
ities and limitations can become discriminators for candidate implementations,
just as storage capacity, computational speed, or message throughput are used
today.

Intentionality is essential to effective forgetting; systems must have the nec-
essary forgetting capability, and systems layered on top of the implementing
system must give advance notice of intent to use that capability. Implementa-
tions of remembering provide an analog: for a computer program to remember a
value throughout a computation, the programmer first declares a variable, pro-
viding an identifier and, often, a type, which indicates an intent to store and refer
to the named data in the future. When a runtime system executes the program
in the context of an appropriate operating system and computer hardware, some
hardware memory is reserved. As the program executes, it may store data in the
memory that was reserved and named by the declared variable. The capability
to remember the value of a variable is offered to the programmer through fea-
tures of a programming language and supporting system software and, finally,
implemented in hardware. The declaration of the intent to store a value leads
the layers of implementation to instrument the underlying system software and
hardware to prepare to remember a value to be supplied later. Programming
languages with implicit typing often compile first to an intermediate bytecode that enables the bytecode interpreter to identify and reserve the necessary memory space. Regardless of the approach used to reserve memory space for future use, programmers specify the intention to use memory to store data; the system software and hardware instrument the system to make that use possible.

Intentionality is also required to enable concurrency control in distributed systems. If concurrent processes share a resource (e.g., communicate via a shared variable), it is often necessary to ensure that only one process at a time accesses (reads or writes to) the resource at a time to prevent undesirably unpredictable system behavior. Parallel programming languages offer a method for excluding access to the resource unless a process has first acquired some form of a lock (or mutex or semaphore). Other processes must wait until the lock is released before they can access the resource. The programmer must first declare and name a lock, which processes can later request to acquire. While different operating systems provide different implementations of locking, all require advance system instrumentation to enable future use by executing processes.

Intentionality in forgetting is displayed by systems that implement transactions. If Alice wants to transfer $10 from her bank account to Bob’s account at a different bank, a number of intermediate actions must take place, including the reduction of the value of Alice’s account and the increase in value of Bob’s account. At the end of the day, regardless of computer, software, or network failures, both banks must account for the disposition of the $10 in the same way; it must appear in either Alice’s account or Bob’s account and all of the intermediate steps of the money transfer are “forgotten” from Alice’s and Bob’s points of view. Enabling the forgetting required for transactional semantics (“atomicity”) requires significant software instrumentation in the form of multi-phase commit protocols and their implementations. While atomicity is achieved at the application or user level, the banking system logs do not forget. All of the records of intermediate activity are logged to enable a future audit; intentional forgetting is achieved within one level of abstraction, but is explicitly avoided at the implementation layer below.

The remainder of this paper discusses the capabilities that are needed to enable intentional forgetting. We identify work in some research domains that may be applicable and call attention to some of the challenges that must be addressed to produce viable solutions. Section 2 discusses a two phase-based specification of forgetting and compares with other systems that operate in two phases: an application first declares an intention to take future action and, later, calls upon the system to act. Forgetting capabilities may be easier to implement in some systems if specifications enable system instrumentation in a phase prior to forgetting actions. Section 3 highlights some current approaches to instrumenting systems to track information. The conceptual and engineering tradeoffs in instrumentation approaches may help to guide consideration of tradeoffs that are likely to arise in implementations of forgetting. Section 4 focuses on the modeling of intentional forgetting at the abstraction and implementation layers and the coordination and composition of forgetting capabilities. Detectors, discussed
in Section 5 model the information recovery capability of different adversaries. A determined adversary may present a much more capable detector (e.g., well-resourced, clever) than a casual observer, so presenting a system’s forgetting capability in terms of its resistance to different types of detectors provides a means of expressing the strength of forgetting. Section 6 touches on areas of related work, and Section 7 outlines research opportunities, ranging from theory and modeling to system performance. Section 8 concludes with a brief summary.

2 Specifying intentional forgetting

The examples of programming, concurrency control, and distributed bank transactions in Section 1 contain a prepare phase, followed by an action phase. The abstraction layer calls some form of prepare command, which causes the implementation layer to begin instrumenting the system to be ready to later respond to an appropriate command for action. The action command of interest to us is the forget command. Although a universal language or method of specifying intentional forgetting is not likely possible, we expect the prepare/forget phases and commands to follow a common pattern across a variety of abstraction and implementation layers.

Consistent with their usual behavior, the abstraction and implementation layers dictate the syntax and approach to indicating an item that is to be forgotten (or tbf) and then, later, to request that the forgetting take place. For example, when the abstraction layer is a high-level programming language and the implementation layer is an operating system, the programming language might include the reserved word TBF for designating a variable x as tbf at the time the variable is declared. Later, the program makes a system call forget(x) to cause the value of x to be forgotten.

Consider rollbacks of distributed transactions, for example. After nodes supporting a distributed transaction are asked to prepare, each node executes instructions to allocate local resources, record redo logs, and set locks. Later, each node receives either a commit instruction, which causes the node to make permanent its local portion of the transaction, or a rollback instruction, which causes the node to return to the same local state as before the prepare instruction was received. A node uses the information recorded in its local redo log to correctly reset any local values to their earlier state. Rollbacks are often used to address failures (often network failures) that happen while a transaction is executing to ensure that the system as a whole is not left in an inconsistent state. Rollback is an form of forgetting that tidies the abstraction layer but does not clean up residual evidence of an attempted transaction at the implementation layer. System logs will show the intermediate steps that were attempted to execute the transaction and can be used to diagnose problems in the system. Because rollback does not tidy the implementation layer, it does not address the challenge of cross-layer forgetting that motivates this study. However, the prepare/rollback pattern that distributed systems programmers use to ensure
correctness in transactional semantics is similar to the prepare/forget pattern that is needed to provide cybersecurity assurance of forgetting.

If the implementation layer is a hardware device, then it may offer a forget command via a device driver installed in an operating system. The language of the forget command would be similar to that for other operations of that hardware device.

In each of these examples, the prepare and forget commands are made available for explicit use by the abstraction layer and are implemented by the layer below. The nature of the specification fits the particular abstraction and implementation layers involved.

3 Instrumenting systems for intentional forgetting

To thoroughly forget an information item on demand, the system must be able to identify all the item’s implementation layer elements of the item and take action to remove them. A prepare command initiates a prepare phase during which the implementation layer instruments the system. After the prepare phase, the implementation continues to manage the instrumentation to enable later forgetting. Instrumentation takes many forms depending on the system and the type of information to be forgotten. Computer systems have typically used one of two classes of instrumentation techniques to enable information to be deleted.

The first approach involves marking an item so it can be traced as it is manipulated within the system. Examples of systems that mark include 1) garbage collection [15] and Automatic Reference Counting (ARC), which is implemented by the LLVM compiler for Objective C [1]; 2) page replacement algorithms for virtual memory managers [3] that mark a modified memory page with a modified or dirty bit to note the need to write that page to stable storage before swapping out the page and reclaiming the memory space; 3) dynamic taint tracking [26], which can trace the propagation of data objects during program execution to, for example, identify the impact of un-validated input data; and 4) static analysis tools [11,12,14,22] that use data flow techniques to track the use of data within a program. All of these marking techniques are fine-grained, enabling systems to track and address individual data items or their implementation-level representations. For example, a garbage collector can determine that a specific integer variable is no longer in use and reclaim its memory space for other uses.

A second approach is coarse-grained, clustering together items and treating them similarly at the implementation layer; all of the items in the cluster are either remembered or deleted. For example, magnetic drives can be degaussed to delete their entire contents. Flash-based solid state drives (SSDs) require different techniques [29] to ensure that data is removed. This coarse-grained approach is currently used by encrypted memories, firmware and self-encrypting drives to reliably delete a large amount of data by forgetting only a single encryption key.

Both the fine-grained marking approaches and the coarse-grained approaches require ongoing system instrument management. Instrument management consumes resources, which leads to various engineering tradeoffs in system design.
Specialized, resource-constrained systems often forego most such techniques, due to resource constraints. Experience with a variety of system instrumentation and management approaches indicates that a forgetting capability is likely to be expensive to implement, so research into techniques for optimizing forgetting instrumentation is of great practical importance.

4 Modeling intentional forgetting

Currently, application developers and users do not have a basis for forming realistic expectations about the residual system information that might be found if someone were to look for it. Some systems offer weaker qualities of forgetting, which yield information to a curious amateur, while other systems withhold the information from all but the most determined professional sleuth. In short, application developers and users need a clear description of the forgetting capabilities of the system. Capabilities of interest include the granularity of information that can be forgotten (i.e., can the system be instructed to forget just an integer or does it forget much coarser “chunks” of information?) and the strength or quality of the forgetting (i.e., how hard is it to recover information that the system is instructed to forget?)

To provide rigorous specification of forgetting capabilities to support precise communication, we recommend the development of formal models to describe the abstraction layer, the implementation layer, the composition of forgetting capabilities as systems are constructed from components, and the actors that seek residual information. For concreteness in this section, we focus on an abstraction layer where a programmer writes software and the corresponding implementation layer that provides computation, storage, networking and other services that will be used to implement the application logic.

At the abstraction layer visible to the programmer, a possible approach is to model behavior of a system design as an abstract machine (an automaton) that specifies changes in state and interactions with the external world. An implementation of an abstract machine on a more concrete machine may have intermediate states using information not visible at the abstract level. The language runtime system, operating system, CPU, and other hardware that interpret the implementation machine may expose even more information. For example, speculative execution or manipulation of a memory management system may expose timing information or leave traces of sensitive data. Stuttering (bi)simulations can show that a lower layer (implementation) is correct with respect to the upper layer (specification). Can such relations be augmented to show that the lower layer adequately implements forgetting?

Here are some questions to consider when addressing intentional forgetting.

– How can the programmer or designer annotate data that should be forgotten after the program or process is done with it? The annotation must be propagated along the execution and to the lower levels. The annotations should

\[^{1}\text{A bisimulation is a 1-1 correspondence between states of executions at the two layers. In a stuttering bisimulation, at one layer, usually the lower, states may be skipped.}\]
be able to express different levels of sensitivity which would then result in instrumentation for different levels of forgetting. The programmer may also wish to express a minimal level of forgetting that is acceptable, to allow some flexibility.

- What program structures might be better able to support forgetting (e.g., scoping mechanisms or data abstractions)?
- What additional information (beyond the instruction API) does a compiler need to know about its target platform (operating system and hardware) to support instrumentation of the machine-level code to achieve sufficient forgetting?
- A model of accessibility and information extraction ability/cost (attack model) is needed to say when something has been forgotten. For example, all the memory may be accessible but how does one know which blocks represent information of interest. How much work is required to extract usable information?

To discuss forgetting requirements and challenges in more detail, the following section introduces some mathematical notation for describing processes at two layers (abstraction and implementation) and the relationships between them. Section 5 discusses detectors as measures of forgetting and attack strength.

### 4.1 Modeling the abstraction and implementation layers

The abstraction layer has a state transition automaton with states $S = q, D$ ($q$ for abstract program state, $D$ for data state) and actions $a$, which include input, output, and application of data transformations. For purpose of illustration, $D$ is assumed to be a data dictionary, i.e., a mapping from names to data structures and the named entities will be the unit of forgetting. An execution trace for such an automaton has the form

$$S_0 \xrightarrow{a_1} \ldots \xrightarrow{a_k} S_k$$

where the action $a_{i+1}$ is determined by the automaton transition system, the state $S_i$, and, possibly, external input.

To prepare for forgetting, the programmer must specify

- $\text{tbf}$ data initially present in $S_0$ by specifying which names bind $\text{tbf}$ data
- the effect of actions, whether they introduce new $\text{tbf}$ data (such as reading or generating a secret), and how a primitive operation or function call propagates $\text{tbf}$ status
- conditions that trigger forgetting, such as program exit

The $\text{tbf}$ status of a named data item may include a desired level of forgetting. The level relates to the computational cost of forgetting, and to the difficulty of detecting. Making these relations explicit is important for making both conceptual and engineering tradeoffs.

The $\text{tbf}$ annotations of the initial state and actions allow the $\text{tbf}$ annotations to be automatically propagated to newly created and transformed data. For an
execution as above, \( S_{t_j} \) for \( 1 \leq j \leq k \) denotes the result, \( S_{t_0} \), of annotating \( S_0 \) and propagating annotations according to annotation of actions.

The implementation layer contains a state transition machine with states \( M_i \) that include elements \((pc, regs, mem)\) where \( pc \) is the program counter, \( regs \) is the register set, and \( mem \) includes cache levels and any temporary storage used in execution. Transitions are labeled by machine actions \( x \) (processing instructions, input-output actions, \ldots).

\[
M_0 \overset{x_1}{\rightarrow} \ldots \overset{x_i}{\rightarrow} M_i
\]

In general, \( k < l \) as a program level action may be implemented by multiple machine-level instructions.

Assume that \( \sim \) is a (stuttering bi) simulation relation between abstract states \( S_i \) and a subset of implementation states \( M_i \) showing the correctness of the machine model (and compilation). Thus if \( M_0 \) is the compilation of \( S_0 \) then \( S_0 \sim M_0 \). And if

\[
S_0 \overset{a_1}{\rightarrow} \ldots \overset{a_k}{\rightarrow} S_k
\]

then there is a subsequence of indices \( i_j \) for \( 1 \leq j \leq k \) such that \( S_j \sim M_{i_j} \) for \( 1 \leq j \leq k \).

\[
M_0 \overset{x_1}{\rightarrow} \ldots \overset{x_i}{\rightarrow} M_{i_k}
\]

where \( \overset{i_j}{\rightarrow} \) indicates a sequence of machine instructions and intermediate states, and \( i_j \) is an increasing sequence of indices picking out the simulation points. Thus \( i_j > = j \) and \( k < = i_k < = l \). For example, the machine state corresponding to abstract state \( S_1 \) is \( M_3 \), i.e. two machine states are intermediate instructions, thus for \( j = 1, i_1 = 3 \).

Relevant properties of \( S_i \) are preserved by the \( \sim \) relation as corresponding properties of \( M_{i_j} \) which capture the sense in which the machine is a correct implementation. Properties could include correctness of data representations, data invariants, or axiomatic theories to be satisfied by both levels.

The annotation of abstract actions needs to be compiled to instrumentation of implementing machine instructions that determine how \( \textbf{tbf} \) annotation is introduced and propagated. Points where a \( \textbf{tbf} \) class should be forgotten should be compiled to suitable forgetting instructions.

Suppose memory blocks of some convenient size can be \textit{colored} with a finite set of colors. Then memory holding \( \textbf{tbf} \) data could be colored according to forgetting class, such that data of the same color can be forgotten together, at the same level. For example, let \( M_{C_0} \) be \( M_0 \) with the image of \( \textbf{tbf} \) data in \( S_{t_0} \) (i.e., the first state in the annotated execution trace) colored according to the forgetting class to which the named data is assigned. The idea is to lift the simulation relation \( \sim \) to a relation on annotated program level states and colored machine-level states. First we require \( S_{t_0} \sim M_{C_0} \). Next we need to propagate colors using annotated machine instructions and check that at simulation points \( S_j \sim M_{i_j} \), we have \( S_{t_j} \sim M_{C_{i_j}} \). In particular, in addition to preserving functional properties (that should not be affected by annotation or instrumentation), the image of \( \textbf{tbf} \) data in \( S_{t_j} \) is suitably colored in \( M_{C_j} \). The image of a data element
needs to include its total footprint in memory (including cache) and registers (that have not been overwritten by other data). Thus,

- if \( S_j \xrightarrow{a_j+1} S_{j+1} \) adds a tbf structure then its image in \( M_{j+1} \) should be suitably colored
- if \( S_j \xrightarrow{a_j+1} S_{j+1} \) forgets a level then the image of data of the corresponding color in \( M_{j+1} \) should be not detectable (i.e., no information about the tbf data can be detected (with the given effort))
- if \( S_j \xrightarrow{a_j+1} S_{j+1} \) reads tbf data from an external source, then the corresponding read instructions \( M_i \xrightarrow{\bar{x}} M_{i+1} \) should color every storage location including temporary locations such as buffers, registers, or cache, in which the tbf data resides
- dually, if tbf data is transmitted to an external target (external machine, database, file) actions beyond the local interface can not be controlled by local forgetting, but every storage location in which the data resides (even temporarily) must be colored and managed by the local forgetting machinery.

Figure 1 illustrates these ideas with two forgetting capabilities of different strengths: level blue, which deletes a file by removing its entry in the file index; and level red, which deletes the file using a cryptographic erasure technique.

**Fig. 1. Simulation of a forgetting aware abstract machine.** At the abstraction layer, circles represent abstract states and \(+, ++\) tbf data requiring high and low strengths of forgetting. The corresponding implementation data is indicated by red and blue within rectangles representing the implementation state.

Figure 1 shows that the programmer’s preparation marking data at the abstract level is reflected by the implementation-level instrumentation (coloring).
The vertical arrows labelled by the simulation sign show related abstract and implementation states. The propagation of annotations at the abstract level is reflected by the tracking done by the instrumentation. When the abstract level specifies forget at the + level, then the implementation executes `iforget(red)` (the file is unrecoverable), and when `aforget(++)` is specified, the implementation executes `iforget(blue)`. The grey indicates that the file is not erased but is not accessible via the file index.

Some things are outside the direct control of machine-level instructions. We assume that the registers and local data of an executing process is suitably protected from access by external processes. Other issues must be considered.

- One example is virtual memory. When a page is brought in, presumably its remote copy is freed and any colored blocks must be forgotten.
- If state is check-pointed for exploratory computation, any colored blocks copied must be forgotten if the computation fails and the original state is restored.
- A process running in a multiprocessing environment is subject to being interrupted or paused while another process runs. The forgetting mechanism must account for `tbf` data contained in saved state and make sure no `tbf` data is left exposed when state is restored. In addition `tbf` data in the unsaved process state should be forgotten during execution of the interrupting process; i.e., it should not be accessible to the foreign process.

### 4.2 Coordinating and composing forgetting capabilities

The preceding section focused on basic sequential processes which are already complex and challenging. Intentional forgetting gets even more complicated when an application or system is composed of a (possibly distributed) network of interacting processes or when the hardware supporting the implementation is considered to be made up of interconnected components (e.g., CPU, GPU, RAM, secondary storage, network interfaces), each with different capabilities for remembering and forgetting.

In the case of interacting processes `tbf` data may flow between processes. Thus forgetting instrumentation must support propagation of `tbf` annotation and forgetting instructions across process boundaries. Also, communication mechanisms, such as shared memory, buffers, pipes, buses, and sockets, must provide support for forgetting. The overall achievable level of forgetting will depend on which data flows across the interfaces, the level of forgetting that can be achieved by each process, and the forgetting achievable by the communication mechanisms. One question is whether the overall forgetting level is the minimum of the component and communication forgetting levels or if the minimal level can be improved. Using dataflow analysis should make it possible to identify `tbf` data that remains local to a process and can be forgotten locally. For example, secure communication protocols must ensure that keys and other sensitive material is not leaked in transit, when sessions end, if negotiations are aborted, or if power
fails. Protocol designs and implementations would benefit from systematic, se-
manically defined annotations to automate much of the needed protection and
provide input for verification tools.

In addition to information flow, information may be split across entities so
that no one entity has a sufficient share to be considered useful. What constitutes
forgetting in this case? Is it possible to make it sufficiently difficult to obtain
enough shares to reconstruct useful information without requiring that all shares
be forgotten?

It maybe that actions must be transactional. In this case, processes must ei-
ther succeed or forget that they tried, including forgetting all changes. Transac-
tion protocols such as two-phase commit are examples of mechanisms to prepare
for forgetting. Here, what is forgotten is a partially completed action, which, if
not forgotten, might leave sensitive information behind and leave the world in an
inconsistent and/or undesired state. In addition to forgetting (undoing) partially
complete actions if the actions involved sensitive data, additional instrumenta-
tion may be needed to make sure this data is not accessible to unauthorized
entities.

To address forgetting in cases involving composing hardware components we
must consider

- what tbf data crosses which interfaces?
- is data no longer tbf after crossed a boundary, or does it possibly require
  stronger forgetting?
- is some form of forgetting contract needed?
- where is the tbf data propagated and does it move (i.e, its original loca-
  tion should forget the data) or replicate (i.e., the data is stored at multiple
  locations)?
- the data must be suitably annotated so that the external entity knows how
to protect it
- will exported tbf data cross back to its source or cross another interface?

Flow of tbf data into one or a bank of GPUs is a particularly interesting
challenge. What is the attack model? What possible forgetting mechanisms are
compatible with efficiency requirements? Another challenge is storage systems
that use striping and replication across multiple partitions for fault tolerance.

When should tbf data be allowed to cross an interface, for example, from
local memory to a database or across a network boundary? This is a matter of
higher level policy and mechanisms to protect information in transit. It requires
communicating entities to agreed on languages for specifying forgetting policies
and supporting protocols and interfaces. What is relevant for forgetting instru-
mentation and enforcement is making sure that system interfaces are considered,
and that lower level mechanisms that cause information to cross interfaces are
exposed at higher levels to allow appropriate protections to be put in place.
5 Detectors as a measure of forgetting capability

The concept of detector is introduced as a measure of information recovery capability. A detector observes and/or probes implementation layer resources (e.g., machine state, register values) for bits and changes that reveal information (keys, indications of code executed, ...).

Detectors have several roles:

– characterizing forgetting by resistance to detection and/or recovery
– measuring the “strength” of forgetting
– modeling attack capability
– formalizing forgetting guarantees

As a forgetting measure the detector provides a way of characterizing how much data and what data or actions should be forgotten to prevent detection, reduce the confidence of an attacker, or make it prohibitively expensive.

As an attack model, a detector can be used to characterize the ability of an attacker, including what information can be extracted, the potential utility of the information and how much effort the attack requires. It can characterize and quantify an attacker’s ability to see residual information and to distinguish between machine states, for example, before and after forgetting.

As a way to formalize a guarantee, a detector can be used to specify what a component can forget. For example, a memory manufacturer could specify that it’s product supports d54 level forgetting.

It is not enough for a detector to observe bits, it must interpret the bits to recognize them as providing desired, useful information, such as an encryption key, a password, or the highest bid on an item. For this purpose, the detector needs some knowledge, such as

– general knowledge about the size and shape of the bits it needs
– specific knowledge about the application code, the data structures the code uses, what the code creates, reads, and stores
– knowledge about the machine, such as register and stack layout and usage, memory management procedures and policies, etc.
– knowledge of standard access patterns that provide clues to the operations being carried out.

In addition to what a detector can detect, given certain knowledge, a detector is characterized by the amount of effort required to succeed. Measures that are important for forgetting include the efforts to detect, use, and forget information. Work measures include time (how long detection takes), CPU cycles, memory, and possibly access to other resources. The quality of the detection and the detector’s confidence in what was detected is likely to be related to the detection effort and to the available information.

For example, an attacker that needs to decrypt cipher text might use a detector to find the corresponding decryption key stored in memory. One detector could use a brute force approach to identify all bit sequences in memory that are
plausible candidate keys. A second detector could, instead, focus on regions of memory that are used by system services or applications that are known to perform encryption. By focusing on limited regions of memory that have a higher likelihood of containing a cryptographic key, the second detector reduces the time and level of effort to produce candidate keys.

Another factor to consider is time of detection

- a detector that runs in parallel with an application, and can observe changes in shared resources concurrently or when the application is paused or interrupted.
- a detector that runs when application terminates and releases its resources
- a detector that observes execution patterns by electrical signals

Also, the time of detection relative to data generation is important. If the observation is too early, the relevant information is not available, and if it is too late, the information could be diluted by noise due to ongoing independent activities. This implies considering a measure of skill on the part of the user of a detector, or additional intelligent capabilities of the detector itself.

In Figure 1, the ++ (blue) detector could be a file recovery application that restores the “deleted” file’s index entry to the file system’s index so that it can be accessed as usual. A + (red) detector could be a sophisticated tool that watches for user access to financial or medical information and can access residual data stored in memory by a browser. Forgetting techniques to thwart such a + (red) detector are much more complex and expensive to implement than those needed to prevent the recovery of deleted files.

A Detector Algebra New detectors can be formed by combining existing detectors. In some cases, one detector may provide knowledge for a second detector to use, or, two detectors can use independent methods to detect the same thing, to increase confidence. In a distributed context multiple detectors observing at distinct locations may be more powerful than a single detector.

Realizing the potential of detectors requires the development of a theory of detectors, their capabilities, required resources, cost, complexity, and composition. The theory can incorporate and build on information theory, complexity theory, and logical inference tools. In contrast to the formal analysis of relations between abstraction layers where the set of behaviors is bounded, detectors are trying to approximate what we do not know and must expose.

A theory of detectors must

- characterize the different kinds of information that can be detected,
- measure information quality, including confidence, probabilistic, and information theoretic measures
- characterize the knowledge and other resources needed to detect and, dually, to forget
- provide measures of the work (hardness of the detection problem) required to detect its target information, and, dually, the work needed to forget
provide mechanisms for combining and composing detectors and for determining the properties of the resulting detectors in terms of the properties of the components
provide a means to measure the effectiveness of different kinds and levels of forgetting

A key aspect of the theory will be a partial order on detectors, \( d_0 < d_1 \) (read \( d_1 \) is stronger than \( d_0 \)). If \( d_0 \) can detect information \( I \), and \( d_0 < d_1 \) then \( d_1 \) also detects \( I \). Dually, if instrumented code forgets to level \( d_1 \) and \( d_1 \) is stronger than \( d_0 \) then the instrumented code is secure against an attacker of strength \( d_0 \).

The theory of detectors should not only provide a sound and rich mathematical foundation for reasoning about forgetting, it should also provide a practical foundation for specifying tbf information, for correctly instrumenting code, showing that manufacturer’s forgetting claims are valid, and for showing that instrumented code makes correct use of forgetting capabilities.

6 Related work

While our motivation for intentional forgetting is rooted in cybersecurity and privacy concerns, the need for the assurance of system correctness and reliability have motivated many computer science techniques such as those for ensuring modularity, scope of naming, synchronization of concurrent processes, and virtualization mechanisms. All such techniques provide tools to help people assert fine-grained control over the execution details of a system. In some cases, the techniques enable automated tracking of items throughout a system execution so those items can be examined or otherwise managed when necessary. In other cases, they enable aggregation of items to ensure that they are managed similarly. Many of these techniques may inform the development of intentional forgetting capabilities; some may be directly adaptable to forgetting, while the fundamental insufficiencies of others may prove instructive. The following sections highlight a few of the many areas that seem likely to inform efforts toward intentional forgetting.

*Programming language semantics* A variety of programming language constructs have some relevance to intentional forgetting. For example, many programming languages define the lexical scope, or region of a program, in which a name binding to a program object is valid [27]. Outside that scope, the binding is forgotten (i.e., the name is forgotten). Some approaches to lexical scope may prove helpful in identifying items that are tbf outside a logical region of a program.

*Language processing, execution environments, and tools for programmers* When intentional forgetting is applied at the level of application software, instrumentation techniques that assist in program execution may be relevant to intentional forgetting. For example, garbage collection [18] and ARC automate the process of software memory management. Both techniques instrument application code
as it is running to reclaim system resources that are no longer in use. In [8], Cohn-Gordon and other authors from FaceBook discuss the challenge of robust deletion in online social networks and describe their DelF deletion framework that enables developers to annotate data type definitions and use the framework to automatically map deletion actions into asynchronous, reliable and temporarily reversible operations on backing data stores. All of these techniques track data items for abstraction layer tidying and may prove instructive for cross-layer forgetting.

Synchronization techniques Forgetting requires control over the data associated with the state of the implementation layer machine. Many techniques for synchronizing processes in distributed computing or ensuring the state of a cyber-physical system address obligations for aligning states between two different types of executing systems. Such alignment is a critical element of cross-layer forgetting, as implementation layer data must be removed exactly (i.e., all of the implementation layer data that matches the abstraction layer item must be removed, but no more).

Current erasure methods Although intentional forgetting has not yet been rigorously treated, a variety of techniques for erasure or data destruction [25] have emerged to partially address the need. For example, self-encrypting memory or hard drives use encryption techniques to prevent detectors without a cryptographic key from reading stored data. Many current techniques are likely to be viable implementations of intentional forgetting. Paired with methods for rigorously specifying their capabilities (e.g., in terms of resistance to specific detectors), even weak implementations of forgetting may be acceptable in contexts where only weak detectors are present.

Modeling techniques Foundations for modeling include computational models of processes and programs at different levels of abstraction, representation of properties, and relating different levels and models.

The use of various automata (timed, IO, Mealy, Constraint, networked) and state transition systems is well known [15]. Rewrite theories [20] provide a rich formalism for describing states at many levels of detail, as well as representing transitions as rewrite rules. Such models can be directly executed. In all of these cases a trace semantics provides the basis for reasoning about execution properties. Properties as sets of traces, expressed in various logics or as mathematical formulae are the basis for reasoning about individual runs. These can be mechanically checked using tools for reachability analysis and model-checkers [5]. Hyperproperties [6], sets of traces, are important to compare executions. They allow one to express observational equivalence, information flow, and contracts.

In [10], a simulation relation is used to relate an automata model and a simple machine model of a password storage application to show that the machine can not be tricked into revealing a password. In [19], a microarchitectural model with execution semantics is used to model information that can be extracted from normally hidden microarchitecture structure and operations.
In [21], a bisimulation relation is used to show that under suitable conditions, a synchronous model of a real time system satisfies the same properties as an asynchronous, distributed model.

Observational equivalence is a notion of equivalence of programs, processes, or systems based on an ability to observe. What is observed could be output, interaction sequences, or detectibles. This capability has been well developed for concurrent and distributed programs [2] and for security protocols with and without timing considerations [9,11,13,23].

7 Research opportunities

Intentional forgetting is essential to enable systems to meet the cybersecurity and privacy requirements of users. It is a challenging capability for systems to provide and for software and hardware developers to use judiciously. Research is needed in a variety of different domains to advance the theory, specification techniques, system foundations, implementation tools, and methodologies for effective, practical forgetting. In particular, we see research challenges and opportunities in the following areas:

Theory, modeling, and formal methods Section 4 outlines several of the issues that arise in the formal modeling of forgetting across layers of abstraction. It is always a challenge to capture with appropriate fidelity the relationship between an abstraction layer and an implementation layer, but forgetting requires consideration of model fidelity from the perspective of a detector (as discussed in Section 5). Producing models of detectors that parallel real-world use cases will be essential to establishing a useful theory of forgetting. Recovery of data from accidental system damage (e.g., failures of hard drives and other components) is a very common use case, so modeling detectors that represent various data recovery paths are as important as modeling detectors that represent cyber attackers. Underlying models of detectors will be abstract machines and models of machine architectures and their representation of information. Three key challenges include 1) finding levels of detail that expose what is important to consider from an information detection perspective that are feasible to reason about; 2) developing simulation relations that capture both data and information content (these will be essential for verifying forgetting claims); 3) defining abstraction relations that allow us to prove properties of machine level execution by reasoning at a more abstract program level of execution (this will be important to make (semi-) automatic verification of forgetting properties feasible).

Methods of specification It is essential to specify not only what is true but also the forgetting capabilities, expressed in terms of resistance to detection, of the implementation layer. However, code developed for one environment may later execute in a very different environment and may be combined with other components to create new systems. Specification methods must support new compositions (e.g., system integration processes) and new environments (e.g., shifting
from on-premises execution to a cloud-hosted environment) to enable access to forgetting functionality and enable the assurance of the forgetting capabilities of the composed system. Assurance might take the form of formal arguments, such as mathematical proofs, statistical arguments, or information flow arguments. System architecture and physical properties also could contribute to assurance arguments. Research into methods for specifying intent to forget and the forgetting capabilities of a system, along with forgetting-related constraints on composition or deployment environments will be necessary to build a language for interested parties to communicate precisely about forgetting. An important component of this research will be identifying conceptual abstractions at the specification, program, and implementation levels that can be successfully used by non-experts in designing and developing systems.

System foundations Important conceptual properties often require foundational support from the system. Distributed and other concurrent systems require synchronization primitives that might be implemented via shared memories, locks based on interrupt signals, or synchronization protocols. Cryptographic software relies on a system-provided source of randomness (or often, pseudo-randomness). Virtualization of every kind relies on a suite of system functions to record, map, schedule, copy, and signal. On what hardware and software system foundations will forgetting concepts rely? What new program abstractions will help ensure correct forgetting? How must these new (or repurposed) system functions be designed to safely interact with other system functions?

Persistence Technologies for ensuring data persistence have evolved and driven changes in computer system architecture. Until recently, Random Access Memory (RAM) has required a constant source of power to maintain a representation of stored data. When data stored in RAM is ephemeral, programmers grouped data items together into a file that could be written to secondary storage media (e.g., magnetic media such as drives or tapes). Recent technology advances are enabling architectural changes at the level of a computer [28] and at the level of a distributed, cloud-hosted file system [24]. Computer architecture may change considerably due to the development of non-volatile main memory (NVMM) technology, which provides persistent storage (i.e., data remains in the memory after the system is powered off and can be accessed again when it is powered on again), and distributed systems architectures have changed considerably due to the availability of Internet-accessible cloud-hosted storage systems that can store an immense amount of data. With such technologies in wide use, the meaning and expectation of data persistence is shifting. Some detectors may be intentionally architectured through system design processes. Is persistence the dual of forgetting? It is possible that a better understanding of both forgetting and persistence could emerge if these concepts were studied together? Do stronger persistence capabilities necessarily lead to weaker forgetting capabilities (i.e., are the two concepts competitive or synergistic duals?)
Tools Conceptual, software, and hardware tools are all essential to support specification, reasoning, and implementation of forgetting. Without purpose-built forgetting tools at every layer of abstraction, ad hoc attempts to erase information will lead to ongoing misunderstandings about the quality of erasures and additional rounds of cat-and-mouse with cybersecurity researchers and attackers. How can tools that support forgetting provide high assurance against various detector models and be efficient enough for real-world use? Performance issues have limited the applicability of system instrumentation techniques for a variety of useful properties. Can the performance of forgetting tools be designed to scale with the demands of detectors (i.e., a stronger forgetting capability requires more tolerance for system performance impacts)?

Methodology for effective forgetting What are best practices for forgetting information? When to forget? How should the need for forgetting be balanced against the need for accountability or timeliness in a system? For example, when an application is designed to assiduously log every action, how should a forget instruction be interpreted? Over time, software engineers have defined design patterns to capture engineering best practices. Will these patterns adapt to incorporate forgetting? Will new patterns emerge as system designers identify best practices for cleaning up or shutting down that incorporate forgetting as a step in a larger process?

Forgetting in nature Natural processes have been used in support of computing. For example, natural processes that exhibit randomness, such as cosmic ray flux, can be used as sources of entropy for strong cryptographic systems. Are there natural forgetting processes that might provide insights or help to support strong forgetting mechanisms or measures? During sleep, synaptic connections are broken and cleared biochemically to make room for new connections. Wind and rain erase footprints and tire tracks. Is there a physics of forgetting that we can leverage?

Artificial intelligence and cloud storage When a system architect, designer, or developer is building on a well-defined implementation layer, forgetting is challenging even in the presence of weak detectors. Forgetting will be more challenging when detectors gain access to a tremendous volume of data and capabilities for information inference. For example, an attacker that can access files of passwords previously leaked from a variety of systems may be able to supplement local information to more quickly infer sensitive system information that would be effectively forgotten with respect to locally constrained detectors. Must the detector concept itself be extended to account for detectors that can use externally gained contextual information to infer local information? How should we approach intentional forgetting when powerful AI systems and enormous cloud-based storage systems offer such tremendous reasoning assistance and memory aids to detectors?
To advance the goal of enabling intentional forgetting, research is needed in many domains. The topics and questions above are only a few examples of research areas that require attention.

8 Conclusion

This position paper introduced the concept of intentional forgetting and discussed the capabilities that are needed to enable it. Intentional forgetting is important for traditional types of applications and systems and emerging IoT and cloud-based systems. Big data and powerful learning and reasoning algorithms amplify the challenges in forgetting by providing powerful observation capabilities.

While current technologies instrument systems to keep track of data or enable data deletion (e.g., garbage collection, encrypted memory), they do not enable a general forgetting capability. However, these instrumentation technologies offer a foundation of knowledge that can inform advancements in systems design to support intentional forgetting. Essential to intentional forgetting is the ability to clearly specify and rigorously reason about the forgetting capability provided by a system. We have discussed approaches to modeling computations at both the system abstraction and implementation layers, and highlighted the need to model detectors.

Developing intentional forgetting capabilities that are robust enough to support the cybersecurity and privacy needs of future systems will require research advances in a variety of theoretical and systems-oriented domains. We reviewed a number of well developed techniques to build on and use for inspiration. However, real progress will require cross-disciplinary collaboration and fundamentally novel approaches.

We hope readers are intrigued by the challenges and are motivated to contribute to the research that will one day result in a robust theory and practice of intentional forgetting.

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