BRON
Linking Attack Tactics, Techniques, and Patterns with Defensive Weaknesses, Vulnerabilities and Affected Platform Configurations

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Abstract—Many public sources of cyber threat and vulnerability information exist to serve the defense of cyber systems. This paper proposes BRON which is a composite of MITRE’s ATT&CK MATRIX, NIST’s Common Weakness Enumerations (CWE), Common Vulnerabilities and Exposures (CVE), and Common Attack Pattern Enumeration and Classification, CAPEC. BRON preserves all entries and relations while enabling bi-directional, relational path tracing. It exploits attack patterns to trace between the objectives and means of attacks to the vulnerabilities and affected software and hardware configurations they target. We inventory and analyze BRON’s sources to gauge any gap between information on attacks and information on attack targets. We also analyze BRON for information that is a by-product of its mission.

I. INTRODUCTION

Cyber threats are harmful and hard to defend against. However, multiple sources of information about potential threats and vulnerabilities are publicly available to help. These kinds of sources are intended to be used by cyber security specialists and threat hunters to develop cyber defense strategies, operations and tactics. This paper takes an interest in these sources, aiming to fuse a coherent, purposefully selected set in a way that provides additional support and ease of use.

One source we will explore is the MITRE ATT&CK matrix [7], [24], [23]. It abstractly describes cyber attack Techniques organized across twelve sequenced cyber attack Tactics. One Tactic is Persistence, occurring after Initial Access and before Privilege Escalation. ATT&CK lists T1098/004 as a Technique that achieves persistence. This technique describes a type of enterprise account manipulation through SSH authorized keys [8].

We also explore two other database sources in the NIST National Vulnerability Database (NVD). The NVD provides information on security-related software flaws, related product configurations, and impact metrics. Both sources – the Common Weakness Enumerations (CWE) [11] and Common Vulnerability Enumerations (CVE) [10] – are built upon and fully synchronized with lists maintained by MITRE.

The CWE enumerations are a community-developed source of software and hardware weakness types. “Weaknesses are flaws, faults, bugs, and other errors in software and hardware design, architecture, code, or implementation that if left unaddressed could result in systems, networks, and hardware being vulnerable to attack.” [12] CWE-269: Improper Privilege Management is an example CWE entry, i.e. a Weakness. It is described as software that “does not properly assign, modify, track, or check privileges for an actor, creating an unintended sphere of control for that actor” [13].

The CVE list holds publicly known cybersecurity vulnerabilities. In its context, a Vulnerability is defined as a “weakness in the computational logic (e.g., code) found in software and hardware components that, when exploited, results in a negative impact to confidentiality, integrity, or availability.” [19] Each CVE entry, i.e. Vulnerability, contains an identification number, a description, and at least one reference—for publicly known cybersecurity vulnerabilities. Additional entry information can include fix information, severity scores and impact ratings according to the Common Vulnerability Scoring System (CVSS), and hyperlinks to external exploit and advisory information [14]. CVE-2019-12183 is one example of a CVE Vulnerability [17]. The Vulnerability description is “Incorrect Access Control in Safescan Timemoto TM-616 and TA-8000 series allows remote attackers to read any file via the administrative API.” The entry’s severity score is 7.5 (High).

About half the time, a CVE entry has a relational link to a CVE entry. For example, Weakness CWE-269 links to CVE-2019-12183. The relationship implies that the Vuln-
ability is an example of the (type of) Weakness. In this case it indicates that Safescan's TimeMoto® Intelligent Time Clock has a vulnerability in firmware that could lead to improper privilege management. The CVE entry provides a field with severity score in CVSS format and Known Affected Hardware or Software Configurations. These Affected Product Configurations (or Affected Prod Conf’s, our abbreviations) document specific software or hardware releases that are affected.

Affected Product Configurations specifically are of interest, because, with an inventory, security operators and analysts can regularly scan them to be alerted to specific targets within their systems.

In addition to ATT&CK Tactics and Techniques, NVD CVE Weaknesses, NVD CWE Vulnerabilities and Affected Product Configurations, we also explore MITRE’s Common Attack Pattern Enumeration and Classification (CAPEC) list. CAPEC enumerates and classifies Attack Patterns to support identifying and understanding attacks. An example of an Attack Pattern is CAPEC-142: DNS Cache Poisoning.

Of compelling interest are Attack Patterns that connect the ATT&CK matrix to the CWE source. Such Attack Patterns function as bridges that relate a Technique to a CWE entry, i.e. Weakness, hence they tie a means of attack (serving a specific tactical objective, i.e. Tactic) to its targeted weakness. Since a Weakness in CWE can link to a Vulnerability in CVE, and that entry can link to specific Known Affected Hardware or Software Configurations, Attack Patterns with this “end-to-end” linkage are means of connecting all the way from a Tactic that an attacker may choose, to specific Known Affected Hardware or Software Configurations that could be affected. Vice versa, given some Affected Product Configuration, these Attack Patterns make it possible to see what Tactic and Techniques an adversary could use to target it.

In a top-down example, a Discovery Tactic with a Technique named System Network Configuration Discovery links to CAPEC-309, Network Topology Mapping which is related to Weakness CWE-200, Exposure of Sensitive Information to an Unauthorized Actor. For this Weakness there are 6,624 Vulnerabilities such as CVE-2018-8433, Microsoft Graphics Component Information Disclosure Vulnerability. CVE-2018-8433 is linked to 15 Affected Product Configurations.

Figure 1 schematically depicts our selected threat (i.e. Tactics and Techniques) and defensive target (i.e. Weaknesses, Vulnerabilities, and Affected Product Configurations) and Attack Patterns information sources and their relational linkage. This composite set of information enables both cyber-hunting and reactive, preventative and forensic security analysis on strategic, operational and tactical levels.

Beyond the schematic’s abstraction, unfortunately, the extent of the relational information in this composite set is not reported. For example, CAPEC-142: DNS Cache Poisoning is related to six CWE Weaknesses: (CWE-348, -345, -349, -346, -441 and -350) according to the CAPEC. However none of these Weaknesses are linked to a Vulnerability and whether or not it is linked to a Technique is unknown without full enumerative search of a different information source. To date, these sources have never been aggregated nor holistically examined.

Essentially, ATT&CK tells us the tactics and techniques that attackers could inflict upon a vulnerable system. The CWE, CVE and Affected Product Configurations inform us as to where those weaknesses and vulnerabilities exist in a system. Attack patterns link potential attack actions to weaknesses that would become attack targets. While it is possible to span sources, tracing paths in some directions can be improved to require less exhaustive efforts.

For these reasons, we present BRON. BRON follows the schematic (see Figure 1) and combines the entry data from these sources, preserving their internal and external linkages. It uses a graph to represent the unified data. Each layer of the graph denotes a different source. It is possible to traverse the graph from abstract Tactics all the way down to concrete Affected Product Configurations by following BRON’s bi-directional paths. One can start from ATT&CK Tactics, find their Techniques, then cross information sources via CAPEC Attack Pattern linkage, to Weaknesses then Vulnerabilities and Affected Product Configurations. Nodes within a layer are entries from the source. For example, the second top-most layer has all Techniques, and the second from the bottom has Vulnerabilities. Edges in the graph correspond to relational links between entries from different sources.

While these links are not bi-directional in the sources, they can be traversed bi-directionally in BRON’s graph. This makes it easy to trace back the relational connections among the sources, when, in their original form, this cross-referencing is not supported. BRON offers a more coherent access point to new data consumers of these sources. It lowers the entry bar for performing cross-referenced analyses and enables analysts to think more contextually about attacks and vulnerabilities.

We have open-sourced BRON and with example data analyses. They inventory BRON and showcase how it can be used to explore the complex information within its sources. In this paper we present these analyses and also demonstrates BRON’s investigative power. Our efforts offer both the elu-

Fig. 1: Schematic of BRON’s graph of the combined sources. Source and list entries are nodes and relational links are edges. In the original source most types of links are uni-directional. The graph facilitates search in the opposite direction of the source links.

https://github.com/ALFA-Group/BRON
cification of these high-value information sources and their relationships, and conceptual and operational convenience.

The contributions of this paper are:

- **BRON**: a graph that stores and unifies an explicit set of security information sources while preserving the inter and intra relationships of their entries. BRON offers convenience and coherence.
- An inventory of BRON that reveals the extent of the public sources and their inter-relationships.
- A preliminary demonstration of BRON’s ability to support exploration of the information.
- Open source of BRON and our analyses.

Section II describes the sources more formally, how we assembled the graph, and how we use it for analyses. Section III describes our analyses. Section IV situates BRON within related sources. Section V concludes with BRON’s concept, the outcome of our analyses and summarizes BRON’s key purpose. Finally, Section VI presents future work.

II. DATA AND IMPLEMENTATION

We present the information sources BRON combines in Table I. There is documentation available for all sources online, see [1], [2], [11], [10], [16].

1) BRON Implementation Overview: BRON is implemented as a relational graph which represents the entries of its different information sources as specific types of nodes and their internal and external linkages as edges. Links that are unidirectional in the sources are tagged as such and represented bi-directionally in BRON’s graph. A BRON graph node has properties which are the (verbatim) information on the specific entry. Node properties have been standardized across the different entry types for ease of analysis and extension, e.g. we maintain the CPE notation for Affected Product Configuration.

To reference BRON’s information is to therefore query a graph. For example, to quantify relationships, we trace edges and count them and/or nodes. Since it uses a bi-directional graph, BRON offers path finding all the way from abstract attacker tactical goals, such as Persistence, down to the specific applications that can be targeted as part of an attack, or vice versa. This can be done with its information sources “in the wild”, but less conveniently. BRON essentially eliminates the need for enumerative search needed to invert a directional link. BRON offers direct searching capability originating from any node, and makes it possible to traverse along any edge relation, starting and ending from any two entries of different sources.

2) Analysis data: We use BRON to collect products of a vendor by parsing the CPE notation for Affected Product Configurations which includes the vendor, product, and version.

The data for Figure 12 are extracted by finding the number of products of each vendor that are vulnerable to each Tactic. We find the set of Tactic reachable by any version of each product via path tracing. If multiple versions of a product are affected by the same Tactic, that product is counted only once for that Tactic. Similarly, the data for Figure 13 are extracted by finding the number of versions of each vendor product that are vulnerable to each Tactic. We find the set of Tactics reachable by each version of a vendor product via path tracing.

The data for Figure 13a are extracted by finding the severity scores of products of each vendor. Products are referenced within Vulnerabilities which also have severity scores. Since a product may link to multiple Vulnerabilities with each Vulnerability having its own severity score, we take the maximum severity score among the product’s set of Vulnerabilities as that product’s severity score. We plot the distribution of severity scores for products of each vendor. Similarly, the data for Figure 13b are extracted by finding the severity scores of products of each vendor that are exposed to the Tactics of Discovery and Defense Evasion. We find the subset of products of each vendor that is reachable by the specific Tactic via path tracing. For that subset of products, we take the maximum severity scores of Vulnerabilities linked to each product as that product’s severity score. We plot the distribution of severity scores for products of each vendor reachable by the Tactics of Discovery and Defense Evasion. The data for Figure 16 are extracted by using all severity scores of all Vulnerabilities linked to each vendor product.

III. ANALYSES

We used the data available from the information sources in Table I as of March 2020 and updated only the CVE data as of June 2020 to populate BRON. All code and data for the analysis are available in Python with tutorials in Jupyter notebooks. Our analyses are organized by different lenses. In Subsection III-A we inventory BRON’s entries and relations. In Subsection III-B we describe the paths from Vulnerabilities. In Subsection III-C we use BRON to analyze vulnerability severity. In Subsection III-D we investigate the paths. In Subsection III-E we explore some example queries. In Subsection III-F we consider a set of vendors and count the number of Techniques (per Tactic) that target their products. In Subsection III-G we examine the severity scores for some vendors. Finally, we apply a specific product lens (web browsers) for Tactic analysis in Subsection III-H.

A. Entry and Relational Analyses

Our first set of analyses determine the breadth and depth of the entries and relations within BRON. This involves counting BRON’s nodes and edges by type using different filters. The analyses are at different resolutions. First, we look at BRON in the aggregate, followed by considering each source (a.k.a. entry type). Finally, we consider severity scores.

1) Aggregate Entry and Relational Analysis: We start by aggregating the number of entries by information source and investigating the relational connectivity between them. By source, we visualize how many entries are connected in Figure 7. We observe what we call “Floating Entries”, i.e. entries that are isolated or “orphaned”. Only a small fraction of Techniques are Floating Entries (1 of 266). By definition, no Weaknesses or Affected Product Configurations are Floating Entries. There are however two obvious sets of Floating Entries. Of the 71, 715 Vulnerabilities, 28% are floating entries. Of the 519 Attack Patterns, 25% are Floating Entries. This draws attention to a level of incompletion within BRON. However, BRON’s sources are constantly being updated and
Affected Product Configuration

The number of Vulnerabilities how this changed the quantities of relational connections not the most recent version of a software product and examined BRON of Windows. A vulnerability in Windows 10 may extend to all prior versions has been latent, many historical versions of the same software product. Depending on how long a s are different versions and, further, inquire into the key Attack Patterns, those that relationally unify Techniques and Weaknesses.

Techniques can serve more than one Tactic, and we observe that each of the 266 Techniques serves at least one Tactic but very few serve multiple Tactics. The Technique Valid Accounts serves two Tactics, and six Techniques each serve three Tactics. We can inventory Technique and Attack Pattern relationships. The relationship associates the means of an attack, i.e. Techniques, to the attack itself. We find that 74% of the Techniques are not associated with any Attack Pattern. Each of the remaining Techniques, except for two, serve only one Attack Pattern. The two exceptions are (1) the Supply Chain Compromise which serves three Attack Patterns and (2) Endpoint Denial of Service which serves four Attack Patterns. From a Technique analysis, an overall lack of relational information connecting the objectives of Tactics and the means of Techniques with Attack Patterns becomes apparent. We will next look at Attack Patterns to consider their relations to Techniques and, further, inquire into the key Attack Patterns, those that relationally unify Techniques and Weaknesses.

Pivoting to Attack Patterns, we can recall that of the 519 Attack Patterns, 25% are Floating Entries. They are named attacks with no indication of how they could be accomplished or what weakness in a system they would exploit. We observe that only 10% of Attack Patterns span both Techniques and Weaknesses. Per Figure 3c, most Attack Patterns only have one relational link and, at most, an Attack Pattern has 13. There are 3 Attack Patterns with 13 relational links:

1) Using Leading ‘Ghost’ Character

TABLE I: BRON information sources and types, organization and short descriptions.

| Source and Type of Entry | Organization | Description |
|--------------------------|--------------|-------------|
| ATT&CK Tactics [7]       | MITRE        | 12 common tactics of attack staging. The columns of the ATT&CK matrix. |
| ATT&CK Techniques [7]    | MITRE        | Means of achieving a tactical objective, organized by Tactic, the row elements of the ATT&CK matrix. In BRON, a Technique is a child of a Tactic. |
| CAPEC Attack Patterns [9] | MITRE | A naming of a relational concept linking to a Technique (parent) and/or Weakness (child). Relates to abstract how and why (Tactic and Technique) of an attack objective and/or to abstract “where” (Weakness) target of the attack. |
| NVD CWE Common Weakness Enumeration [11] | NIST | Security-related flaws in architecture, design, or code. |
| NVD CVE Common Vulnerabilities and Exposures [13] | NIST | Security-related flaws in software and applications. |
| NVD CVE entry field: Known Affected Hardware or Software Configuration | NIST | Specific software application or hardware platform releases that are affected, given a parent Vulnerability. Abbreviated herein as Affected Product Configuration. We follow the Common Platform Enumeration (CPE) naming specification for Affected Product Configurations [15] that is used in this field. |
| NVD CVE entry field: Severity score [4] | NIST | Severity is scored using the Common Vulnerability Scoring System (CVSS). The higher the score, the greater the impact of a Vulnerability. CVSS scores range from 0 to 10. |

![Fig. 2: Visualization of BRON with Vulnerabilities from 2015-2020 and only the latest version of Affected Product Configurations.](image-url)

that Techniques are a more recent source of information. A valid question is whether it will ever be possible to keep up.

Figure 2 also show Super Entries which equate to specific entries that are the destination and/or source of many relational cross-references, i.e. nodes with many edges. We expect Super Entries given that there are many more Vulnerabilities and Affected Product Configurations than other entry types. These naturally will be more densely inter-connected. We find that many Affected Product Configurations are different versions of the same software product. Depending on how long a Vulnerability has been latent, many historical versions of the software may be affected when it is identified. For example, a vulnerability in Windows 10 may extend to all prior versions of Windows. BRON presently compiles Vulnerability data dating back to 1999 so this could explain Super Entries. We therefore filtered out Affected Product Configurations that were not the most recent version of a software product and examined how this changed the quantities of relational connections between Vulnerabilities and Affected Product Configurations. The number of Affected Product Configurations decreased approximately 80%, from 219,767 to 42,061 and the number of links of both Affected Product Configurations and Vulnerabilities also decreased significantly.

2) Source Analysis: We next focus on each information source.

Starting with Tactics, see Figure 3a, we find that all of the Tactics are linked to at least 10 Techniques. Recall ATT&CK is a matrix of Techniques, organized by a column per Tactic, and a link implies that a Technique serves the tactical objective named by the Tactic. The number of Techniques serving each Tactic varies. Several Tactics are served by a number of Techniques. However, the magnitude of the difference between the Tactic with the least and most links is 62 (while the median number of relational links is 22.5). The Tactic served by the most Techniques is Defense Evasion which is linked to 72 Techniques.

Techniques can serve more than one Tactic, and we observe that each of the 266 Techniques serves at least one Tactic but very few serve multiple Tactics. The Technique Valid Accounts serves two Tactics, and six Techniques each serve three Tactics. We can inventory Technique and Attack Pattern relationships. The relationship associates the means of an attack, i.e. Techniques, to the attack itself. We find that 74% of the Techniques are not associated with any Attack Pattern. Each of the remaining Techniques, except for two, serve only one Attack Pattern. The two exceptions are (1) the Supply Chain Compromise which serves three Attack Patterns and (2) Endpoint Denial of Service which serves four Attack Patterns. From a Technique analysis, an overall lack of relational information connecting the objectives of Tactics and the means of Techniques with Attack Patterns becomes apparent. We will next look at Attack Patterns to consider their relations to Techniques and, further, inquire into the key Attack Patterns, those that relationally unify Techniques and Weaknesses.
Sequences to Bypass Input Filters,
2) Manipulating Web Input to File System Calls, and
3) Using Slashes in Alternate Encoding.

All 13 links of each of these Attack Patterns span from Attack Pattern to Weakness. None of the links relate the Attack Pattern to a Technique. The Attack Pattern Remote Services with Stolen Credentials identifies the most means of attack – 4 through its 4 Technique links. It also links to one Weakness – CWE-522 Insufficiently Protected Credentials.

One can think of an ideal Attack Pattern as a bridge. It connects an attack to how it is executed and to where it is targeted. At this point in time, BRON users could benefit from more connected relational bridges. It is reasonable to expect that future efforts will more completely enumerate Attack Patterns to assure a more relationally informative set of sources. However, given threat assessment technologies make use of these sources, this inventory-based analysis reveals possible blind spots.

Analyzing the number of links to and from each Weakness entry, we observe a large comparative increase (orders of magnitude) in the range, see Figure 4 versus the information sources we have just analyzed. When, regardless of year, relationships to and from each Weakness entry are counted, the range is the highest for all information sources at 12,291. The facts that Vulnerabilities, to which Weaknesses connect, have the greatest quantity of entries and that Weaknesses are general abstract concepts which explains this ranking.

Around 45% of Weaknesses are targets identified by Attack Patterns. Does this imply that there exist no attacks targeting 55% of the Weaknesses? Or, is the record lacking? The Weaknesses with large number of relations are mostly connected to Vulnerabilities and are identified as the targets of attacks. The Weakness Information Exposure is a target of 57 Attack Patterns (the highest number among Weaknesses) and it further details 6,624 Vulnerabilities, i.e. more specific targets. The Weakness CWE-79, Improper Neutralization of Input During Web Page Generation, (Cross-Site Scripting) connects to the most Vulnerabilities at 1,292. Six Attack Patterns identify this Weakness as a target. However, 44% of these Vulnerabilities date before 2015. When we focus only on Weaknesses from 2015-2020, the range of number of Vulnerabilities decreases significantly but is still quite substantial with several Super Entries. In the future, we can look at parent-child connections within Weaknesses to better understand the extent of comprehensive linking.

Moving to Vulnerabilities, most Vulnerabilities on average, regardless of what years they were reported and how many Affected Product Configuration versions are referenced, tend to connect to 600 or fewer entries, either Weaknesses or Affected Product Configurations. Figure 5 shows four combinations of connections: all or recent Vulnerabilities, and all or latest Affected Product Configurations. The distribution when all Affected Product Configuration versions are referenced is right-skewed with a long tail. The distribution when only the latest version of Affected Product Configurations is used is also right-skewed but has a shorter tail. As would be expected when removing earlier versions of a software application from consideration, many Vulnerability Floating Entries emerge and the number of Super Entries decreases drastically. When we filter down to only recent Vulnerabilities, while considering all Affected Product Configuration entries, we observe an increase in the number of Floating Entry Vulnerabilities but we see a decrease when the number of Affected Product Configuration entries decreases.

Severity scores are assigned by CVE Numbering Authorities (CNAs). All 10 members of this vendor set are CNAs. Although CVSS is an industry-standard, the calculated severity score within a vendor and among vendors is likely to vary. Variance can depend on the interpretation and details within vulnerability report. Additionally, analysts who calculate severity scores for vulnerabilities that do not contain sufficient details and data assume a worst-case scenario and assign a 10 to Vulnerabilities with no information. As a result, some vendors may have Vulnerabilities with higher severity scores because of missing data.

The Vulnerability with the most connections, when all versions of an Affected Product Configuration are considered, is CVE-2016-1409. This describes a bug in Cisco IOS

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Fig. 3: Plots showing relational linkage statistics for (a) Tactics, (b) Techniques, and (c) Attack Patterns.

![Fig. 3: Plots showing relational linkage statistics for (a) Tactics, (b) Techniques, and (c) Attack Patterns.](https://nvd.nist.gov/vuln-metrics/cvss)
that creates a vulnerability to Denial of Service attacks. It has a severity score of 6.25 (on the CVSS scale of 0 to 10). However, the Vulnerability with the most connections changes when only the latest version of any Affected Product Configuration is considered. It is CVE-2020-0551 which describes a vulnerability in an Intel product with a severity score of 3.75.

In general, the large portion of floating Vulnerabilities indicates a gap between the data informing its users of an abstract vulnerability - i.e. what types or features of products pose risk versus informing them of an operational vulnerability that indicates specific products and versions that are affected and indicates what may need to be patched or updated. In addition, Figure 5 shows difference of which CVEs to select and which versions to use for analysis. It verifies what we expected regarding version “noise”. This can be useful when considering versions of applications.

Affected Product Configuration connection statistics are shown in Figure 6. The distribution when all versions are referenced is right-skewed with a long tail. The distribution when only the latest version of Affected Product Configurations is referenced is right-skewed but has a shorter tail. The vendor and product that has the most connections spanning Vulnerabilities and its versions is Linux Version 8 from Debian. However, when we only consider one version of a Affected Product Configuration, the Affected Product Configuration with the most connections is a Windows Server from 2012. The Debian Linux 8 connections decrease because there are more recent versions of Debian Linux. We see a similar pattern when focusing on more recent Vulnerability data. Debian Linux 8 is the most commonly linked Affected Product Configuration when all versions are considered, but a version of Windows 8 RT (which is discontinued) is the most commonly linked when only the latest version of a product is considered. We can observe how the tail of the connection distribution shrinks as more recent data is in focus and multiple older versions are filtered, see Figure 6.

We provide precise aggregate source and connective quantities in Table II. We consider every version of a Affected Product Configuration. The mean number of links from a Tactic to a Technique is 28.4 (stdev 18.9), and the mean number of Weakness links is 8.16 (stdev 46.70).

### B. Vulnerability paths

We can also consider paths connecting through Vulnerabilities, dubbing them Vulnerability paths. Figure 7a shows yearly trends of how many such paths start from, respectively, a Tactic, an Attack Pattern, or a Weakness, and end at a Vulnerability. It also shows how many Vulnerabilities are
TABLE II: BRON source and relational quantities for non-Floating Entries. Median refers to the median number of relations in or out of an entry. The rightmost column provides the lowest and highest counts of entries’ relations with the range in brackets.

| Source                      | Total Entries | Median No. of Links | Count Range |
|-----------------------------|---------------|---------------------|-------------|
| Tactic                      | 12            | 22.5                | 10-72 (62)  |
| Technique                   | 266           | 1                   | 1-4 (3)     |
| Attack Pattern              | 519           | 1                   | 1-13 (12)   |
| Weakness                    | 314           | 4                   | 1-12,292 (12,291) |
| Vulnerability               | 144,594       | 1                   | 1-4,891 (4,890) |
| Affected Prod Conf          | 219,767       | 1                   | 1-2,573 (2,572) |

The amount of Floating Entry severity was unexpected when we tried to answer questions about where the severity was, see Figure 3 The length of the tails for the different public threat data types are very interesting. Does that imply categorization error (should have more refined categories) or that some analysts spend more effort finding and writing out the vulnerabilities?

D. BRON’s Longest Paths

A central merit of BRON is that it unifies independent sources to provide a seamless set of paths that connect them to one another. To showcase this, we consider the longest paths within BRON that run between Tactics and Affected Product Configurations. A sample of these sets can be examined by querying BRON for all entries connected to the Persistence Tactic (TA0003). This set is outlined in Figure 10. One example path is from the Persistence Tactic to the Google Chrome product.

The entries in this path are:

- **Tactic** (TA0003) Persistence: The adversary is trying to maintain their foothold. Persistence consists of techniques that adversaries use to keep access to systems across restarts, changed credentials, and other interruptions that could cut off their access. Techniques used for persistence include any access, action, or configuration changes that let them maintain their foothold on systems, such as replacing or hijacking legitimate code or adding startup code.
- **Technique**: (T1574) Hijack Execution Flow, Adversaries may execute their own malicious payloads by hijacking the way operating systems run programs. Hijacking execution flow can be for the purposes of persistence, since this hijacked execution may reoccur over time. Adversaries may also use these mechanisms to elevate privileges or evade defenses, such as application control or other restrictions on execution.
  - **Sub-Technique** (T1574.010) Services File Permissions Weakness. Adversaries may execute their own malicious payloads by hijacking the binaries used by services. Adversaries may use flaws in the permissions of Windows services to replace the binary that is executed upon service start. These service processes may automatically execute specific binaries as part of their functionality or to perform other actions. If the permissions on the file system directory containing a target binary, or permissions on the binary itself are improperly set, then the target binary may be overwritten with another binary using user-level permissions and executed by the original process. If the original process and thread are running under a higher permissions level, then the replaced binary will also execute under higher-level permissions, which could include SYSTEM.
- **Attack Pattern** CAPEC-17: Using Malicious Files An attack of this type exploits a system’s configuration that allows an attacker to either directly access an executable file, for example through shell access; or in a possible worst case allows an attacker to upload a file and then execute it. Web servers, ftp
servers, and message oriented middleware systems which have many integration points are particularly vulnerable, because both the programmers and the administrators must be in synch regarding the interfaces and the correct privileges for each interface.

- **Weakness** (CWE-264) Permissions, Privileges, and Access Controls
- **Vulnerability** CVE-2011-1185
  - Known Affected Hardware or Software Configuration cpe:2.3:a:google:chrome:*:*:*:*:*:*:*:*, Up to (excluding) version 10.0.648.127.
  - Vendor-Product: extracted as 3rd and 4th fields of Known Affected Hardware or Software Configuration, obtaining Google Chrome.

A brief top-down narration of this path is: Given an attack’s objective is Persistence, an attack Using Malicious Files, by means of exploiting a Services File Permissions Weakness Technique, could be used to hijack execution flow and run a malicious binary due to Permissions, Privileges, and Access Controls weaknesses in all versions of Google Chrome “before 10.0.648.127”. These “do not prevent (1) navigation and (2) close operations on the top location of a sandboxed frame”.

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**Fig. 7:** Number and percentage of Vulnerabilities reported by year connected to a Tactic, Attack Pattern, or Weakness. Note 2020 has only \( \approx 5 \) months of data. In general, the number and percentage of Vulnerabilities connected to each data type is increasing over the years.

**Fig. 8:** Annual Total Severity and Non-demonstrated Severity. Note 2020 has only \( \approx 5 \) months of data.

**Fig. 9:** Severity scores when referencing all Vulnerabilities from 1999-2020 or only recent Vulnerabilities from 2015-2020. Operational and non-demonstrated severity are shown.
Bottom-up, the narration of this path is: If any of a given network’s computers are running Google Chrome versions before 10.0.648.127, the administrators need to be on alert for the browser being hijacked to execute a malicious payload that can achieve persistence by exploiting services file permission weaknesses that allow the attack to run at a higher permission level where they can replace legitimate binaries with malicious ones.

We next select Oracle’s product Argus Safety. It has a vulnerability that allows an attacker with low privilege and network access via HTTP to compromise Argus Safety. This can impact additional products and result in unauthorized update, insert or delete access to some of Oracle Argus Safety accessible data, as well as unauthorized read access to a subset of Oracle Argus Safety accessible data. In the second row, we query BRON for the means of attacking this vulnerability. BRON identifies 13 Techniques one of which is T1553.004 Install Root Certificate.

We then select Google Chrome and, in the third row, ask BRON about the attack patterns it is involved in and the tactics which an attack may be pursuing that target the browser. We find out that five different tactics can target the browser, one of which is Privilege Escalation. We also find out that the browser is the vulnerability endpoint of 147 attack patterns, e.g. UDP Scan. Since Chrome has many versions, we compare the same information in BRON about two versions in the 4th and 5th rows to see the difference in exposure. We choose a recent and older version. The older version (5.0.375.0) serves the objective of 4 tactics, while the more recent version (v52.0.2743.82), lists no tactics. The more robust recent version also shows a reduction in attack patterns from 12 to the older’s 120.

F. Vendors and Tactics

In Figure 11 we pursue the idea of isolating vendor information within BRON. How many times is a vendor cited in an Affected Product Configuration? While some vendors are cited in a large number of Affected Product Configurations, most vendors are cited in few fewer. Even when referencing all versions of an Affected Product Configuration, the vast majority of vendors have fewer than 1,000. When only one version of Affected Product Configurations is referenced, most vendors have fewer than 250 Affected Product Configurations. This difference shows that many vendors are represented by multiple Affected Product Configurations of one product.

We decide next to focus upon a smaller set of vendors whose products have significant market share and are likely, therefore, to have significant representation in BRON. We approximate market share by selecting the top 10 technology vendors in the Fortune 500. Members of our “Top-10” are Apple, Google, Microsoft, Dell, IBM, Intel, HP, Facebook, Cisco and Oracle.

Depending on Tactic, how many exposures do the Top-10 vendors have? Figure 12 is a heat map that shows the number of unique products for each vendor that are exposed to each Tactic. For each Tactic, looking column-wise, the map provides a count of how many different products of each vendor are vulnerable to it. A row is provided for each vendor. Intel has many more unique products that are vulnerable to Defense Evasion and Discovery tactical objectives compared to other Tactics or other vendors. For example, Intel has 1,369 products exposed to Defense Evasion and 1,084 products exposed to Discovery, while it has 54 or fewer products exposed to each of the other Tactics. In general, more products are exposed to Discovery, Defense Evasion, Persistence, and Privilege Escalation than the other Tactics. Scanning across rows, for each vendor, we

**E. Example Queries**

Given Persistence or any other Tactics, BRON can be used to retrieve the related Techniques, Attack Patterns connected to the Techniques, the Weaknesses connected to the Attack Patterns, the Weaknesses connected to the Vulnerabilities, the Affected Product Configurations listed within Vulnerabilities, and the Vendor and Product field in the Affected Product Configuration entry formatting. This powerful capability allows interesting queries to be posed of BRON by coding in e.g. Python.

Some examples are shown in Table 11. We start, in the first row, by asking about the Affected Product Configurations related to Persistence. Our query script retrieves 1,352 Affected Product Configurations, one of which is a vulnerability in the Oracle Argus Safety component of Oracle Health Sciences Applications.
TABLE III: Example queries illustrating some ways **BRON** can be used. (Note that only a subset of the threat data results are shown for each query.)

| Query                                                                 | Results (Abbreviated)                                                                 | Number of Results |
|----------------------------------------------------------------------|--------------------------------------------------------------------------------------|------------------|
| Affected Product Configurations affected by Tactic of Persistence    | Affected Product Configurations: Oracle hospitality, . . .                          | Affected Product Configurations: 1,352 |
| Techniques connected to CVE-2019-2432 (vulnerability in Oracle health sciences application) | Techniques: Install Root Certificate, . . .                                      | Techniques: 13   |
| Tactics and Attack Patterns for Google Chrome (all versions)          | Tactics: privilege-escalation, . . .                                                 | Tactics: 5       |
| Attack Patterns: UDP Scan, . . .                                      | Attack Patterns: 147                                                                | Attack Patterns: 147 |
| Tactics and Attack Patterns for Google Chrome (version 5.0.375.0)    | Tactics: privilege-escalation, . . .                                                 | Tactics: 4       |
| Attack Patterns: Buffer Overflow via Environmental Variables, . . .   | Attack Patterns: 120                                                               | Attack Patterns: 120 |
| Tactics and Attack Patterns for Google Chrome (version 52.0.2743.82) | Tactics: NONE                                                                     | Tactics: 0       |
| Attack Patterns: Overflow Binary Resource File, . . .                 | Attack Patterns: 12                                                                | Attack Patterns: 12 |

![Fig. 11](image1.png)

**Fig. 11:** Number of Affected Product Configurations for different vendors when all versions of Affected Product Configurations and when only the latest version of Affected Product Configurations is referenced.

We can observe how many different products are vulnerable to different **Tactics**. Many vendors have higher vulnerability to Persistence, Privilege Escalation and Defense Evasion. Oracle stands out with a significantly higher number of products vulnerable to Lateral Movement. This may be due to more documentation or to actual greater vulnerability. The connection analysis can help identify areas that have a lot of data, and which have little, e.g. as in Figure 12.

### G. Vendors and Severity Scores

We next consider the severity of **Vulnerabilities** of this set of vendors. Figure 13a shows the distribution of severity scores of vendor products across all **Tactics**, collecting the maximum Vulnerability severity score of all versions. The distributions across vendors are significantly different. Some vendors such as Google have more **Affected Product Configurations** with severity scores around 7 and 10. In contrast, the distribution for Intel shows three main peaks with severity scores between 3 and 7, which indicates that Intel tends to have Affected Product Configurations with low and medium severity.

![Fig. 12](image2.png)

**Fig. 12:** Heat map showing number of unique products by vendor that are exposed to nine Tactics. Three Tactics are not shown because they did not expose any of these vendors. Most counts are between 0, 250, but there are a few instances where a vendor has more than 500 unique products vulnerable to a **Tactic**.

In Figure 13b we compare the corresponding distributions of severity scores. We see that severity is distributed somewhat the same (see symmetry in the violin plot along the vertical-axis) for Apple, Google, Dell and Oracle but we see differences for the other vendors. The question of what products specifically fall prey to these tactics and their specific severity score distributions is a topic of future work.

The severity score distribution for Affected Product Configurations connected to specific Tactics is sometimes different than severity score distribution for all Affected Product Configurations of a vendor. For example, the severity score distribution for Intel’s Known Affected Hardware or Software Configurations connected to the Tactic of Discovery remains similar to its distribution when connected to all Known Affected Hardware or Software Configurations. However, the severity scores for Intel’s Known Affected Hardware or Software Configurations connected to the Tactic of Defense Evasion is mostly near a score of 4.

For each vendor, we count the number of entries per source affecting them, given there are paths in **BRON** from **Attack**
Patterns up to Techniques. Figure 14 shows this data when all Vulnerabilities and all versions of Affected Product Configurations are referenced. Some vendors such as Cisco and Intel have a high Affected Product Configurations to Vulnerability ratio, while others such as Apple have a high Vulnerability to Affected Product Configurations ratio. Dell and Facebook look similar while the other vendors have similar relative Attack Patterns, Vulnerabilities and Affected Product Configurations. For Tactics and Techniques, Facebook has fewer entries while the other nine are roughly equal. There is also a very similar count of Attack Patterns across all vendors within BRON.

We also check the number of Affected Product Configurations a particular vendor incurs over time (no figure shown). It is not distributed equally across years. Vendors, like Google and HP, appear to have very few Affected Product Configurations before 2015. This raises a warning about making sure cross-vendor comparisons are on similar bases. Referencing data at the same date, after the same number of versions, at the start or end of a release version would help with this.

We next select one O/S product, Oracle Linux, and inquire into the importance of its versions within Affected Product Configurations. The number of entries per source for Oracle Linux versions is shown in Figure 15. Over the versions (and time), the number of unique Vulnerabilities for each version is increasing. The number of Tactics, Techniques, Attack Patterns, and Weaknesses increases between version 4 and 5 and then remains similar between version 5 and 7. Versions 5, 6, and 7 each has the same 5 Tactics and 27 Techniques. Not all products have monotonically increasing exposure to the different data types. In future work, this inquiry can be expanded to other products and looking into how much these increases are due to attack techniques increasing or larger and more feature-laden software introducing more vulnerabilities.

H. Vendors and their browsers

On a new tact, we consider data for a specific product category. Here, we choose web browsers. We form a set of 5: Apple Safari, Google Chrome, Mozilla Firefox, Microsoft Edge and Explorer. We note that Edge is a Chromium based
The distributions of severity scores for all versions of these browsers are shown in Figure 16. These violins can be cross-referenced to the number of entries per source per Figure 17. All browsers are identifiable in the same rough number of Tactics, Techniques, and Attack Patterns. We observe Edge has significantly fewer Affected Product Configurations over all versions than any other browser, but relatively similar counts of entries in others sources as compared to Explorer, another Microsoft browser. Figure 18 shows how many tactics the browser products are exposed to for all the product versions. Because browser versioning could impact the results, future work could examine data for the most recent release of each browser. This could afford a sense of whether Microsoft Edge is prone to fewer and less severe attacks and exposes fewer Vulnerabilities.

IV. RELATED SOURCES

The sources of BRON are variously described as industry standard of common names (CVE), a list (CVE and CWE), an encyclopedia (CWE), comprehensive dictionary and classification taxonomy (CAPEC) and knowledge base (ATT&CK). They have multiple counterparts, also with a variety of descriptors. Among them, but not exclusively are MISP [26], CTI [6], OVM [27], FireEye OpenIOC [2], STIX [20], IDS rules [21], OpenC2 [15], UCO [25], VERIS [4], and IODEF [1]. We chose BRON’s sources for their composite information value and their popularity. Collectively they also aim to support cyber-hunting or active cyber security research, so users can proactively impede and attribute attackers by looking at their potential objectives, techniques and targets.

Similar threat and vulnerability data within knowledge graphs and ontologies exist. For example, the STUCCO ontology and knowledge graph incorporates information from 13 structured data sources and provides relationships among 15 entity types including software, vulnerabilities, and attacks [3]. The SEPSES knowledge graph links information from standard data sources including CVEs, CAPECs, CWEs, CPEs, and CVSS for vulnerability scoring [5]. SEPSES provides use cases for vulnerability assessment and intrusion detection with sample queries. SEPSES uses some of BRON’s sources but BRON is unique, to our knowledge, in incorporating the tactics and techniques from the MITRE ATT&CK matrix and bridging them to CWE via CAPEC. This allows BRON to support a broader set of analyses and inform users of the extent of the data. This same claim holds for www.cvedetails.com which provides an easy to use web interface to CVE vulnerability data only. It supports browsing and statistics for vendors, products and versions and viewing Vulnerabilities related to them but it doesn’t source CVE, CAPEC, and ATT&CK entries.

Threat modeling models the software system, potential attacker goals and techniques, and potential threats to the...
system so that cyber defenders can identify and mitigate vulnerable assets. There are several threat modeling methods that vary in comprehensiveness, abstraction, and focus. These methods include but are not limited to STRIDE, PASTA, LINDDUN, and Attack Trees [22]. BRON uses a single graph to relationally connect entries from sources ranging from attack objectives to vulnerable software. It is possible that in the future such a consolidated graph plus queries and paths of BRON could support threat modeling.

V. DISCUSSION

The idea behind BRON is succinct but powerful: provide a conveniently connected graph of multiple public sources in the domain of cyber security that are already connected but challenging to traverse coherently. We believe that: 1) threat analysts (attending to immediate tactical and operational threats in the Security Operation Center), 2) system administrators (who are in charge of a cyber system), 3) cyber risk annotators (who tally the risk of discovered vulnerabilities) and 4) cyber risk analysts (who gauge strategic threats to an organization) may find BRON useful in their work. More generally, BRON provides context that could improve the comprehensibility and analysis of cyber threat intelligence. BRON can function as a coherent, more accessible resource for potential consumers who are interested in these sources.

Our analyses reveal inherent information complexity arising from historical record keeping, changes wrought by time, and the human role in populating the sources and assigning scores such as severity. They serve current consumers of the sources and future consumers, particularly those in the machine learning community, who seek statistical information about the data they train and use for modeling.

To summarize, BRON supports quantitative cataloging of the composite set of sources. For example, we showed the number of connected and Floating Entry entries of each source. It also supports trend analyses. We showed annual numbers of connected Vulnerabilities and tracked the distribution of CVSS scores over the years. These approximate inventories also indicate the extent to which a complete narrative of known vulnerabilities is needed to be well-informed when considering a network’s security. BRON can also potentially support threat modeling and network vulnerability analysis of existing networks.

ACKNOWLEDGMENT

This material is based upon work supported by the DARPA Advanced Research Project Agency (DARPA) and Space and Naval Warfare Systems Center, Pacific (SSC Pacific) under Contract No. N66001-18-C-4036

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