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Threat Model for BGP Path Security
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Abstract

This document describes a threat model for BGP path security (BGPSEC). BGPSEC is assumed to make use of the Resource Public Key Infrastructure (RPKI) already developed in the SIDR WG [I-D.ietf-sidr-arch], and thus threats and attacks against the RPKI are part of this model. The model assumes that BGP path security is achieved through the application of digital signatures to AS_Path Info. The document characterizes classes of potential adversaries that are considered to be threats, and examines classes of attacks that might be launched against BGPSEC. It concludes with brief discussion of residual vulnerabilities.

Status of this Memo

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1. Introduction

This document describes the security context in which BGPSEC is intended to operate. It discusses classes of potential adversaries that are considered to be threats, and classes of attacks that might be launched against BGPSEC. Because BGPSEC depends on the Resource Public Key Infrastructure (RPKI), threats and attacks against the RPKI also are discussed.

The motivation for developing BGPSEC, i.e., residual security concerns for BGP, is well described in several documents, including "BGP Security Vulnerabilities Analysis" [RFC4272] and "Design and Analysis of the Secure Border Gateway Protocol (S-BGP)" [Kent2000]. All of these papers note that BGP does not include mechanisms that allow an Autonomous System (AS) to verify the legitimacy and authenticity of BGP route advertisements. (BGP now mandates support for mechanisms to secure peer-peer communication, i.e., for the links that connect BGP routers. There are several secure protocol options to addresses this security concern, e.g., IPsec [RFC4301] and TCP-AO [RFC5925]. This document briefly notes the need to address this aspect of BGP security, but focuses on application layer BGP security issues that are addressed by BGPSEC.)

RFC 4272 succinctly notes:

> BGP speakers themselves can inject bogus routing information, either by masquerading as any other legitimate BGP speaker, or by distributing unauthorized routing information as themselves. Historically, misconfigured and faulty routers have been responsible for widespread disruptions in the Internet. The legitimate BGP peers have the context and information to produce believable, yet bogus, routing information, and therefore have the opportunity to cause great damage. The cryptographic protections of [TCPMD5] and operational protections cannot exclude the bogus information arising from a legitimate peer. The risk of disruptions caused by legitimate BGP speakers is real and cannot be ignored.

BGPSEC is intended to address the concerns cited above, to provide significantly improved path security, and to build upon the secure route origination foundation offered by use of the RPKI. Specifically, the RPKI enables relying parties (RPs) to determine of the origin AS for a path was authorized to advertise the prefix contained in a BGP update message. This security feature is enabled by the use of two types of digitally signed data: a PKI [I-D.sidr-res-certs] that associates one or more prefixes with the public key(s) of an address space holder, and Route Origination Authorizations (ROAs) [I-D.roa-format] that allows a prefix holder to

specify the AS(es) that are authorized to originate routes for a prefix.

The security model adopted for BGPSEC does not assume an "oracle" that can see all of the BGP inputs and outputs associated with every AS or every BGP router. Instead, the model is based on a local notion of what constitutes legitimate, authorized behavior by the BGP routers associated with an AS. This is an AS-centric model of secure operation, consistent with the AS-centric model that BGP employs for routing. This model forms the basis for the discussion that follows.

This document begins with a brief set of definitions relevant to the subsequent sections. It then discusses classes of adversaries that are perceived as viable threats against routing in the public Internet. It continues to explore a range of attacks that might be effected by these adversaries, against both path security and the infrastructure upon which BGPSEC relies. It concludes with a brief review of residual vulnerabilities.

2. Terminology

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in RFC 2119.

The following security and routing terminology definitions are employed in this document.

Adversary - An adversary is an entity (e.g., a person or an organization) perceived as malicious, relative to the security policy of a system. The decision to characterize an entity as an adversary is made by those responsible for the security of a system. Often one describes classes of adversaries with similar capabilities or motivations, rather than specific individuals or organizations.

Attack - An attack is an action that attempts to violate the security policy of a system, e.g., by exploiting a vulnerability. There is often a many to one mapping of attacks to vulnerabilities, because many different attacks may be used to exploit a vulnerability.

Autonomous System - An AS is a set of one or more IP networks operated by a single administrative entity.

AS Number (ANS) - An ASN is a 2 or 4 byte number issued by a registry to identify an AS in BGP.

Certification Authority (CA) - An entity that issues digital certificates (e.g., X.509 certificates) and vouches for the binding between the data items in a certificate.

Countermeasure - A countermeasure is a procedure or technique that thwarts an attack, preventing it from being successful. Often countermeasures are specific to attacks or classes of attacks.

Border Gateway Protocol (BGP) - A path vector protocol used to convey "reachability" information among autonomous systems, in support of inter-domain routing.

False (Route) Origination - If an ISP originates a route for a prefix that the ISP does not hold (and that it has not been authorized to originate by the prefix holder, this is termed false route origination.

Internet Service Provider (ISP) - An organization managing (and, typically, selling,) Internet services to other organizations or individuals.

Internet Number Resources (INRs) - IPv4 or IPv6 address space and ASNs

Internet Registry - An organization that manages the allocation or distribution of INRs. This encompasses the Internet Assigned Number Authority (IANA), Regional Internet Registries (RIRs), National Internet Registries (NIRs), and Local Internet registries (LIRs, ISPs).

Man in the Middle (MITM) - A MITM is an entity that is able to examine and modify traffic between two (or more) parties on a communication path

Prefix - A prefix is an IP address and a mask used to specify a set of addresses that are grouped together for purposes of routing.

Public Key Infrastructure (PKI) - A PKI is a collection of hardware, software, people, policies, and procedures used to create, manage, distribute, store, and revoke digital certificates.

Relying Parties (RPs) - An RP is an entity that makes use of signed products from a PKI, i.e., relies on signed data that is verified using certificates, and CRLs from a PKI.

RPKI Repository System - The RPKI repository system consists of a distributed set of loosely synchronized databases

Resource PKI (RPKI) - A PKI operated by the entities that manage INRs, and that issues X509 certificates (and CRLs) that attest to the holdings of INRs.

RPKI Signed Object - An RPKI signed object is a Cryptographic Message Syntax (CMS)-encapsulated data object complying with the format and semantics defined in [draft-ietf-sidr-signed-object-02.txt].

Route - In the Internet, a route is a prefix and an associated sequence of ASNs that indicates a path via which traffic destined for the prefix can be directed.

Route leak - A route leak is said to occur when AS-A advertises routes that it has received from an AS-B to AS-A's neighbors, but AS-A is not viewed as a transit provider for the prefixes in the route.

Threat - A threat is a motivated, capable adversary. An adversary that is not motivated to launch an attack is not a threat. An adversary that is motivated but not capable of launching an attack also is not a threat.

Vulnerability - A vulnerability is a flaw or weakness in a system's design, implementation, or operation and management that could be exploited to violate the security policy of a system.

3. Threat Characterization

The following classes of threats are addressed in this document.

BGP speakers - A BGP speaker, e.g., an ISP or a multi-homed non-ISP subscriber, may be a threat. (For simplicity, the remainder of this document refers to BGP speakers as ISPs.) An ISP may be motivated to cause BGP routers controlled by the ISP to emit update messages with inaccurate routing info. Such updates might cause traffic to flow via paths that would otherwise be rejected as less advantageous by other ISPs. Because the ISP controls the BGP routers that it operates, it is in a position to modify their operation. Routers operated by the ISP are vehicles for mounting MITM attacks on both control and data plane traffic. If the ISP participates in the RPKI, it will have at least CA resource certificate and may be able to generate an arbitrary number of subordinate CA certificates and ROAs. It will be authorized to populate (and may even host) its own repository publication point. If it implements BGPSEC, it will have the ability to issue certificates for its routers, and to sign updates in a fashion that will be recognized by BGPSEC-enabled ISP neighbors.

Hackers - Hackers are considered a threat. Hackers might assume control of network management computers and routers operated by ISPs, including ISPs that implement BGPSEC. In such cases, hackers would be able to act as a rogue ISP (see above). It is assumed that hackers generally do not have the capability to effect MITM attacks on most links between ISPs. Hackers might be recruited, without their knowledge, by criminals or by nations, to act on their behalf.

Criminals - Criminals may be a threat. Criminals might persuade (via threats or extortion) an ISP to act as rogue ISP (see above), and thus be able to effect a wide range of attacks. Criminals might persuade telecom staff to enable MITM attacks on links between routers. The motivation for criminals may include the ability to extort money from other ISPs or ISP clients, e.g., by adversely affecting routing for these ISPs or clients. They may wish to manipulate routing to conceal the sources of spam or of DoS attacks.

Registries - Any registry in the RPKI could be a threat. Staff at the registry are capable of manipulating repository content or mismanaging RPKI certificates. These actions could adversely affect the operation of an ISP or a client of an ISP. The staff could be motivated to do this based on political pressure from the nation in which it operates (see below).

Nations - A nation may be a threat. A nation may control one or more ISPs that operate in the nation, and thus can cause them to act as rogue ISPs. A nation may have a technical active wiretapping

capability (e.g., within its territory) that enables it to effect MITM attacks on inter-ISP traffic. It may have an ability to attack and take control of routers or management network computers of ISPs in other countries. A nation may control a registry that operates within its territory, and might force the registry to act as a rogue capacity. National threat motivations include the desire to control the flow of traffic to/from the nation or to divert traffic destined for other nations (for passive or active wiretapping, including DoS). A manifest associated with a CA's repository publication point contains a list of:

4. Attacks

This section describes classes of attacks that may be effected against Internet routing. Attacks are classified based on the target of the attack, as an element of the routing system, or the routing security infrastructure on which BGPSEC relies. In general, attacks of interest are ones that attempt to violate the integrity or authenticity of BGP traffic, or which violate the authorizations associated with entities participating in the RPKI. Attacks that violate the implied confidentiality of routing traffic are not considered significant (see 4.1 below).

4.1. Active wiretapping of links between routers

An adversary may attack the links that connect BGP routers. Passive attacks are not considered, because it is assumed that most of the info carried by BGP will otherwise be accessible to adversaries. Several classes of adversaries are assumed to be capable of MITM effecting attacks against the control plane traffic. MITM attacks may be directed against BGP, BGPSEC, or against TCP or IP. Such attacks include replay of selected BGP messages, selective modification of BGP messages, and DoS attacks against BGP routers.

4.2. Attacks on a BGP router

An adversary may attack a BGP router, whether it implements BGPSEC or not. Any adversary that controls routers legitimately, or that can assume control of a router, is assumed to be able to effect the types of attacks described below. Note that any router behavior that can be ascribed to a local routing policy decision is not considered to be an attack. This is because such behavior could be explained as a result of local policy settings, and thus is beyond the scope of what BGPSEC can detect as unauthorized behavior. Thus, for example, a router may fail to propagate some or all route withdrawals or effect "route leaks". (These behaviors are not precluded by the specification for BGP, and might be the result of a local policy that

is not publicly disclosed. As a result, they are not considered attacks.)

AS Insertion: A router might insert one or more ASNs, other than its own ASN, into an update message. This violates the BGP spec and thus is considered an attack.

False (route) Origination: A router might originate a route for a prefix, when the AS that the router represents is not authorized to originate routes for that prefix. This is an attack.

Secure Path Downgrade: A router might remove signatures from a BGPSEC update that it receives, when forwarding this update to a BGPSEC-enabled neighbor. This behavior violates the BGPSEC spec and thus is considered an attack.

Invalid Signature Insertion: A router might emit a signed update with a "bad" signature, i.e., a signature that cannot be validated by other BGPSEC routers. (This might occur due to use of a revoked or expired certificate, a computational error, or a syntactic error.) This behavior violates the BGPSEC spec and thus is considered an attack.

Stale Path Announcement: An announcement may be propagated with an origination signature segment expiry value that is not current. This behavior violates the BGPSEC spec and is considered a possible replay attack.

Premature Path Announcement Expiration: A router might emit a signed update with an origin expiry time that is very short. The BGPSEC protocol specification does not mandate a minimum expiry time. However, an immediate neighbor of a route originator should expect to see an expiry time that not substantially less than XX in the future. Later routers along a path generally cannot determine if a shorter expiry time is "suspicious" since they cannot know how long a route may have been held by an earlier AS, prior to being released. Thus this consideration applies only to an immediate neighbor of a route originator.

MITM Attack: A cryptographic key used for point-to-point security (e.g., TCP-AO or IPsec) between two BGP routers might be compromised (e.g., by extraction from a router). This would enable an adversary to effect MITM attacks on the link(s) where the key is used.

Compromised Private Key: The private key associated with an RPKI EE certificate issued to a router might be compromised by an

attack against the router. An adversary with access to this key would be able to generate updates that appear to be from this router (or from any routers that share this key and certificate). If the adversary controlled another ISP, it could use this key to forge signatures that appear to come from the router(s) in question, thus making it appear that those routers were misbehaving.

Replay Attack: An update may be signed and announced, and later withdrawn. The adversary controlling intermediate routers does not propagate the withdrawal but instead re-announces (i.e., replays) the previous announcement within its expiry time if it has not yet expired.

4.3. Attacks on ISP management computers (non-CA computers)

An adversary may choose to attack computers used by an ISP to manage its network, especially its routers. Such attacks might be effected by an adversary that has compromised the security of these computers. This might be effected via remote attacks, extortion of selected ISP staff, etc. If an adversary compromises NOC computers, it can execute any management function that authorized ISP staff would have performed. Thus the adversary could modify local routing policy to change preferences, to black-hole certain routes, etc. This type of behavior cannot be externally detected as an attack.

If the ISP participates in the RPKI, the adversary could manipulate the RP tools that extract data from the RPKI, causing the output of these tools to be corrupted in various ways. For example, an attack of this sort could cause the ISP to view valid routes as not validated, which could alter its routing behavior.

If the adversary invoked the tool used to manage the repository publication point for this ISP, it could delete any objects stored there (certificates, CRLs, manifests, ROAs, or subordinate CA certificates). This could affect the routing status of entities that have allocations/assignments from this ISP (e.g., by deleting their CA certificates).

An attacker could invoke the tool used to request certificate revocation, causing router certificates, ROAs, or subordinate CA certificates to be revoked. An attack of this sort could affect not only this ISP, but also any ISPs that receive allocations/assignments from it, e.g., because their CA certificates were revoked.

It the ISP is BGPSEC-enabled, an attack of this sort could cause the affected ISP to be viewed as not BGPSEC-enabled, possibly making routes it emits be less preferred.

If an adversary invoked a tool used to request ROAs, it could effectively re-allocate some of the prefixes allocated/assigned to the ISP (e.g., by modifying the origin AS in ROAs). This might cause other BGPSEC-enabled ISPs, and other RPKI-enabled ISPs, to view the ISP as no longer originating routes for these prefixes. Multi-homed subscribers of this ISP who received a PA allocation from the ISP might find their traffic was now routed via other connections.

If the ISP is BGPSEC-enabled, and the adversary invoked a tool used to request certificates, it could replace valid certificates for routers with ones that might be rejected by BGPSEC-enabled neighbors.

4.4. Attacks on a repository publication point

A critical element of the RPKI is the repository system. An adversary might attack a repository, or a publication point within a repository, to adversely affect routing.

This section considers only those attacks that can be launched by any adversary who controls a computer hosting one or more repository publication points, without access to the cryptographic keys needed to generate valid RPKI signed products. Such attacks might be effected by an inside or an external threat. Because all repository objects are digitally signed, attacks of this sort translate into DoS attacks against the RPKI RPs. There are a few distinct forms of such attacks, as described below.

Note first that the RPKI calls for RPs to cache the data they acquire and verify from the repository system. Attacks that delete signed products, that insert products with "bad" signatures, that tamper with object signatures, or that replace newer objects with older (valid) ones, can be detected by RPs (with a few exceptions). RPs are expected to make use of the cached repository data until attacks that violate the integrity of publication points (and which are detected) are resolved. Thus the impact of such attacks is mitigated in part by the design of the repository system.

If an adversary inserts an object into a publication point, and the object has a "bad" signature, the object will not be accepted and used by RPs.

If an adversary modifies any signed product at a publication point, the signature on the product will fail, and cause RPs to not accept it. This is equivalent to deleting the object, on many respects.

If an adversary deletes one or more CA certificates, ROAs or the CA's

CRL at a publication point, the manifest for that publication point will allow an RP to detect this attack. (The RP would be very unhappy if there is no CRL for the CA instance anyway.) An RP can continue to use the last valid instance of the deleted object as a local policy option), thus minimizing the impact of such an attack.

If an adversary deletes a manifest (and does not replace it with an older instance), that is detectable by an RP, and should result in the CA being notified of the problem. An RP can continue to use the last valid instance of the deleted object as a local policy option), thus minimizing the impact of such an attack.

If an adversary deletes newly added CA certificates or ROAs, and replaces the current manifest with the previous manifest, the manifest (and the CRL that it matches) will be "stale" (see [ietf-sidr-manifest]). This alerts an RP that there may be a problem, and, hopefully, the CA responsible for the publication point will be asked to remedy the problem (republish the missing CA certificates and/or ROAs). An RP cannot know the content of the new certificates or ROAs that are not present, but it can continue to use what it has cached.

If a CA revokes a CA certificate or a ROA (via deleting the corresponding EE certificate), and the adversary tries to reinstate that CA certificate or ROA, the adversary would have to rollback the CRL and the manifest to undo this action by the CA. As above, this would make the CRL and manifest stale, and this is detectable by RPs. An RP cannot know which CA certificates or ROAs were deleted, and so it would use the cached instances of the affected objects. Here too one hopes that the CA will be notified of the problem and will attempt to remedy the error.

In the attack scenarios above, when a CRL or manifest is described as stale, this means that the next issue date for the CRL or manifest has passed. Until the next issue date, an RP will not be detect the attack. Thus it behooves CAs to select CRL/manifest lifetimes (the two are linked) that represent an acceptable tradeoff between risk and operational burdens.

Attacks effected by adversaries that are legitimate managers of publication points can have much greater effects, and are discussed below under attacks on or by CAs.

4.5. Attacks on an RPKI CA

Every entity to which INRs have been allocated/assigned is a CA in the RPKI. Each CA is nominally responsible for managing the repository publication point for the set of signed products that it

generates. (An INR holder may choose to outsource the operation of the RPKI CA function, and the associated publication point. In such cases, the organization operating on behalf of the INR holder becomes the CA, from an operational and security perspective. The following discussion does not distinguish outsourced CA operations.)

Note that attacks attributable to a CA may be the result of malice by the CA (i.e., the CA is the adversary) or they may result from a compromise of the CA.

All of adversaries listed in Section 2 are presumed to be capable of launching attacks against the computers used to perform CA functions. Some adversaries might effect an attack on a CA by violating personnel or physical security controls as well. The distinction between CA as adversary vs. CA as an attack victim is important. Only in the latter case should one expect the CA to remedy problems caused by a attack once the attack has been detected. Note that most of the attacks described below do not require disclosure of a CA's private key to an adversary. If the adversary can gain control of the computer used to issue certificates, it can effect these attacks, even though the private key for the CA remains "secure" (i.e., not disclosed to unauthorized parties). However, if the CA is not the adversary, and if the CA's private key is not compromised, then recovery from these attacks is much easier. This motivates use of hardware security modules to protect CA keys, at least for higher tiers in the RPKI.

An attack by a CA can result in revocation or replacement of any of the certificates that the CA issued. Revocation of a certificate should cause RPs to delete the (formerly) valid certificate (and associated signed object, in the case of a revoked EE certificate) that they have cached. This would cause repository objects (e.g., CA certificates and ROAs) that are verified under that certificate to be considered invalid, transitively. As a result, RPs would not consider as valid any ROAs or signed updates based on these certificates, which would make routes dependent on them to be less preferred. Because a CA that revokes a certificate is authorized to do so, this sort of attack cannot be detected, intrinsically, by most RPs. However, the entities affected by the revocation or replacement of CA certificates can be expected to detect the attack and contact the CA to effect remediation. If the CA was not the adversary, it should be able to issue new certificates and restore the publication point.

An adversary that controls the CA for a publication point can publish signed products that create more subtle types of DoS attacks against RPs. For example, such an attacker could create subordinate CA certificates with Subject Information Access (SIA) pointers that lead RPs on a "wild goose chase" looking for additional publication points

and signed products. An attacker could publish certificates with very brief validity intervals, or CRLs and manifests that become "stale" very quickly. This sort of attack would cause RPs to have to access repositories more frequently, and that might interfere with legitimate accesses by other RPs.

An attacker with this capability could create very large numbers of ROAs to be processed (with prefixes that are consistent with the allocation for the CA), and correspondingly large manifests. An attacker could create very deep subtrees with many ROAs per publication point, etc. All of these types of DoS attacks against RPs are feasible within the syntactic and semantic constraints established for RPKI certificates, CRLs, and signed objects.

An attack that results in revocation and replacement (e.g., key rollover or certificate renewal) of a CA certificate would cause RPs to replace the old, valid certificate with the new one. This new certificate might contain a public key that does not correspond to the private key held by the certificate subject. That would cause objects signed by that subject to be rejected as invalid, and prevent the affected subject from being able to sign new objects. As above, RPs would not consider as valid any ROAs issued under the affected CA certificate, and updates based on router certificates issued by the affected CA would be rejected. This would make routes dependent on these signed products to be less preferred. However, the constraints imposed by the use of RFC 3779 [RFC3779] extensions do prevent a compromised CA from issuing (valid) certificates with INRs outside the scope of the CA, thus limiting the impact of the attack.

An adversary that controls a CA could issue CA certificates with overlapping INRs to different entities, when no transfer of INRs is intended. This could cause confusion for RPs as conflicting ROAs could be issued by the distinct CAs.

An adversary could replace a CA certificate, use the corresponding private key to issue new signed products, and then publish them at a publication point controlled by the attacker. This would effectively transfer the affected INRs to the adversary, or to a third party of his choosing. The result would be to cause RPs to view the entity that controls the private key in question as the legitimate INR holder. Again the constraints imposed by the use of RFC 3779 extensions do prevent a compromised CA from issuing (valid) certificates with INRs outside the scope of the CA, thus limiting the impact of the attack.

Finally, an entity that manages a repository publication point can inadvertently act as an attacker (as first noted by Pogo). For example, a CA might fail to replace its own certificate in a timely

fashion (well before it expires). If might fail to issue its CRL and manifest prior to expiration, creating stale instances of these products that cause concern for RPs. A CA with many subordinate CAs (e.g., an RIR or NIR) might fail to distribute the expiration times for the CA certificates that it issues. An ISP with many ROAs might do the same for the EE certificates associated with the ROAs it generates. A CA could rollover its key, but fail to reissue subordinate CA certificates under its new key. Poor planning with regard to rekey intervals for managed CAs could impose undue burdens for RPs, despite a lack of malicious intent. All of these example of mismanagement could adversely affect RPs, despite the absence of malicious intent.

5. Residual Vulnerabilities

The RPKI, upon which BGPSEC relies, has several residual vulnerabilities that were been discussed in the preceding text (Sections 4.4 and 4.5). These vulnerabilities are of two principle forms:

- the RPKI repository system may be attacked in ways that make its contents unavailable, or not current. It is anticipated that RPs will cope with this vulnerability through local caching of repository data, and through local settings that tolerate expired or stale repository data.

- any CA in the RPKI may misbehave within the bounds of the resources allocated to it, e.g., it may issue certificates with duplicate resource allocations or revoke certificates inappropriately. This vulnerability is intrinsic in any PKI. It is anticipated that RPs will deal with this through

BGPSEC has a separate set of residual vulnerabilities:

- BGPSEC is not able to prevent what is usually referred to as route leaks, because BGP itself does not distinguish between transit and non-transit ASes- BGPSEC signatures do not protect all attributes associated with an AS_path. Some of these attributes are employed as inputs to routing decisions. Thus attacks that modify (or strip) these other attributes are not detected by BGPSEC.

6. Security Considerations

A threat model is, by definition, a security-centric document. Unlike a protocol description, a threat model does not create security

problems nor purport to address security problems. This model postulates a set of threats (i.e., motivated, capable adversaries) and examines classes of attacks that these threats are capable of effecting, based on the motivations ascribed to the threats. It describes the impact of these types of attacks on BGPSEC, including on the RPKI on which BGPSEC relies.

7. IANA Considerations

[Note to IANA, to be removed prior to publication: there are no IANA considerations stated in this version of the document.]

8. Acknowledgements

The author wishes to thank . . .

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