PKCE: Proof Key for Code Exchange

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Abstract

As an open standard, OAuth has grown significantly since its initial release in 2007. In 2010, the IETF published it as a standard with RFC 5849, The OAuth 1.0 Protocol. The standard has evolved to solve many complex use cases through a structured standards development process. OAuth has seen many updates in the nearly 20 years since its initial release. This article describes one such update that started as a standalone RFC but has been incorporated into the upcoming OAuth 2.1 specification, "Proof of Key Code Exchange."

Introduction

OAuth has been a transformative standard in the field of Identity and Access Management. Being an open standard, OAuth has risen to challenges proposed by the nature of interconnected systems and adapted to emergent issues. For instance, OAuth v1.0 had a session fixation attack that, when discovered, had an advisory put out about it and a revision published to help address the issue. Through this process, standards get closer to being "alive" in nature; each release iteration (such as OAuth v1.0 and OAuth v1.0a) addresses concerns in the specification. The wide adoption gives developers a shared framework when designing systems that need to handle delegated authorization. This commonality is important, as it allows systems to understand who should have access to what quickly.

As of this writing, OAuth v2.0 is the latest approved specification. OAuth 2.0 is tied to RFCs 6749 ("The OAuth 2.0 Authorization Framework")[i] and 6750 ("The OAuth 2.0 Authorization Framework: Bearer Token Usage")[ii], both released in October 2012. Since the inception of OAuth 2.0, the RFC Editor has published numerous RFCs that address additional concerns or extend functionality. In light of this, OAuth v2.1 is in draft[iii] as of this writing and intended to replace OAuth 2.0 – it will contain a roll-up of many of the released RFC materials as well as the best common practices released for OAuth. The new elements being integrated into the base OAuth spec for 2.1 are important— from the removal of the resource owner password credentials grant flow to the considerations around OAuth for browser-based applications— and all could merit their own articles. We focus in this article on RFC 7636 ("Proof Key for Code Exchange by OAuth Public Clients.")[iv]

Terminology

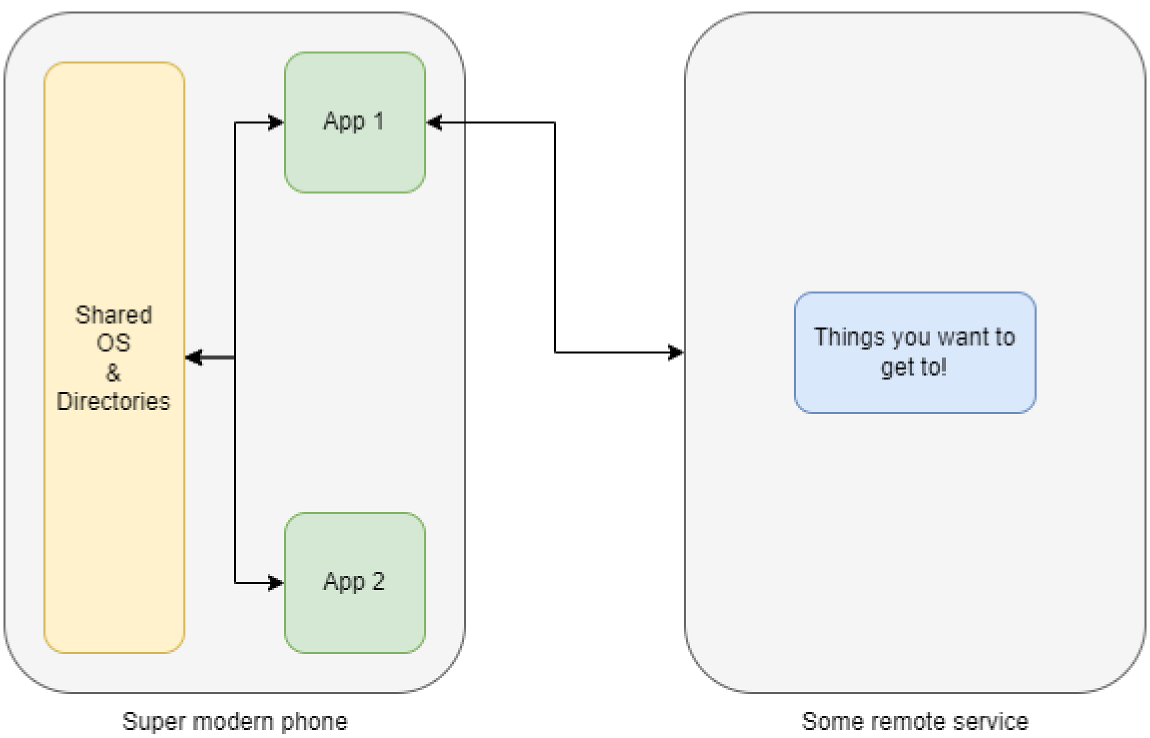
Term	Description
OAuth	Refers to the standards-based delegation protocol, described in several RFCs, that facilitates the transmission of authorization decisions between HTTP-aware services.
Proof of Key Code Exchange (PKCE)	Proof of Key Code Exchange (pronounced "Pixy"), initially defined in RFC 7636, is a technique to mitigate an attack that may occur through a malicious actor intercepting the authorization code using OAuth 2.0's authorization code grant. A verification process is performed through the use of a single-use key sent to the authorization server. This verification process is such that the client that makes the initial request, assuming OAuth's security premises hold true, must be the requester.
Hash (Cryptographic hash)	A hash is the output of a cryptographic hash function for a given input.

Cryptographic Hash Function	A cryptographic hash function is a function that takes a given input of an unspecified length and returns an output of a fixed length. Given an input, the hash function should always output the same hash. Provided an adequately constructed hash function, the resultant hash should be difficult to reverse (Commonly called preimage resistance), and it should be difficult to find another input that produces the same hash (Collision resistance).
Transport Layer Security ("TLS")	A cryptographic protocol designed to provide confidentiality and integrity of communications between two endpoints.

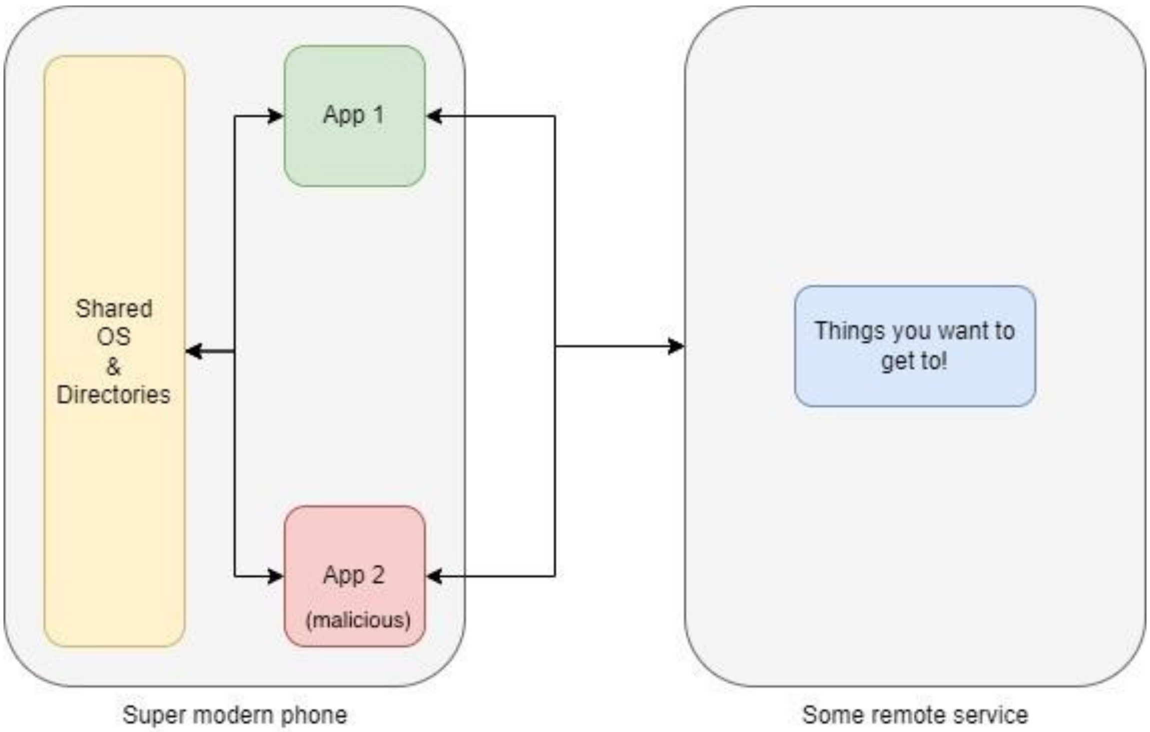
What Are We Solving?

Proof Key for Code Exchange or PKCE (pronounced "Pixy") initially came about to solve for a common scenario with an increasingly exposed attack vector.

Let us pretend we have a smartphone with two applications on the device. Both applications are run by the same user and have effectively the same general permissions on the local system. In this scenario, both applications connect to the broader internet, and no special sandboxing or advanced file access mechanisms are in play.



In an ideal world, there are no issues here. However, what if one of the applications were malicious?



The malicious application, having access to the same local resources as the good application, fulfills one of the conditions necessary to perform an authorization code interception attack. These preconditions are spelled out directly in the spec, but it is worthwhile to go over them in more detail.

1. The malicious application needs to be able to register a custom URI scheme that mimics the good application. For instance, if we use a banking app with a custom URI scheme of com.example.banking://oauth/ the malicious app can also register to utilize this.
2. OAuth 2.0's authorization code grant is used.
3. The attacker can access the OAuth 2.0 client_id and client_secret if one is set. We should understand that this requirement is relatively trivial for a dedicated attacker—public-facing applications expose client_id readily. If Shannon's Maxim holds, we can expect that any client_secret embedded in any application on a smartphone will not be secret for very long.[v] The spec itself notes this, but it is a point to remember.
4. Either one of two conditions must be met:
    a. The attacker can observe only responses from the authorization endpoint.

b. The attacker can observe requests from the good application as well as responses from the authorization endpoint. This second condition, specifically the addition of observability into requests from other applications, is a fault of the operating system (OS) and can result in information placed in logs by the OS or the application, or some other condition within the OS that makes information available across applications, available to the malicious application. The spec indicates that in this scenario, the attacker would not be able to act as a man in the middle—which, if they were already executing an MITM attack, the countermeasures here would not be able to help. Indeed, RFC 6819 ("OAuth 2.0 Threat Model and Security Considerations")[vi] assumes that a secure transport-layer protocol, such as *TLS*, is being used.

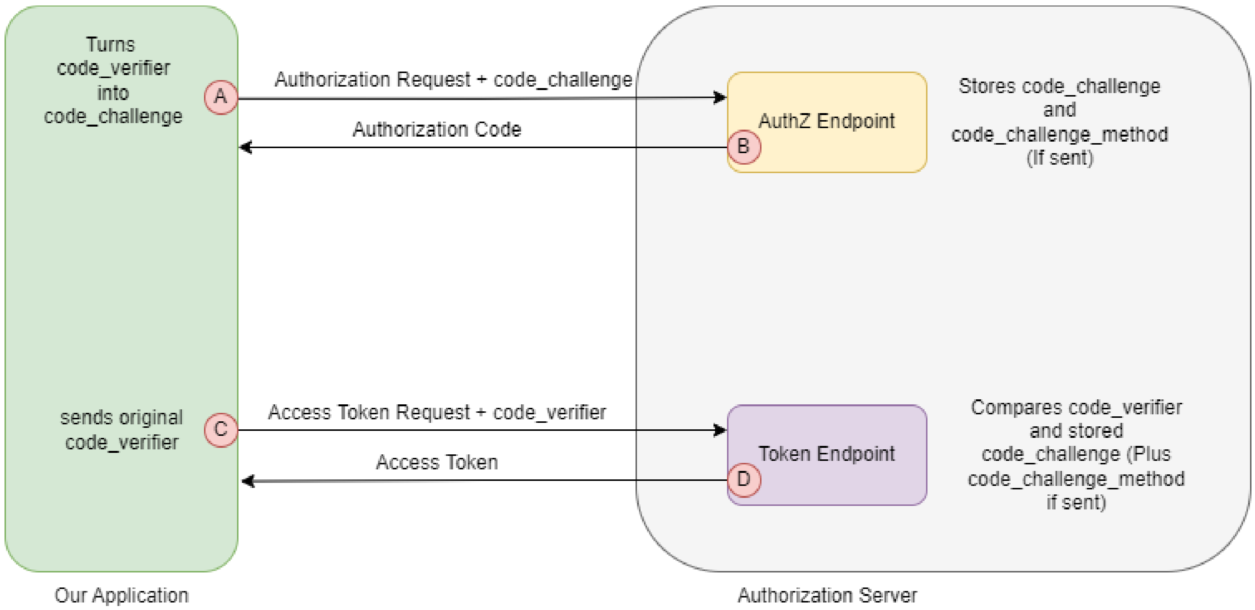
Assuming these preconditions are met, an attacker can, at minimum, observe responses from the authorization endpoint by way of the malicious app. This ability, in turn, would give the malicious application the capability to procure a valid token to do whatever it wanted to do within the scope of the API it sought to access.

This scenario may offer unapproved access into a sensitive application, which could result in unapproved actions taken on behalf of the user- such as the transferring of money from a bank account, wholesale transfer of private emails to the controller of the malicious application, and so on depending on what exactly the authorization request would have allowed for.

It should be noted that while this is the use case in the spec, there are many other scenarios where authorization code injection attacks can occur. RFC 9700 ("Best Current Practice for OAuth 2.0 Security")[vii] discusses authorization code injection attacks more broadly. As Aaron Parecki and Micah Silverman discussed and demonstrated elsewhere, a path to authorization code injection exists without a connection between a client-provided state parameter and the authorization code.[viii]

The PKCE Fix

PKCE aims to fix this by requiring a client-side piece of information to be passed to the authorization server. The authorization server then remembers this information, as it must be used in order to request an access token (alongside anything else required during the authorization code grant flow). This state information mitigates the attack described above, as well as a range of other authorization code injection attacks. The flow looks like this at a high level per the spec:



It behooves us to understand the new pieces that PKCE brings forward in this flow. Namely, we should understand the code verifier and code challenge components, as well as how the introduction of PKCE modifies requests.

All of this assumes that the authorization server has implemented PKCE and thus will understand the information we give it around PKCE and what to do with it. The key thing we care about in this example is that when we hand the authorization server the code_challenge and code_challenge_method values, it will hold on to them and use them for verification through the steps.

The Code Verifier

The first step to mitigate the above attack is through the use of a dynamic, single-use key, which they call a code verifier. This key is not just any key, however; per spec, it needs to meet a few requirements:

- It must be a "High-entropy cryptographic random string"; the means of generating this value are not prescribed but must be suitably random to be usable for cryptographic purposes.
- The characters used in this string must be US-ASCII unreserved characters; that is to say uppercase/lowercase letters, decimal digits, as well as the special characters hyphen, period, underscore, and tilde.
- The string needs to be at least 43 characters and no longer than 128 characters.

The spec goes on to give recommendations on generation methods. It is recommended that a cryptographically secure pseudorandom number generator (CSPRNG) be used to create a 32-octet sequence, and then that sequence be Base64 URL-Encoded to create a

URL-safe string to use as the code verifier. Once this generation process is performed, we move on to building the code challenge.

The Code Challenge

This code verifier can be sent one of two ways: it can either be sent as it is (plain), or it can be *hashed*. Whether it is plain or hashed is known as the code challenge method.

So, for instance, let's say generate a string for the code verifier as so:

```
7.zNCb.ENi-zKmyyt3DvNt8-mAkynWE~k.p6UWd4B.DrLu2XNHCuobRddpkCHg2s
```

A "PLAIN" code challenge would be that string, and the client could either send no code_challenge_method parameter (which the server should then assume is "PLAIN") or send the code_challenge_method parameter with a value of "PLAIN". By doing this, we mitigate cases where an attacker can observe responses from the authorization endpoint, which is great but not a complete fix.

To fully resolve the issue, we can hold on to the "PLAIN" string, but when transmitting it, we can hash it, and tell the authorization endpoint it is hashed. Per the spec, we must base64 URL-encode the raw bytes of the SHA-256 hash generated from our code verifier input. The code_challenge_method in this case would be "S256". Once we have done that, we get:

```
sQY_rBb7KxD-oqW_FrlskCHdUQbxTxoLPju4-C1jfXU
```

This result is now the code challenge. It is then passed to the authorization endpoint, along with the code challenge method.

Sending the Code Challenge

An example URL might look something like this (with line breaks after every parameter for readability):

```
https://www.example.com/auth?
response_type=code&
client_id=someValue&
redirect_uri=someURI&
scope=profile&
state=someStateValue&
code_challenge= sQY_rBb7KxD-oqW_FrlskCHdUQbxTxoLPju4-C1jfXU&
code_challenge_method=S256
```

With this, the stage is set. The server returns the authorization code, and the process can move forward. We should note that it now becomes the authorization server's duty to remember the code_challenge and the code_challenge_method. This need not be a long time; indeed, it should persist as long as the authorization code is allowed to persist. The time this should persist is dictated by RFC 6749; a maximum lifespan of 10 minutes is recommended, but in practice, it should be much shorter. Due to the linked nature of the authorization code, the code_challenge and the code_challenge method having different timeout values for those settings would not make sense.

Requesting the Token

The code authorization flow proceeds as normal until we move to exchange the authorization code for a token. The resulting data in the POST to receive a token will look something like this (again, line breaks for readability):

```
grant_type=authorization_code&
code=someCode&
redirect_uri=someURI&
client_id=someValue&
code_verifier=7.zNCb.ENi-zKmyyt3DvNt8-mAkynWE~k.p6UWd4B.DrLu2XNHCuobRddpkCHg2s
```

We are sending the code verifier – but why? Let's go back to our assumptions, specifically point 4:

1. The attacker can observe responses from the authorization endpoint.
2. The attacker can observe requests from both the good application and responses from the authorization endpoint.

If, in our initial response, we have sent a hashed value of the code_verifier (which is again the code_challenge post-transformation via hash), and this is somehow logged or otherwise made observable by a malicious application, they will not know what the code_verifier actually is. It will be available only to the application that should rightfully be performing this series of requests. By sending the code_verifier, the token endpoint can perform the hashing on its side with the previously noted hashing algorithm and perform a comparison. Since the code_verifier should generally not be stored outside of memory and should be single-use, a malicious application should not have access to it. Assuming the code_verifier is rightfully verified, the code authorization flow continues as normal.

Additional Points

A person reading the spec (or indeed this article) may ask themselves, "Why only SHA-256"? As of this writing, SHA-256 is currently "safe" — there are no documented collision attacks (as there are with SHA-1). While SHA-256 is a part of FIPS 180-4, which means it is largely trusted by the US federal government, there may be reasons a particular organization may not want to use SHA-256. This is to say an enterprising organization could support RIPEMD-160 if they choose; nothing directly in the spec keeps them from building this hashing method into the application and extending their authorization server to know how to deal with RIPEMD-160. However, we should understand the role the hash serves (when hashing is used) and why, even if SHA-256 collisions were feasible, it may not be a huge issue from a security perspective.

If we look back to the security assumptions that drive PKCE, the value of the code_challenge is that it helps ensure a malicious application or service cannot derive anything meaningful from our requests or responses. Assuming we take the OAuth spec at its word, a code_challenge has an effective maximum lifespan of 10 minutes (from generation to token). This means if the code_challenge is hashed and the hash is leaked into a space that a malicious application can access, it has 10 minutes to work out what the pre-hashed string was.

Ten minutes of time, at max, is not a trivial constraint! A malicious application either needs to directly attack using the resources available to it on the device, or it needs to exfiltrate the hash to be attacked "offline" by a system with more computing resources. Reducing this time to a minute, or 30 seconds, increases the required computing power to perform an attack like this tremendously — an attack, it should be noted, that does not currently exist.

SHA-256 adequately and admirably serves its purpose of making it computationally infeasible to derive the initial input from the hashed value. PKCE, and SHA-256 used within the context of PKCE, are likely safe for the near to moderate term.

In Conclusion

PKCE, as an addition to OAuth, solves a whole range of issues. Not just the issue we outlined above for native phone applications, but for more traditional websites that may rely on OAuth's code authorization flow, single-page applications, and other HTTP-aware clients (Such as thick clients on a PC). Because of how impactful this change is, there is little to wonder about why it was brought forward into the draft for OAuth 2.1 and why PKCE is widely adopted despite being (until retired and made officially a part of the spec) a standalone RFC. It is tremendous to see OAuth as a standard evolve and rise to operational and security concerns, and to see organizations embrace these changes to drive meaningful security impact for their users.

Acknowledgements

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Author Bio

Rusty Deaton has been in Identity and Access Management for over a decade. He began in technology as a technical support engineer for a Broker-Dealer and has since worked across many industries, carrying forward a passion for doing right by people. When not solving problems, he loves to tinker with electronics and read.

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[ii] Jones, M. and D. Hardt, "The OAuth 2.0 Authorization Framework: Bearer Token Usage", RFC 6750, DOI 10.17487/RFC6750, October 2012, <https://www.rfc-editor.org/info/rfc6750>.

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