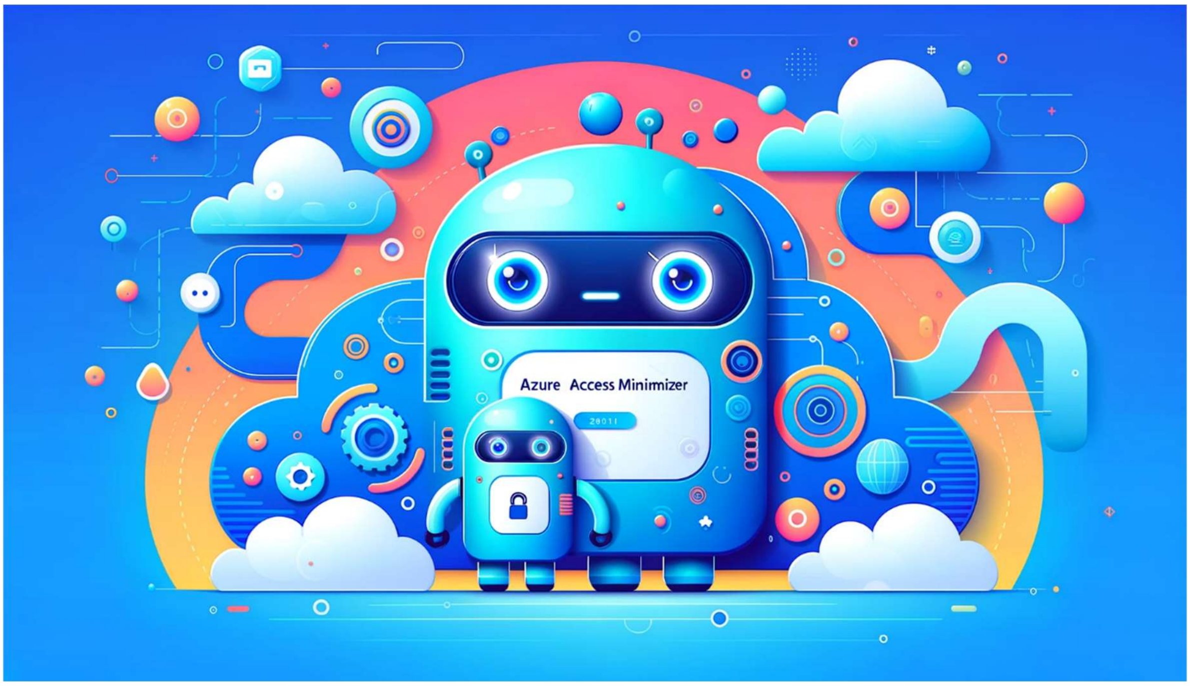
# A Foundation for Azure Security

# Part 3:

# Theory of de-escalation

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## Introduction

Measuring the extent of an Entra principal's right in Azure is an absolute necessity. Without such a metrics, cloud customers cannot determine whether assigned roles and permissions meet least privilege principles. However, doing so accurately with the current native tools remains challenging.

In this chapter, we propose,

1. a way to measure RBAC rights and to compare them with a desired value;
2. a scalable way to customize SPN role assignments so that control plane rights get de-escalated to the desired value in an automated way, using machine learning techniques.

# Pre-requisites

## N-tuples

An n-tuple is an ordered set of n items $x = (x1, \dots\ xn)$.

For integer n-tuples, one can define the L1 norm as $||x||_1=|x1|+\dots+|xn|$.

Let's consider the absolute value of the sum of items in an integer n-tuple: $|x1 + \dots\ xn|$

Recall that the absolute value follows the triangle inequality:

For all integers x1 and x2, $|x1+x2|\leq|x1|+|x2|$

Therefore, the sum is bounded from above by the L1 norm:

For all x, $|x1 + \dots + xn| \leq ||x||_1$

Due to this property, let's call this summing operation L1-minus.

Is L1-minus a norm? Yes, because the absolute value is a norm. Let's use the symbol $||x||_-$ to depict it.

## Induced distances

The induced distance d(,) of a norm is defined as: $d(x,y)=||x-y||$

It is well known that the induced distance of L1 is a distance, but is it true for L1-minus? In general, no. To see why, consider the following tuples: x=(10,12) and y=(5,17),

- $||x||_-=|x_1+x_2|=|10+12|=22$
- $||y||_-=|y_1+y_2|=|5+17|=22$
- $d(x,y)=||x-y||_-=|(x_1-y_1)+(x_2-y_2)|=|(10-5)+(12-17)|=|5-5|=0$

We see that L1-minus is not point separating: if the distance between two tuples x and y is zero, it doesn't mean that x is equal to y.

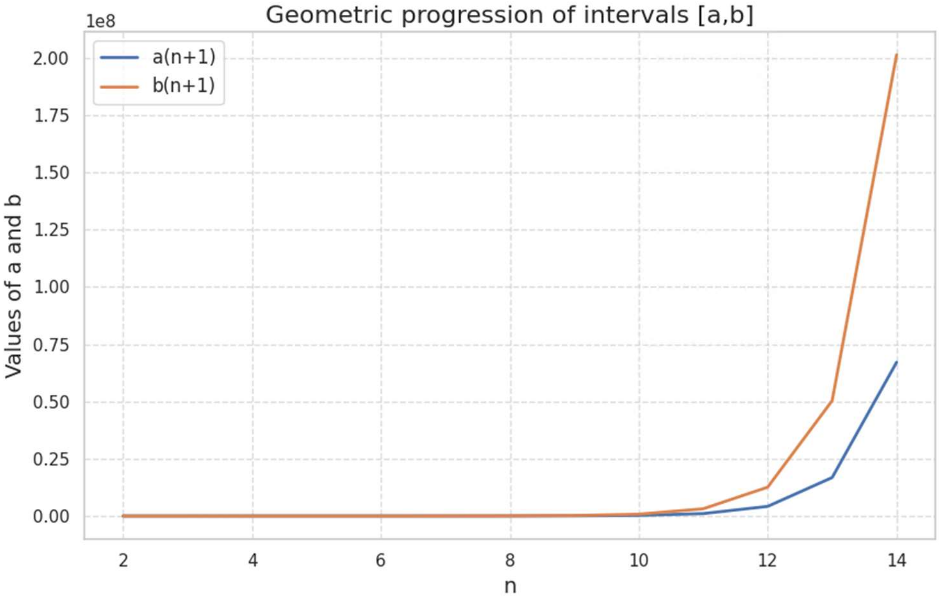
Now, if the items contained in the n-tuple are defined over non-overlapping (except at origin O) well-chosen intervals, then we can make L1-minus point-separating. There are many ways to go, here is the one we will resort to throughout this chapter:

Consider intervals $I_i = [a_i, b_i]$ with the extra condition that $\forall p,q \in [a_i, b_i] \cup O, p\neq q$: $|p-q| > \Sigma\, b_{i-1}$

Let's call this condition "separation of concerns".

Setting $p=a_i$ and $q=0$, we see that all intervals are disjoints since $a_i > \Sigma\, b_{i-1}$

Setting $p=a_i$ and $q=b_i$, we see that the length of intervals follows a geometric progression. The growth is exponential, as can be shown from the following progression which adheres to the separation of concerns:




*Exponential growth of intervals $I_i=[a_i,b_i]$, with $a_0=1$, $b_0=3$, $card(I_i)=3$ for all $i$,*

$$a_{n+1}=\Sigma b_n$$
$$b_{n+1}=card(I_n)*\Sigma b_n=3\Sigma b_n$$
$$b_{n+1}-a_{n+1}=2\Sigma b_n$$

Our set of n-tuples is going to be built from the cross product of the n intervals I1, … $I_n$, plus the origin point O: $x=(x1,\dots xn) \in I_1 \times \dots \times I_n \cup \{0, \dots, 0\}$

Let's prove that this version of L1-minus is point separating. Take two 1-tuples x and y, and suppose $d(x,y)=0$ (i)

We start at n=1, and consider the single interval $I1 = [a_1,b_1]$.

By definition, $d(x,y)= |x1-y1|$. For n=1 L1-minus equals L1, the absolute value. So x=y=0.

The proof is finished for n=1.

We switch to the general case "n".

$$d(x,y)= |(x_1-y_1)+\dots+(x_n-y_n)|$$

Let's define function $p(x,y)= (x_1-y_1)+\dots+(x_{n-1}-y_{n-1})$

We have $d(x,y)=|p(x,y)+(x_n-y_n)|$ thus $d(x,y)=0$ iff $p(x,y)=y_n-x_n$ (ii)

Let's show that $p(x,y)< y_n-x_n$, to disprove (ii).

Without loss of generality, consider $y_n > x_n$ (otherwise, we carry on the reasoning with d(y,x)).

Setting $p=y_n$ and $q=x_n$ in the extra condition on $I_n$, $\{ \forall p,q \in I_n, |p-q| > \Sigma\, b_{n-1} \}$, we get $(y_n-x_n) > b_1 + \dots + b_{n-1}$ (iii).

Observe that, by definition of b, $(x_1-y_1) < b_1, \dots, (x_{n-1}-y_{n-1}) < b_{n-1}$

So $p(x,y) < b1+\dots+bn-1$

Which we rewrite as $p(x,y) < (y_n-x_n)$ (using condition iii)

Consequently, $d(x,y) \neq 0$ (iv)

(iv) is in contradiction with (i), our initial hypothesis (that $y_n > x_n$) is wrong, hence $x_n=y_n$.

We repeat the reasoning at level n-1 and conclude that $x_{n-1}=y_{n-1}$.

We carry on until we get $x_1=y_1$

Finally, $d(x,y)=0$ implies $x=y$.

The proof is finished.

## The WAR distance

In chapter 1, we explained a core foundation of Azure RBAC: the WAR partition. According to this scheme, each atomic permission is uniquely categorized as belonging to the (W)rite,(A)ction or (R)ead equivalence class.

An Azure role assignment is a set of permissions granted along the W, A and R axes on a scope 's'. For each role, let's define the 3-tuple $(w,a,r)_s$ where w, a and r are natural numbers belonging to the following sets W, A and R:

W = { 950, 900, 850, 800, 750, 700, 600, 500, 400, 300, 200, 100 }

A = { 45, 40, 35, 30, 20, 10 }

R = { 4, 3, 2, 1 }

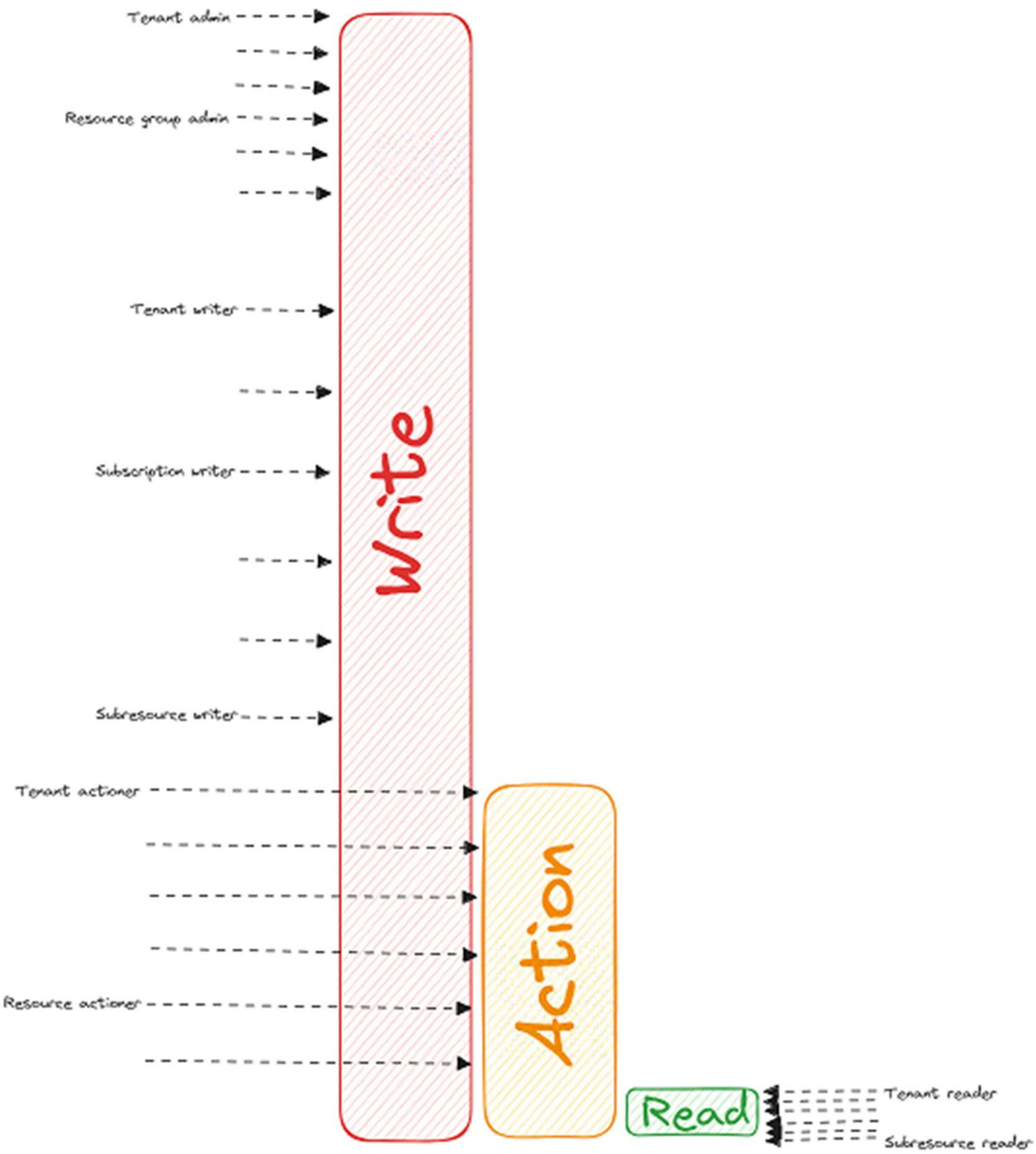
We verify that the minimum difference of any two distinct integers in W, 50, is greater than the sum of the higher bounds for A (45) and R (4), which is 45+4=49.

Likewise, the minimum difference of any two distinct integers in A, 5, is greater than the higher bound of R (4).

So, the induced L1-minus distance over $(w,a,r)_s$ permissions assigned to any Azure scope s is point separating and is indeed a distance. We call it the WAR distance.

The WAR distance ranges from 999 (950+45+4) to 0.

999 is the distance d(S,O) between S, the superadmin tuple with maximum (tenant) permissions, to O, the origin tuple (0,0,0) which is granted no permissions at all.




*Ordering of W, A and R constituting the L1-minus norm of the WAR distance*

**Using the WAR distance to calculate the distance between any two Azure principals**

The norm of tuple $(w,a,r)_s$ at any scope 's' is a natural number attributed according to the following algorithm:

For each principal's role assigned to scope s, we identify any wildcard permission, excluding role assignments: if the scope is the whole tenant, we choose 950. If it is a management group, we choose 900. If it is a subscription or a resource group, we choose 850 or 800 respectively. If it is a resource or a sub-resource, we choose 750 or 700 respectively.

If no wildcard permissions are attached to the assigned role, we look at other putative W permissions, still excluding role assignments: if the scope is the whole tenant, we choose 600. If it is a management group, we choose 500. If it is a subscription or a resource group, we choose 400 or 300 respectively. If it is a resource or a sub-resource, we choose 200 or 100 respectively. If there are no W permissions, we choose 0.

We then switch to A permissions: if the role assignment is attached such permission at tenant level, we choose 45. If it is a management group, we choose 40. If it is a subscription or a resource group, we choose 35 or 30 respectively. If it is a resource or a sub-resource, we choose 20 or 10 respectively. If there are no A permissions, we choose 0. Note that we don't need to exclude role assignments here, because these are only granted through W (or wildcard) permissions.

Finally, we consider R permissions. If the principal's role assignment is attached such permission at tenant scope or at the management group scope, we choose 4. If it is a subscription or a resource group, we choose 3 or 2 respectively. If it is a resource or a sub-resource, we choose 1. If there are no R permissions, we choose 0. Once again, we don't need to exclude role assignments here, because these are only granted through W (or wildcard) permissions.

## Silhouette of a principal

In practice, we coalesce all role assignments of a given principal into a single aggregated "virtual" assignment, its "silhouette".

To aggregate assignments in a meaningful way, we consistently take the maximum scopes 'sw', 'sa' and 'sr' at which a W, A or R permission operates in each role assignment. The resulting silhouette tuple features 3 independent scopes: $(w,a,r)_{sw,sa,sr}$

Here is an illustration of measuring the WAR norm of a principal's silhouette tuple:

| Scope | Has superadmin permission | Has write permission | Has action permission | Has read permission |
|---|---|---|---|---|
| Tenant | +950 | +600 | +45 | +4 |
| Management group | +900 | +500 | +40 | +4 |
| Subscription | +850 | +400 | +35 | +3 |
| Resource Group | +800 | +300 | +30 | +2 |
| Resource | +750 | +200 | +20 | +1 |
| Subresource | +700 | +100 | +10 | +1 |

Thus, a silhouette granting superadmin rights on a subresrource and write + action + read permissions on a tenant would have a norm of 700+45+4=749.

We don't add 600 (tenantwide write permission) to the silhouette because it is superseded by superadmin rights on a subscription (850). Both superadmin and write permissions belong to the W equivalence class, in a staged way ranging from 950 (tenant admin) to 100 (subresource writer).

Note that

1. Being superadmin on a mere subresource takes precedence over being tenantwide writer,
2. Our measurement (749) is strictly lower than resource superadmin's silhouette (750),
3. We don't care what tenants, subscriptions, etc mean from a customer business perspective. These are just resource placeholders. They may not even be nested, but rather, completely independent. What matters is scope maximization.

Takeaway: it is possible to compute the distance of any two principals' RBAC roles, by comparing their silhouettes.

This distance is focused on control plane operations, not IAM operations.

## The Delegate & Assign distance

The previous distance is useful for measuring the extent of purely operational rights. We purposefully excluded role assignments, which are IAM management roles.

Let's build another independent distance for accurately measuring the extent of IAM roles.

Role assignment delegation, currently in preview, opens new avenues to define a wider range of intermediate IAM role than currently supported in Azure and Entra: when these intermediate roles are implemented by Azure customers, the D & A distance will make it possible to measure the extent of IAM roles quite precisely for the first time in Azure's history!

Let's start from an Entra principal 'p' who is assigned an Azure role with the ability to assign other Azure roles. What kind of permissions is this p entitled to grant?

1. Role assignments, in a kind of recursive fashion ("an assignment granting role assignments"),
2. Operational write (including superadmin),
3. Operational action,
4. Operation read,
5. Any combination of the above.

To which population?

1. BRONZE: A group of principals excluding p herself, which p doesn't manage,
2. SILVER: A group of principals including p, which p doesn't manage,
3. GOLD: An arbitrary population of principals (in this case, p is not only role assigner, but doubles up as a group membership manager),
4. Any combination of the above.

Note that the construction of this distance is largely independent from the underlying implementation of the Microsoft Preview (which is based on *constrained conditions*). Should the design be replaced with another logic, the core D&A distance would remain usable.

Here are the main differences between the WAR distance and the D&A distance:

- The WAR distance computes a numeric value for an Azure role assignment which is a pair (role definition, scope), whereas the D&A distance computes a numeric value for a pair (role definition, metallicity of Entra principals) which has no existence in Entra or Azure;
- The WAR distance depends on the WAR partition and scope (or scopes, in case of aggregated assignments), the D&A distance depends on a repartitioning of the permissions space along 4 equivalence classes (W role assignments + W excluding role assignments + A +R) and the metal classification of target population(s).

Let's define the 4-tuple $(da,w,a,r)_m$ of a metal 'm' where da, w, a and r are 4 natural numbers belonging to the following DA, W, A and R sets:

DA = { 192, 128, 64 }

W = { 48, 32, 16 }

A = { 12, 8, 4 }

R = { 3, 2, 1 }

As before, we can easily check that the minimum distance of any two distinct elements in DA, 64, is greater than the sum of the higher bounds of W (48), A (12) and R (3), which is 48+12+3=63.

The same reasoning holds for W, A and R.

So, D&A, the induced L1-minus distance over $(da,w,a,r)_m$ tuples is indeed a distance.

It ranges from 255 (192+48+12+3) to 0. 255 is the distance d(S,O) between S, the superadmin 4-tuple with maximum permissions, to O, the origin 4-tuple (0,0,0,0) which grants no permissions at all.

## Using the D&A distance to calculate the IAM distance between any two Azure principals

The norm of tuple (da,w,a,r) is a natural number attributed according to the following algorithm:

For each principal's role assigned to any scope, we identify the ability for assignees to permit role assignment permissions in the W partition of Microsoft.Authorization' resource provider. If such a permission exists, we identify to which assignees the principal may assign such "roles-assigning" roles: this step depends on the implementation of Azure roles delegation. Currently, this requires examining IAM conditions, which are written in a special language inherited from ABAC conditions (https://learn.microsoft.com/en-us/azure/role-based-access-control/conditions-format)

If this population is GOLD, we choose 192. If it is SILVER, we choose 128. Lastly, if it is BRONZE, we choose 64.

Next, we review the ability for assignees to grant control plane operations in the following order: first we identify write operations (W), then action operations (A) and finally read operations (R).

If, for example, GOLD assignees may grant write operations, we choose 48. If they are SILVER, we choose 32. If they are BRONZE, we choose 16. Likewise for action operations and read operations.

The calculation is additive:

- (additivity along the permissions axis) : if a SILVER population is entitled to grant role assignments and read operations, we choose 128 + 2 = 130.
- (additivity along the population axis): if a BRONZE population is entitled to grant write operations and a GOLD population is entitled to grant action operations, we choose 16+3=17.

Here is an illustration of measuring the D&A norm of a principal's IAM tuple:

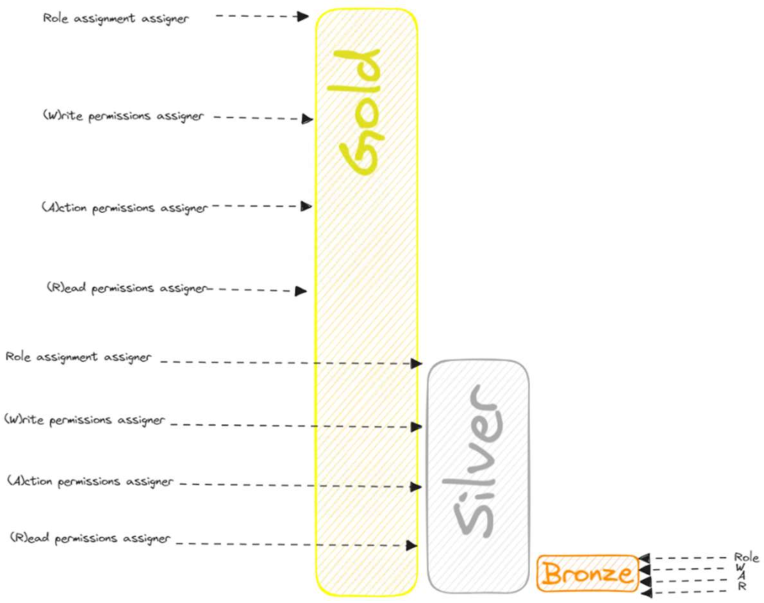
| Assignees | Assignee may assign roles | Assignee may assign W ops | Assignee may assign A ops | Assignee may assign R ops |
|---|---|---|---|---|
| GOLD | +192 | +48 | +12 | +3 |
| SILVER | +128 | +32 | +8 | +2 |
| BRONZE | +64 | +16 | +4 | +1 |

From the above table, it should be obvious that the maximum norm is 192+48+12+3=255 corresponding to an IAM role granting all permissions to arbitrary principals. This corresponds to the default built in Owner role.

The D&A norm of the built-in User Access Administrator role is 192. The very high value attached to this role is consistent with the facts that user access administrators can elevate their privileges to perform arbitrary control plane operations in a scope (which we don't care), and that they can grant such arbitrary powers to uncontrolled third parties.

A corporate User Access Auditor is likely to be assigned D&A norm 0 and WAR norm 4 (an operational, control plane permission to read role assignments in Microsoft.Authorization).

Takeaway: for any two principals, it is possible to compute the distance of their respective IAM roles, regardless of the scopes they manage.



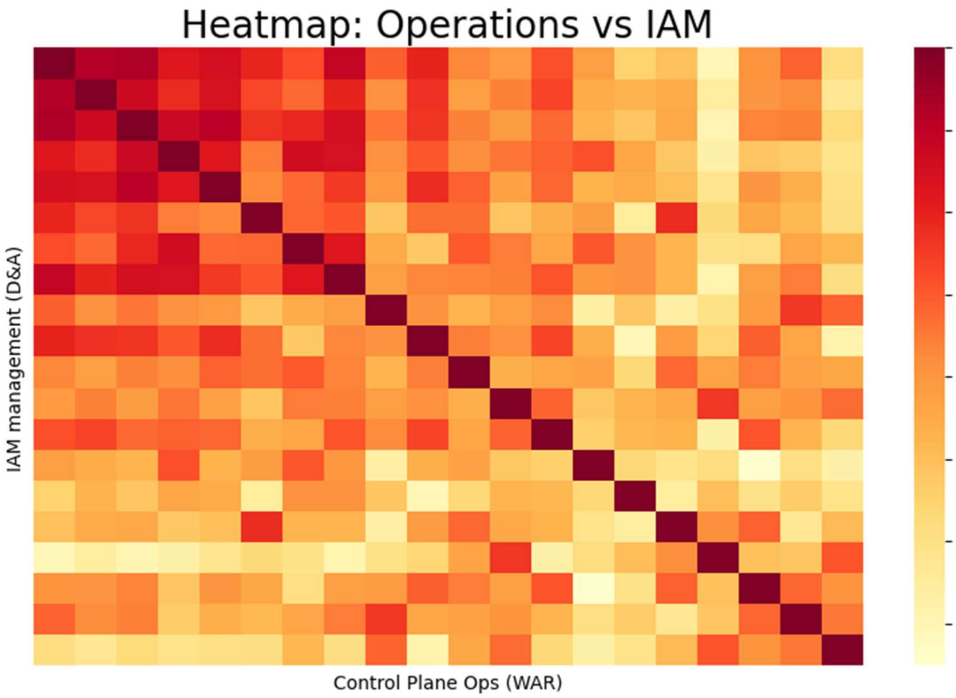

*Ordering of population assignees constituting the L1-minus norm of the D&A distance*

# Solving the long-standing intrication problem in Azure

Up until the preview of role assignment delegation in 2023, building a D&A distance would have made little sense, because in practice only users with Owner or User Administrator roles have the right to assign roles, and these two built-in roles are themselves highly privileged:

- IAM roles and control plane operations roles are intricated;
- Segregation of these administrative duties is difficult.

With the help of the WAR and D&A distances, we may set up a heatmap to illustrate the typical correlation of IAM roles and administrative roles in an Azure tenant, it would look like this:




*Intricated ops rights and IAM rights in Azure (artist view, not actual data)*

As Azure customer adopt roles delegation, attribution of IAM permissions will become gradually more nuanced: the heatmap "concentration of power" is going to spread out. The D&A distance will become a prime instrument to witness de-intrication  factually and with great accuracy

# Distance based de-escalation

Consider the two major IAM sources of truth in the Microsoft Cloud ecosystem:

1. Entra, the golden source of principals, role definitions and role assignments. This directory can be queried using Microsoft Graph API and, for Azure RBAC, may also be queried with Azure Resource Graph API;
2. Log Analytics Workspace, the ground truth of (W)rite and (A)ction control plane operations issuance and outcome. LAW's resource provider may be queried using the Azure Resource Manager API.

Let's introduce two theoretical profiles of Azure principals, called silhouettes:

- The outer silhouette is the principal's extent of Azure rights considered from Entra;
- The inner silhouette is the principal's extent of Azure rights considered from LAW.

The foundational ideas of distance-based deescalation can be expressed as follows:

- Sources of truth being authoritative, any misalignment between any two of them must be treated as a discrepancy in the model,
- A discrepancy is a gap between the outer and inner silhouettes of a principal. Discrepancies arise because Entra tolerates wildcards and arbitrary scope assignments, whereas LAW sees named operations scoped at resource level.
- If we can measure silhouettes using a norm, then we have a formal and reliable way to measure the breadth of the gap using the induced distance of this norm,
- The gap defines a de-escalation range as the interval between a lower bound (the inner silhouette), and an upper bound (the outer silhouette),
- A de-escalation tactic is the process of choosing, for any principal, a target silhouette as a point within de-escalation range. The de-escalation effort of this principal is the difference between the outer silhouette and the target silhouette,
- A de-escalation strategy is the process of prioritizing de-escalation for all principals, by ordering outer silhouettes in descending criticality and constraining de-escalation efforts using IT security risk reduction objectives and financial constraints,

In Azure, it is possible to implement a formal IAM de-escalation strategy because, for any principal:

1. the outer and inner silhouettes can be determined using the L1-minus WAR norm,
2. the de-escalation range can be calculated as the WAR distance between outer and inner silhouettes,
3. the de-escalation effort can be set by picking any point belonging to the de-escalation range.

The WAR distance provides a clear edge when dealing with many principals, or when many privileged roles "look the same", because one can leverage the natural ordering of distances to streamline de-escalation at the scale of the enterprise:

- Quantity: principals can be grouped into risk-based bins, ranging from high-risk (high WAR norm) to low risk (low WAR norm);
- Quality: roles which look similar are often hard to qualify: which role is more risky than which other is prone to subjectivity, inconsistency and interpretation. The WAR distance provides an unambiguous measurement.

# SPN rights de-escalation (control plane)

Automation accounts is one of the most overlooked population when it comes to enforcing strong RBAC. In Azure, Service account SPNs and Managed Identities are no exception. The risk of unmanaging automation accounts is amplified by the fact that they are usually very numerous, and they are generated automatically: in most corporations, they typically scale with the number of assets and subscriptions.

There is one feature, however, that IAM professionals can leverage when dealing with automation accounts: their deterministic behavior. This is really the most outstanding feature of automation.

Machine Learning excels at solving scalability, deterministic problems. We exploit this fact to de-escalate Azure SPNs.

## Principles of scalable SPN rights de-escalation in the control plane

Corporations commonly deploy hundreds, if not thousands, of SPNs to automate their Cloud operations. When determining RBAC distances, it is therefore critical to leverage this deterministic behavior and to reason at the grain of whole SPN clusters, not individual clusters.

As we explained in the first section, one may aggregate all roles of a principal into a silhouette to get a holistic view of the principal's control plane rights : this takes the form of a single measurement, the WAR norm.

Let's expend this idea further and consider groups of SPNs: if we can define clusters of similar SPNs, we may generate a cluster silhouette that maximizes the individual silhouettes of a whole SPNs population.

Takeaway: For SPNs, the WAR distance is calculated at cluster level.

This is line of thoughts doesn't hold for human principals, because business-driven role models are implemented in a *top-down fashion* with Entra groups membership. Automation accounts, however, are rarely business driven, they are driven by technological needs to circumvent purely technical limitations. In that context, going *bottom-up* makes a lot of sense.

## K-Means

K-Means is an unsupervised machine learning algorithm used for grouping multi-dimensional vectors which are close to one another.

We can consider unsupervised machine learning algorithms as categorization "black boxes" which take inputs called features, and which output a single result called the prediction.

In our case, to group accounts by RBAC similarity, we must find some SPN-related features that we shape into the form of a multi-dimensional vector (one for each SPN). Then, we inject each vector into K-Means to "categorize" it. The output category is a cluster ID.

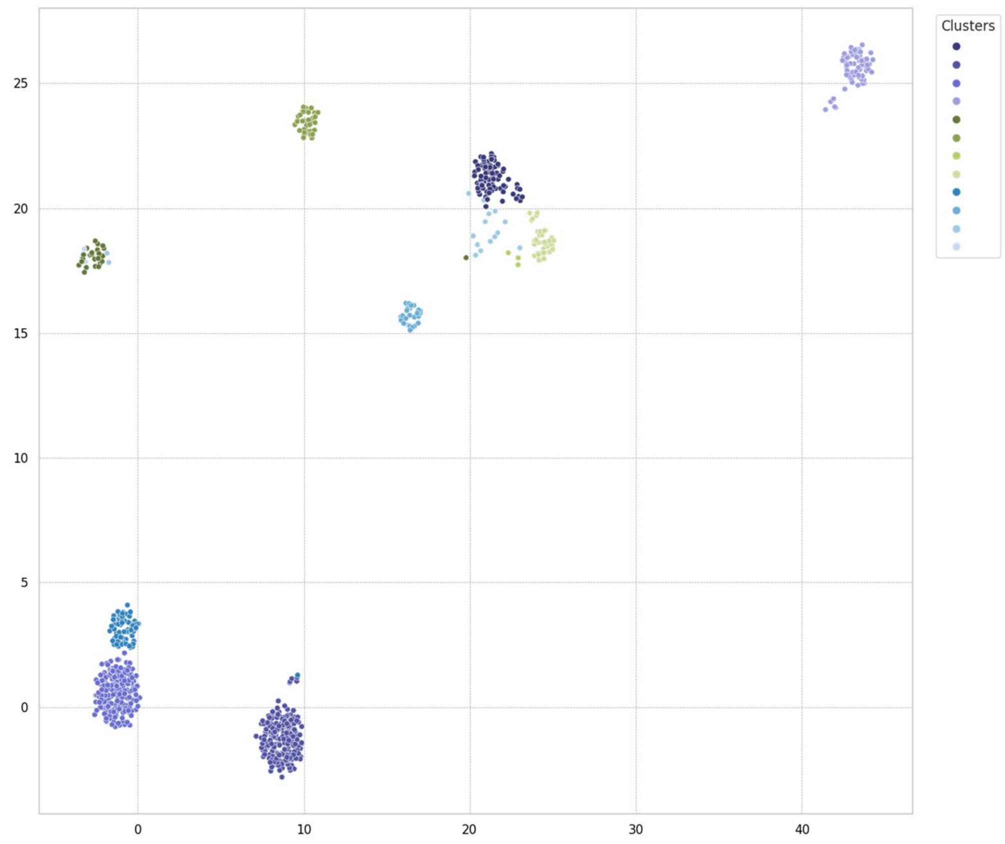
### Features determination

There are many ways to find suitable features for Azure SPNs grouping. It is under active research. What seems to work well is by looking at all the role assignments of an SPN and pick the scope, the WAR permissions and their associated resource providers.

The various resource providers can then be one-hot-encoded before being added to the multi-dimensional vector. The scopes and WAR permissions do not need to be encoded since they are well-defined categories:

- Scopes belong to the Tenant, Management Group, Subscription, Resource Group, Resource, Subresource categorial set;
- Permissions belong to the Write, Action and Read categorial set. (Write can be further subdivided into Superadmin and not superadmin for a better resolution).

To illustrate the efficiency of k-means, the picture below is a 2D UMAP projection of a k-means clustering involving hundreds of SPNs.




*UMAP projection of 12 clusters of Azure SPNs*

A great feature of K-means is that we can pre-set the number of categories that we want.

Since we don't know the optimal number of categories that we need for SPNs clustering, we use a steepest descent algorithm to find an optimum. This optimum is usually rather large, it may be reduced by visually analyzing PCA or UMAP projections, preferably 3D projections.

Projections are also useful to analyze the relative importance of each feature to determine potential dimension reductions. In the case of SPNs clustering, however, using our methodology we haven't found performance issues related to dimensionality, even when a large number of SPNs is fed into the system.

## Calculating a cluster silhouette

Once clusters have been stabilized following the techniques mentioned in the previous section, it becomes possible to build a silhouette for each K-means cluster, using the following algorithm:

For each cluster ID,

Initialize the cluster silhouette: ∅

For each SPN in this cluster,

1. Retrieve the SPN silhouette
2. Aggregate it to the cluster silhouette by using the same aggregation formula (consistently take the maximum scopes sw, sa and sr at which a W, A or R permission operates in each role assignment)

The cluster's outer silhouette (as observed from the golden source of RBAC roles managed in Microsoft Entra) is simply the WAR norm calculated over the aggregated individual SPN silhouettes.

From the outer silhouette, it is a straightforward matter to define a desired silhouette by reasoning along each WAR partition axis in sequence, see where we stand, and where we want to go.

For example, imagine the outer silhouette of a cluster is 938:

- Along the W axis, the cluster currently enjoys management group level modification rights (900) Is that legitimate? For a global CD/CI platform, it might make perfect sense, but to the very least all wildcards should be removed (500). For an application bot, de-escalating modification rights to resource group level (300) could be much more sensible.
- Along the A axis, the cluster enjoys subscription level permissions (35). In most situations, this can be lowered to resource group (30) with little efforts, or even in many cases to resource level (20).
- Along the R axis, the cluster enjoys read access to the management group (4). This should be consistent with W needs, so we could end up sticking to 4 if the cluster SPNs are used by a global CD/CI platform, or to 3 for an application bot.

The desired silhouette of this cluster could stand anywhere between 323 (application bot usage) and 534 (global CD/CI platform).

Note that the inner silhouette defines the absolute lower bound of the target silhouette. In practice, it is unreasonable to attempt setting the target silhouette to the inner silhouette because the latter always operates at resource scope by definition of operations in Azure activity logs.