

A Additional Background

A.1 Additional Examples

We list some examples of popular submodular functions in Table 1.

Problem	Submodular function, $S \subseteq E$ (unless specified)
n experts (simplex), $E = \{1, \dots, n\}$	$f(S) = 1$
k out of n experts (k-simplex), $E = \{1, \dots, n\}$	$f(S) = \min\{ S , k\}$
Permutations over $E = \{1, \dots, n\}$	$f(S) = \sum_{s=1}^{ S } (n+1-s)$
k-truncated permutations over $E = \{1, \dots, n\}$	$f(S) = (n-k) S $ for $ S \leq k$, $f(S) = k(n-k) + \sum_{s=k+1}^{ S } (n+1-s)$ if $ S \geq k$
Spanning trees on $G = (V, E)$	$f(S) = V(S) - \kappa(S)$, $\kappa(S)$ is the number of connected components of S
Matroids over ground set E : $M = (E, (\mathcal{I}))$, $(\mathcal{I}) \subseteq 2^E$	$f(S) = r_M(S)$, the rank function of the matroid
Coverage of T: given $T_1, \dots, T_n \subseteq T$	$f(S) = \bigcup_{i \in S} T_i $, $E = \{1, \dots, n\}$
Cut functions on a directed graph $D = (V, E)$, $c : E \rightarrow \mathbb{R}_+$	$f(S) = c(\delta^{out}(S))$, $S \subseteq V$
Flows into a sink vertex t , given a directed graph $D = (V, E)$ and costs $c : E \rightarrow \mathbb{R}_+$	$f(S) = \max \text{ flow from } S \subseteq V \setminus \{t\} \text{ into } t$
Maximal elements in E , $h : E \rightarrow \mathbb{R}$	$f(S) = \max_{e \in S} h(e)$, $f(\emptyset) = \min_{e \in E} h(e)$
Entropy H of random variables X_1, \dots, X_n	$f(S) = H(\bigcup_{i \in S} X_i)$, $E = \{1, \dots, n\}$

Table 1: Problems and the submodular functions (on ground set of elements E) that give rise to them.

A.2 Strong Convexity and Smoothness

We say a function $g : \mathbb{R}^n \rightarrow \mathbb{R}$ is α -strongly convex if $g(x) - \alpha/2\|x\|^2$ is convex, where $\alpha > 0$. It is easy to see that the sum of a strongly convex function and a piecewise linear function is still strongly convex, and we have

Lemma 3. *When $g : \mathbb{R}^n \rightarrow \mathbb{R}$ is a strongly convex function, then*

$$\text{minimize } g(x) + \max_{w \in \text{conv}(\mathcal{V})} w^\top x \quad (P_{\mathcal{V}})$$

has a unique optimal solution x^ for all $\mathcal{V} \subseteq \mathbb{R}^n$.*

On the other hand, we say a function $g : \mathbb{R}^n \rightarrow \mathbb{R}$ is β -smooth if there exists $\beta > 0$ such that $g(x) - \beta/2\|x\|^2$ is concave. We have[21]:

Lemma 4. *When a function g is α -strongly convex, its Fenchel conjugate g^* is $\frac{1}{\alpha}$ -smooth.*

Lemma 5. *When a function g is β -smooth, its Fenchel conjugate g^* is $\frac{1}{\beta}$ -strongly convex.*

B The Original Simplicial Method (Section 3)

We present the Original Simplicial Method (OSM) in Algorithm 3.

C Limited Memory Kelley's Method (Section 3)

In this section, we provide proofs of some of the results in Section 3.

Proof of Theorem 1.

Proof. We prove this by induction. The claim is true for $i = 0$ since $\mathcal{V}^{(0)}$ has only one element. Suppose that the claim is true for $i < i_0$. When $\Delta > \epsilon$, we have $v^{(i_0)\top} x^{(i_0)} = f(x^{(i_0)}) > f_{(i_0)}(x^{(i_0)})$. From $\mathcal{A}^{(i_0)} \subseteq \{w \in \mathbb{R}^n \mid w^\top x^{(i_0)} = f_{(i_0)}(x^{(i_0)})\}$ we have $v^{(i_0)} \notin \text{affine}(\mathcal{A}^{(i_0)})$. Otherwise when $\Delta^{(i)} \leq \epsilon$, the algorithm terminates in the i_0 th iteration.

Since vectors in $\mathcal{V}^{(i)}$ are affinely independent, we have $|\mathcal{V}^{(i)}| \leq n+1$ for all i since $\mathcal{V}^{(i)} \subseteq \mathbb{R}^n$. \square

Before proving Lemma 1, we first present a lemma that is used in the proof of Lemma 1:

Algorithm 3 OSM: The Original Simplicial Method for (P)

Require: strongly convex function $g : \mathbb{R}^n \rightarrow \mathbb{R}$, submodular function $F : 2^n \rightarrow \mathbb{R}$, tolerance $\epsilon > 0$

Ensure: ϵ -suboptimal solution x^\sharp

- 1: initialize: choose $x^{(0)} \in \mathbb{R}^n$, set $\mathcal{V}^{(0)} = \emptyset$
- 2: **for** $i = 1, 2, \dots$ **do**
- 3: **Convex subproblem.** Define approximation $f_{(i)}(x) = \max\{w^\top x : w \in \mathcal{V}^{(i-1)}\}$ and solve

$$x^{(i)} = \operatorname{argmin} g(x) + f_{(i)}(x).$$

- 4: **Submodular subproblem.** Compute value and subgradient of f at $x^{(i)}$

$$f(x^{(i)}) = \max_{w \in B(F)} w^\top x^{(i)}, \quad v^{(i)} \in \partial f(x^{(i)}) = \operatorname{argmax}_{w \in B(F)} w^\top x^{(i)}.$$

- 5: **Stopping condition.** Break if duality gap $p^{(i)} - d^{(i)} \leq \epsilon$, where

$$p^{(i)} = g(x^{(i)}) + f(x^{(i)}), \quad d^{(i)} = g(x^{(i)}) + f_{(i)}(x^{(i)}).$$

- 6: **Update memory.** Update memory $\mathcal{V}^{(i)}$:

$$\mathcal{V}^{(i)} = \mathcal{V}^{(i-1)} \cup \{v^{(i)}\}.$$

- 7: **return** $x^{(i)}$
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Lemma 6. Given a submodular function $F : 2^V \rightarrow \mathbb{R}$, let $\mathcal{W} \subseteq \operatorname{vert}(B(F))$ be a subset of the vertices of its base polytope. For the piecewise linear function

$$\tilde{f}(x) = \max_{w \in \operatorname{conv}(\mathcal{W})} w^\top x,$$

let $\mathcal{A}(x) \triangleq \{w^* \in \mathcal{W} \mid w^{*\top} x = \tilde{f}(x)\}$ be the points in \mathcal{W} that are active at x . Then given any $\bar{x} \in \mathbb{R}^n$, there exists $\epsilon > 0$ such that

$$\tilde{f}(x) = \max_{w^* \in \operatorname{conv}(\mathcal{A}(\bar{x}))} w^{*\top} x$$

for all $x \in \mathcal{B}(\bar{x}, \epsilon)$.

Proof. Since \mathcal{W} is finite, we have $\tilde{f}(\bar{x}) \geq \max_{\tilde{w} \in \mathcal{W} \setminus \mathcal{A}(\bar{x})} \tilde{w}^\top \bar{x} + \epsilon$, where $\epsilon > 0$. Let $L = \max_{w \in \mathcal{W}} \|w\|$, then for all $x \in \mathcal{B}(\bar{x}, \epsilon/(3L))$, $w^* \in \mathcal{A}(\bar{x})$ and $\tilde{w} \in \mathcal{W} \setminus \mathcal{A}(\bar{x})$, we have

$$\begin{aligned} w^{*\top} x - \tilde{w}^\top x &= (w^* - \tilde{w})^\top \bar{x} + w^{*\top} (x - \bar{x}) + \tilde{w}^\top (\bar{x} - x) \\ &\geq \epsilon - L \frac{\epsilon}{3L} - L \frac{\epsilon}{3L} \\ &= \frac{\epsilon}{3}. \end{aligned} \tag{6}$$

Hence $\tilde{f}(x) > \tilde{w}^\top x$ for all $x \in \mathcal{B}(\bar{x}, \epsilon/(3L))$ and $\tilde{w} \in \mathcal{W} \setminus \mathcal{A}(\bar{x})$, which is equivalent to $\tilde{f}(x) = \max_{w^* \in \operatorname{conv}(\mathcal{A}(\bar{x}))} w^{*\top} x$ for all $x \in \mathcal{B}(\bar{x}, \epsilon/(3L))$. \square

Proof of Lemma 1.

Proof. Let $P_{(i)}(x) \triangleq \min g(x) + \max_{w \in \operatorname{conv}(\mathcal{V}^{(i-1)})} w^\top x = g(x) + f_{(i)}(x)$ and $\tilde{P}_{(i)} \triangleq \min_{x \in \mathbb{R}^n} g(x) + \max_{w \in \operatorname{conv}(\mathcal{A}^{(i)})} w^\top x$. There exists at least one $w^* \in \mathcal{V}^{(i-1)}$ such that $f_{(i)}(x^{(i)}) = w^{*\top} x^{(i)}$. Therefore, $P_{(i)}(x^{(i)}) = g(x^{(i)}) + w^{*\top} x^{(i)} = g(x^{(i)}) + \max_{w \in \operatorname{conv}(\mathcal{A}^{(i)})} w^\top x^{(i)} = \tilde{P}_{(i)}(x^{(i)})$, where the last equality follows from the definition of $\mathcal{A}^{(i)}$. Next, if we can show local optimality of $x^{(i)}$ for $\tilde{P}_{(i)}$, this would imply global optimality of $x^{(i)}$ for $\tilde{P}_{(i)}$ due to convexity of $\tilde{P}_{(i)}$, thus $P_{(i)}$ and $\tilde{P}_{(i)}$ will have the same optimal value. By the definition of $\mathcal{A}^{(i)}$ and Lemma 6, we have $f(x) = \max_{w \in \operatorname{conv}(\mathcal{A}^{(i)})} w^\top x = f_{(i)}(x)$ in $\mathcal{B}(x^{(i)}, \epsilon)$ for some $\epsilon > 0$. Thus $P_{(i)}(x^{(i)}) = g(x) + f(x) = g(x) + f_{(i)}(x) = \tilde{P}_{(i)}(x)$ for $x \in \mathcal{B}(x^{(i)}, \epsilon)$. Hence $x^{(i)}$ is a local optimal solution to $\tilde{P}_{(i)}$, and the lemma is proved. By Lemma 3, $x^{(i)}$ is the unique solution to both $P_{(i)}$ and $\tilde{P}_{(i)}$. \square

Proof of Corollary 1.

Proof. For any $i \geq 1$, by Lemma 3, there exists an $x^{(i)} \in \mathbb{R}^n$ that minimizes $g(x) + f_{(i)}(x)$. Thus we have

$$\begin{aligned}
d^{(i)} &= g(x^{(i)}) + f_{(i)}(x^{(i)}) \\
&= g(x^{(i)}) + \max_{w \in \text{conv}(\mathcal{V}^{(i-1)})} w^\top x^{(i)} \\
&\geq g(x^{(i)}) + \max_{w \in \text{conv}(\mathcal{A}^{(i-1)})} w^\top x^{(i)} \quad \triangleright \mathcal{A}^{(i-1)} \subseteq \mathcal{V}^{(i-1)} \quad (7) \\
&> g(x^{(i-1)}) + \max_{w \in \text{conv}(\mathcal{A}^{(i-1)})} w^\top x^{(i-1)} \quad \triangleright \text{optimality and uniqueness of } x^{(i-1)} \\
&= d^{(i-1)}.
\end{aligned}$$

On the other hand, by $\mathcal{V}^{(i-1)} \subseteq \text{vert}(B(F))$, we have

$$\begin{aligned}
d^{(i)} &= \min_{x \in \mathbb{R}^n} \{g(x) + \max_{w \in \text{conv}(\mathcal{V}^{(i-1)})} w^\top x\} \\
&\leq \min_{x \in \mathbb{R}^n} \{g(x) + \max_{w \in B(F)} w^\top x\} \quad (8) \\
&= \min_{x \in \mathbb{R}^n} g(x) + f(x)
\end{aligned}$$

for all $i \geq 0$. \square

Proof of Corollary 2.

Proof. Note that each $\mathcal{V}^{(i)}$ determines a unique $d^{(i)}$. Suppose for contradiction that there exists $i_1 \neq i_2$ but $\mathcal{V}^{(i_1)} = \mathcal{V}^{(i_2)}$, then we will have $d^{(i_1)} = d^{(i_2)}$, which contradicts the fact that $\{d^{(i)}\}$ strictly increases. \square

Proof of Theorem 2

Proof. Since $\text{vert}(B(F))$ has finitely many vertices, there are only finitely many choices of $\mathcal{V}^{(i)} \subseteq \text{vert}(B(F))$. Thus by Corollary 2, Algorithm 1 terminates within finitely many steps.

Suppose for contradiction that when the algorithm terminates at $i = i_0$, $p^{(i_0)} - d^{(i_0)} > \epsilon \geq 0$. Let $\mathcal{A}^{(i_0)} \triangleq \{w \in \mathcal{V}^{(i_0-1)} : w^\top x^{(i_0)} \triangleq f_{(i_0)}(x^{(i_0)}) \text{ and } v^{(i_0)} \in \mathcal{V}(x^{(i_0)})\}$. Define $\mathcal{V}^{(i_0)} \triangleq \mathcal{A}^{(i_0)} \cup \{v^{(i_0)}\}$ and $f_{(i_0+1)}(x) = \max\{w^\top x : w \in \mathcal{V}^{(i_0)}\}$, then let $x^{(i_0+1)} = \arg\min_{x \in \mathbb{R}^n} g(x) + f_{(i_0+1)}(x)$. By the proof of Corollary 1, we have $d^{(i_0+1)} = g(x^{(i_0+1)}) + f_{(i_0+1)}(x^{(i_0+1)}) > d^{(i_0)}$, so $\mathcal{V}^{(i_0)}$ is different to any $\mathcal{V}^{(i)}$ where $i \leq i_0$, and L-KM should not have terminated at $i = i_0$. Thus L-KM would never terminate when $p^{(i)} - d^{(i)} > \epsilon \geq 0$. \square

D Duality (Section 4)

To prove the strong duality between (P_V) and (D_V) , we first verify the weak duality:

Theorem 9 (Weak Duality). *The optimal value of primal problem (P_V) is greater than or equal to the optimal value of the dual problem (D_V) .*

Proof. We first have

$$\min_{x \in \mathbb{R}^n} \{g(x) + \max_{w \in \text{conv}(\mathcal{V})} w^\top x\} = \min_{x \in \mathbb{R}^n} \max_{w \in \text{conv}(\mathcal{V})} g(x) + w^\top x. \quad (9)$$

For any given $\tilde{w} \in \text{conv}(\mathcal{V})$, we also have

$$\min_{x \in \mathbb{R}^n} \max_{w \in \text{conv}(\mathcal{V})} g(x) + w^\top x \geq \min_{x \in \mathbb{R}^n} g(x) + \tilde{w}^\top x. \quad (10)$$

Thus by the definition of g^* , we can see that

$$\begin{aligned}
\min_{x \in \mathbb{R}^n} \max_{w \in \text{conv}(\mathcal{V})} g(x) + w^\top x &\geq \max_{w \in \text{conv}(\mathcal{V})} \min_{x \in \mathbb{R}^n} g(x) + w^\top x \\
&= \max_{w \in \text{conv}(\mathcal{V})} - \max_{x \in \mathbb{R}^n} (-w)^\top x - g(x) \\
&= \max_{w \in \text{conv}(\mathcal{V})} -g^*(-w). \quad (11)
\end{aligned}$$

Combine (9) and (11), and the theorem follows. \square

Proof of Theorem 3

Proof. By Lemma 3, we know (P_V) has a unique solution \bar{x} . Since g is convex, we have $\partial g(x) \neq \emptyset$. By the optimality of \bar{x} , we also have $0 \in \partial g(\bar{x}) + \partial f(\bar{x})$. Let $\bar{w} \in -\partial g(\bar{x}) \cap \partial f(\bar{x})$, then

$$g^*(-\bar{w}) = (-\bar{w})^\top \bar{x} - g(\bar{x}) \quad (12)$$

by Eq. (4). Note that $\bar{w} \in \partial f(\bar{x})$, we also have $f(\bar{x}) = \bar{w}^\top \bar{x}$ by Equation (2). Thus

$$f(\bar{x}) + g(\bar{x}) = g^*(\bar{w}), \quad (13)$$

\bar{w} is an optimal solution to (D_V) and we have (P_V) and (D_V) via weak duality. \square

E Primal-from-dual algorithm (Section 5)

Now consider the *Primal-from-dual* algorithm presented in Section 5.

Formally, assume g is α -strongly convex. Suppose we obtain $w \in B(F)$ with

$$\|w - w^*\| \leq \epsilon$$

via some dual algorithm (e.g., L-FCFW). Define $x = \nabla_w(-g^*(-w)) = \operatorname{argmin}_x g(x) + w^\top x$. Since g^* is $1/\alpha$ smooth, we have

$$\|x - x^*\| \leq 1/\alpha \|w - w^*\| \leq \epsilon/\alpha$$

Hence if the dual iterates converge linearly, so do the primal iterates.

The remaining difficulty is how to solve the L-FCFW subproblems. One possibility is to use the values and gradients of (a FIRST ORDER ORACLE for) $h = g^*$. To implement a first order oracle for $h = g^*$, we need only solve an unconstrained minimization problem:

$$g^*(y) = \max_{x \in \mathbb{R}^n} y^\top x - g(x), \quad \nabla g^*(y) = \operatorname{argmax}_{x \in \mathbb{R}^n} y^\top x - g(x).$$

This problem is straightforward to solve since g is smooth and strongly convex. However, it is not clear how solving these subproblems approximately affects the convergence of L-FCFW. Moreover, we will see in the next section that L-KM achieves exactly the same sequence of iterates as the above (rather unwieldy) proposal.

F Duality between L-KM and L-FCFW (Section 6)

Lemma 7. *Only vertices in $\mathcal{A}^{(i)}$ can have positive convex multipliers in the convex decomposition of $w^{(i)}$, i.e., if we write $w^{(i)} = \sum_{v \in \mathcal{V}^{(i-1)}} \lambda_v^{(i)} v$ such that $0 \leq \lambda_v \leq 1$ for any $v \in \mathcal{V}^{(i-1)}$, then $\lambda_v^{(i)} = 0$ for any $v \in \mathcal{V}^{(i-1)} \setminus \mathcal{A}^{(i)}$.*

Proof. By the definition of $\mathcal{A}^{(i)}$, we have

$$\begin{aligned} \operatorname{conv}(\mathcal{A}^{(i)}) &= \operatorname{conv}(\{v \in \mathcal{V}^{(i-1)} \mid v^\top x^{(i)} = w^{(i)\top} x^{(i)}\}) \\ &= \operatorname{conv}(\{v \in \mathcal{V}^{(i-1)} \mid v^\top x^{(i)} = \max_{w \in \operatorname{conv}(\mathcal{V}^{(i-1)})} w^\top x^{(i)}\}) \\ &= \operatorname{argmax}_{w \in \operatorname{conv}(\mathcal{V}^{(i-1)})} w^\top x^{(i)}. \end{aligned} \quad (14)$$

Then

$$\begin{aligned} 0 &= (w^{(i)} - w^{(i)})^\top x^{(i)} \\ &= (w^{(i)} - \sum_{v \in \mathcal{V}^{(i-1)}} \lambda_v^{(i)} v)^\top x^{(i)} \\ &= \sum_{v \in \mathcal{V}^{(i-1)} \setminus \mathcal{A}^{(i)}} \lambda_v^{(i)} [(w^{(i)})^\top x^{(i)} - v^\top x^{(i)}]. \quad \triangleright v^\top x^{(i)} = w^{(i)\top} x^{(i)}, \forall v \in \mathcal{A}^{(i)} \end{aligned} \quad (15)$$

Using (14), we have $v^\top x^{(i)} - w^{(i)\top} x^{(i)} < 0$ for any $v \in \mathcal{V}^{(i-1)} \setminus \mathcal{A}^{(i)}$. Thus $\lambda_v^{(i)} = 0$ for any $v \in \mathcal{V}^{(i-1)} \setminus \mathcal{A}^{(i)}$. \square

Proof of Theorem 6.

Proof. We prove by induction. When $i = 1$, $\mathcal{V}^{(0)}$ will naturally refer to the same set of points in L-KM and L-FCFW. By Lemma 3, we have $x^{(1)}$ is the unique solution to $g + f_{(1)}$. Note g^* is strongly convex given g is smooth (Lemma 5), we have $w^{(1)}$ is the unique solution to $\max_{w \in \text{conv}(\mathcal{V}^{(0)})} -g^*(-w)$. Let $\mathcal{V} = \mathcal{V}^{(0)}$ in Theorem 4, we have that $x^{(1)} = -\nabla g^*(-w^{(1)})$ is the unique minimizer of $g + f_{(1)}$. So $x^{(1)}$ in the two algorithms match. Also note that $w^{(1)}$ solves $\max_{w \in \text{conv}(\mathcal{V}^{(0)})} -g^*(-w)$, we have $w^{(1)}$ maximizes $w^\top x^{(1)}$ for all $w \in \text{conv}(\mathcal{V}^{(i-1)})$ by the first order optimality condition, which gives $w^{(i)\top} x^{(i)} = f_{(i)}(x^{(i)})$. Thus $\mathcal{A}^{(1)}, \mathcal{V}^{(1)}$ match consequently. By strong duality in Theorem 3, we have $d^{(1)}$ matches in the two algorithms. Note g^* is strongly convex, which gives the uniqueness of $w^{(1)}$. By Theorem 4, $\nabla g(w^{(1)})$ solves the primal subproblem, so $x^{(1)}$ match in the two algorithms by the uniqueness of $x^{(1)}$.

Suppose that the theorem holds for $i = i_0$, in particular, the $\mathcal{V}^{(i_0)}$ match in the two algorithms. Then for $i = i_0 + 1$, we can use the same argument as in the previous paragraph by substituting 0 with i_0 and 1 with $i_0 + 1$, and show that all the statements hold for $i = i_0 + 1$. Note that by Lemma 7, $\mathcal{A}^{(i)}$ satisfies the condition in Line 6 of L-FCFW. Thus this theorem is valid. \square

G Duality between OSM and L-FCFW (Section 6)

Theorem 10. *If g is smooth and strongly convex and in Algorithm 2 we choose $\mathcal{B}^{(i)} = \mathcal{V}^{(i-1)}$, then*

1. *The primal iterates $x^{(i)}$ of Algorithm 3 and Algorithm 2 match.*
2. *The set $\mathcal{V}^{(i)}$ used at each iteration of Algorithm 3 and Algorithm 2 match.*
3. *The upper and lower bounds $p^{(i)}$ and $d^{(i)}$ of Algorithm 3 and Algorithm 2 match.*

The proof of Theorem 10 is similar to the proof of Theorem 6.

H Definition of Diameter and Pyramid Width

Diameter. The diameter of a set $\mathcal{P} \subseteq \mathbb{R}^n$ is defined as

$$\text{Diam}(\mathcal{P}) \triangleq \max_{v, w \in \mathcal{P}} \|v - w\|_2. \quad (16)$$

Directional Width. Given a direction $x \in \mathbb{R}^n$, the directional width of a set $\mathcal{P} \subseteq \mathbb{R}^n$ with respect to x is defined as

$$\text{dirW}(\mathcal{P}, x) \triangleq \max_{v, w \in \mathcal{P}} (v - w)^\top \frac{x}{\|x\|_2}. \quad (17)$$

Pyramid directional width and pyramid width are defined by Lacoste-Julien and Jaggi in [15] for a finite sets of vectors $\mathcal{V} \subseteq \mathbb{R}^n$. Here we extend the definition of pyramid width to a polytope $\mathcal{P} = \text{conv}(\mathcal{V})$, and it should be easy to see that the two definitions are essentially the same.

Pyramid Directional Width. Let $\mathcal{V} \subseteq \mathbb{R}^n$ be a finite set of vectors in \mathbb{R}^n . The pyramid directional width of \mathcal{V} with respect to a direction x and a base point $w \in \text{conv}(\mathcal{V})$ is defined as

$$\text{PdirW}(\mathcal{V}, x, w) \triangleq \min_{A \in \mathcal{A}(w)} \text{dirW}(A \cup \{v(\mathcal{V}, x)\}, x), \quad (18)$$

where $\mathcal{A}(w) \triangleq \{A \subseteq \mathcal{V} \mid \text{the convex multipliers are non-zero for all } v \in A \text{ in the decomposition of } w\}$ and $v(\mathcal{V}, x)$ is a vector in $\arg \max_{v \in \mathcal{V}} v^\top x$. The pyramid directional width got its name because the set $A \cup \{v(\mathcal{V}, x)\}$ has the shape of a pyramid with A being the base and $v(\mathcal{V}, x)$ being the summit.

Pyramid Width. The pyramid width of \mathcal{P} is defined as

$$\text{PWidth}(\mathcal{P}) \triangleq \min_{\mathcal{K} \in \text{face}(\mathcal{P})} \min_{x \in \text{cone}(\mathcal{K} - w) \setminus \{0\}, w \in \mathcal{K}} \text{PdirW}(\mathcal{K} \cap \text{vert}(\mathcal{P}), x, w), \quad (19)$$

where $\text{face}(\mathcal{P})$ stands for the faces of \mathcal{P} and $\text{cone}(\mathcal{K} - w)$ is equivalent to the set of vectors pointing inwards \mathcal{K} .