Tropical Weierstrass Semigroups

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Catania, 19 April 2023

Goal: tropical analogues of Weierstrass semigroups

X smooth projective curve of genus g

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Theorem (Weierstrass gap theorem)

$$|\mathbb{N} \setminus H(P)| = g$$

numerical semigroup = cofinite submonoid of $\mathbb{N}$

Question (Hurwitz 1893)

Which numerical semigroups are Weierstrass semigroups?

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Example (Buchweitz 1980)

The semigroup $S = \langle 13, 14, 15, 16, 17, 18, 20, 22, 23 \rangle$ is not a Weierstrass semigroup

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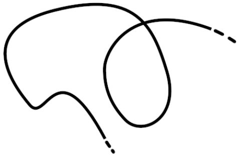
Recent work of Cotterill, Pflueger, Zhang (2022) certifies Weierstrass-realizability of some numerical semigroups.

Theorem (Torres)

Let $\gamma \in \mathbb{N}$ and X be a curve of genus $g \geq 6\gamma + 4$. TFAE:

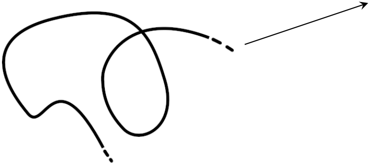
- *X is a double cover of a curve of genus γ,*
- *there exists $P \in X$ such that $H(P)$ is the numerical duplication of a numerical semigroup of genus γ.*

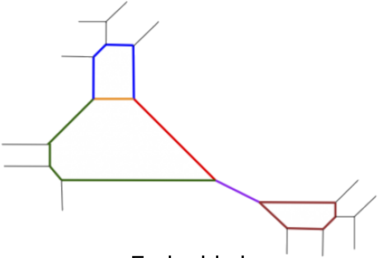
Classical



Classical

Tropical





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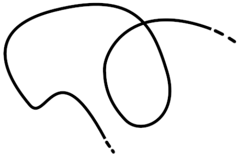

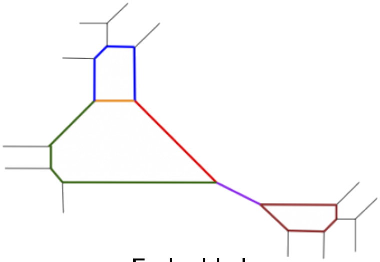

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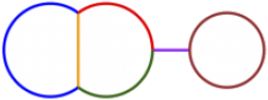

Abstract

Baker and Norine (2007) divisors on graphs

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graph := finite connected multigraph with no loops

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graph := finite connected multigraph with no loops

simple graph := graph with no multiple edges

Divisor theory on graphs

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$$D = a_1 P_1 + a_2 P_2 + \cdots + a_n P_n$$

where $a_i \in \mathbb{Z}$.

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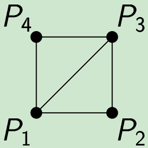
$$D = 3P_1 + P_2 + P_3$$



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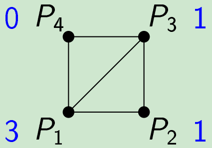

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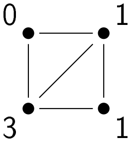

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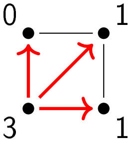

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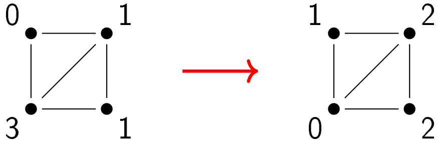

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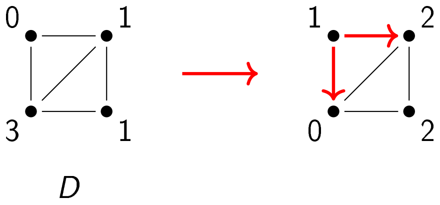

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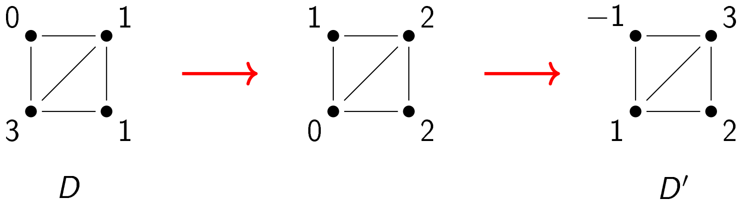

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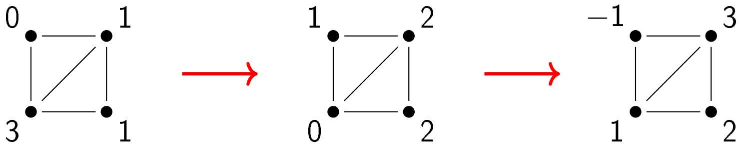
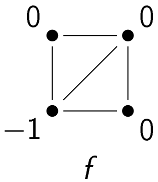


D $\qquad\qquad\qquad\qquad$ D'

$$D \sim D'$$

Principal divisors

Let $f : V(G) \to \mathbb{Z}$



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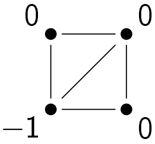

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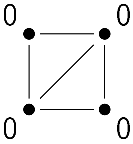

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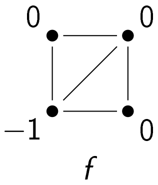

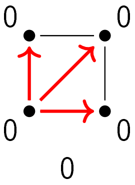

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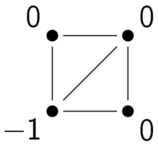

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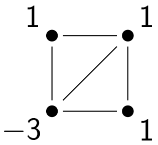

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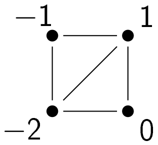

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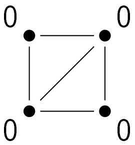

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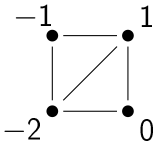

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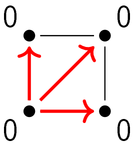

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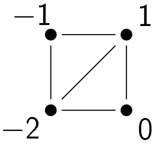

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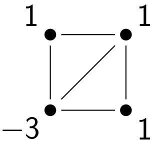

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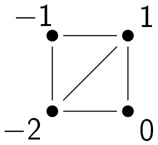

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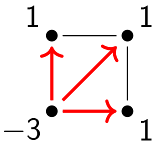

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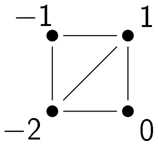

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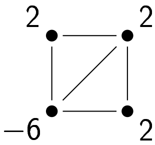

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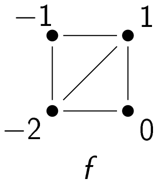

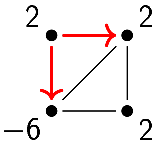

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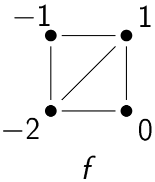

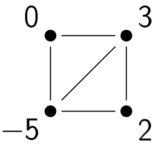

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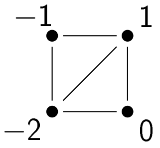

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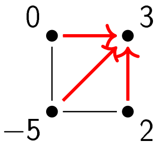

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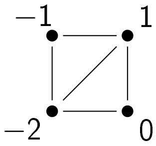

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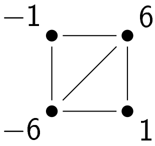

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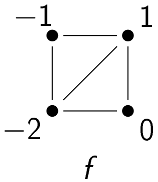

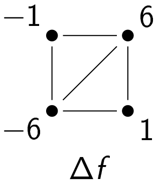

Two divisors $D, D' \in \mathrm{Div}(G)$ are **linearly equivalent** if

$$D - D' = \Delta f \quad \text{for some } f : V(G) \to \mathbb{Z}.$$

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D is **effective** if $D \geq 0$.

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Denote by $\mathrm{Div}_+^d(G)$ the set of effective of divisors of degree d.

The **linear system** of a divisor $D \in \mathrm{Div}(G)$ is

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The **rank** of D is -1 if $|D| = \emptyset$, otherwise

$$r(D) = \max\{d \in \mathbb{N} : |D - E| \neq \emptyset, \forall E \in \mathrm{Div}_+^d(G)\}.$$

Weierstrass sets

Recall (for curves):

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\begin{aligned}
H(P) &= \{n \in \mathbb{N} : \exists f \in K(X) \text{ regular on } X \setminus \{P\}, \operatorname{ord}_P(f) = -n\} \\
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Definition (Kang, Matthews, Peachey 2020)

Let G be a graph and let $P \in V(G)$.

Rank Weierstrass set:

$$H_r(P) = \{n \in \mathbb{N} : r(nP) > r((n-1)P)\}$$

Functional Weierstrass set:

$$H_f(P) = \{n \in \mathbb{N} : \exists f \text{ such that } \Delta f + nP \geq 0, \Delta f(P) = -n\}$$

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For curves: $H_r(P) = H_f(P) = H(P)$,

For graphs: $H_f(P) \setminus H_r(P)$ can be arbitrarily large!

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The **genus** of a graph G is $g = |E(G)| - |V(G)| + 1$.

Lemma (Tropical Weierstrass Gap Theorem)

$$|\mathbb{N} \setminus H_r(P)| = g$$

Not true for $H_f(P)$.

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Lemma (Tropical Weierstrass Gap Theorem)

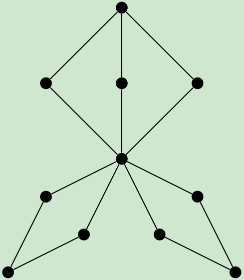
$$|\mathbb{N} \setminus H_r(P)| = g$$

Not true for $H_f(P)$.

$H_f(P)$ is a semigroup, $H_r(P)$ is *not*.

Example

Consider the following graph G



It is the vertex gluing of $K_{2,3}$ and two copies of $K_{2,2}$.
Let $P \in V(G)$ be the vertex of degree 7. Then

$$H_r(P) = \{0, 3, 5, 7\} \cup (8 + \mathbb{N}).$$

Note that $H_r(P)$ is not a semigroup $6 = 3 + 3 \notin H_r(P)$.

This result was conjectured by Kang, Matthews and Peachey:

Theorem (B. 2022)

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$H_r(P) \subseteq H_f(P)$ and $|\mathbb{N} \setminus H_r(P)| = g(K_{n+1})$ imply:

Corollary

For every $P \in V(K_{n+1})$ $\qquad H_r(P) = H_f(P) = \langle n, n+1 \rangle$.

Let $K_{m,n}$ be the complete bipartite graph.

Proposition

For every $P \in V(K_{m,n})$

$$H_r(P) = H_f(P) = n\mathbb{N} \cup (n(m-1) + \mathbb{N})$$

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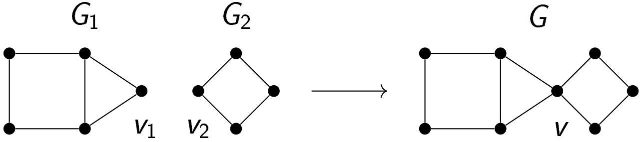
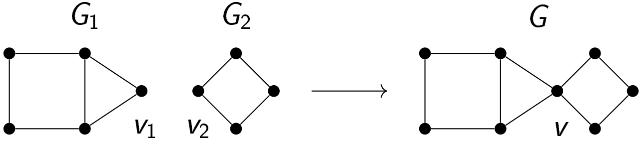
Question

Under which conditions on G we have $H_r(P) = H_f(P)$?



Vertex gluing: the graph G obtained by identifying v_1 and v_1



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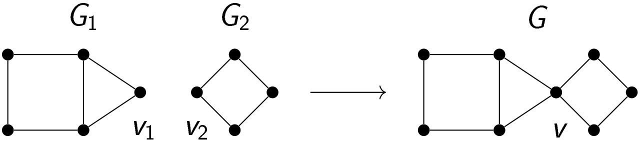
Proposition

$$H_f^G(v) = H_f^{G_1}(v_1) + H_f^{G_2}(v_2)$$



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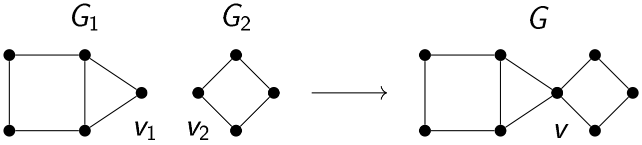
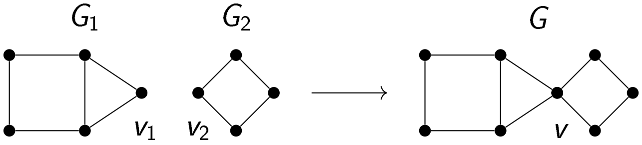
Theorem (B. 2022)

Functional Weierstrass sets of graphs	$\longleftrightarrow$	*submonoids of* $\mathbb{N}$
Functional Weierstrass sets of simple graphs	$\longleftrightarrow$	*numerical semigroups*



Vertex gluing: the graph G obtained by identifying v_1 and v_1

Let $H_r^G(v)_i$ be the i-th element of $H_r^G(v)$.



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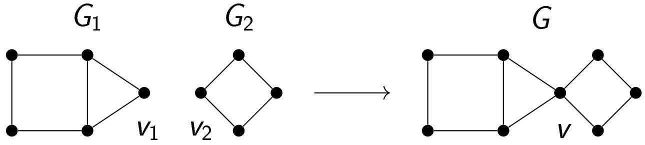
$$H_r^G(v)_k = \max\{H_r^{G_1}(v_1)_{k_1} + H_r^{G_2}(v_2)_{k_2} : k_1 + k_2 = k\}$$



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Theorem (B. 2022)

Let $e_1 \geq e_2 \geq \cdots \geq e_n \geq 0$ be integers, and set $s_i = \sum_{j=1}^{i} e_j$. There exists a simple graph G with a vertex $P \in V(G)$ such that

$$H_r(P) = \{0, s_1, \ldots, s_{n-1}\} \cup (s_n + \mathbb{N})$$

Thank you very much!