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The 24th IEEE/ACM International Symposium on Cluster, Cloud and Internet Computing

A Distributed, Asynchronous Algorithm for Large-Scale Internet Network Topology Analysis

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Habanero Extreme Scale Software Research Lab
Georgia Institute of **Tech**nology

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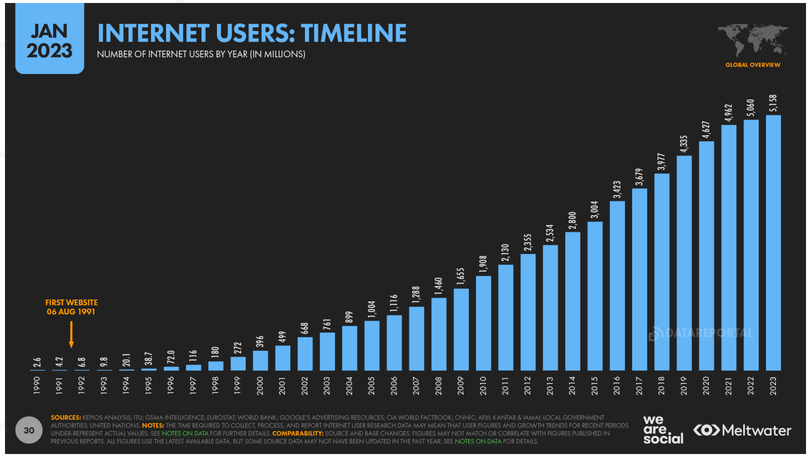
The Growth of the Internet and the increasing complexity of its global network topology



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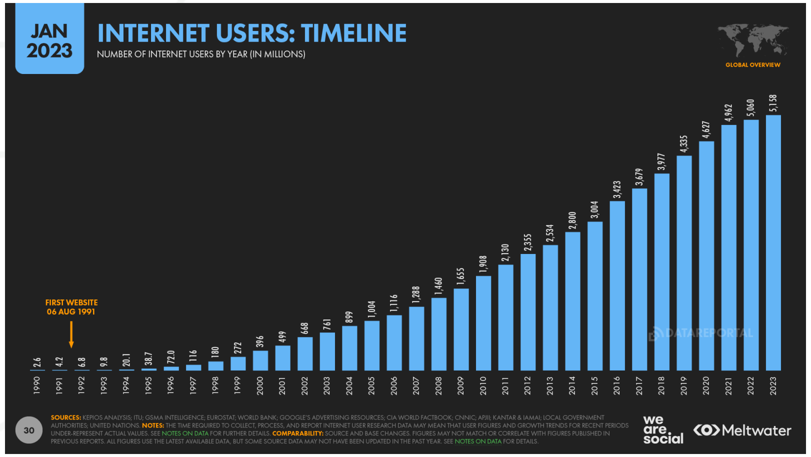

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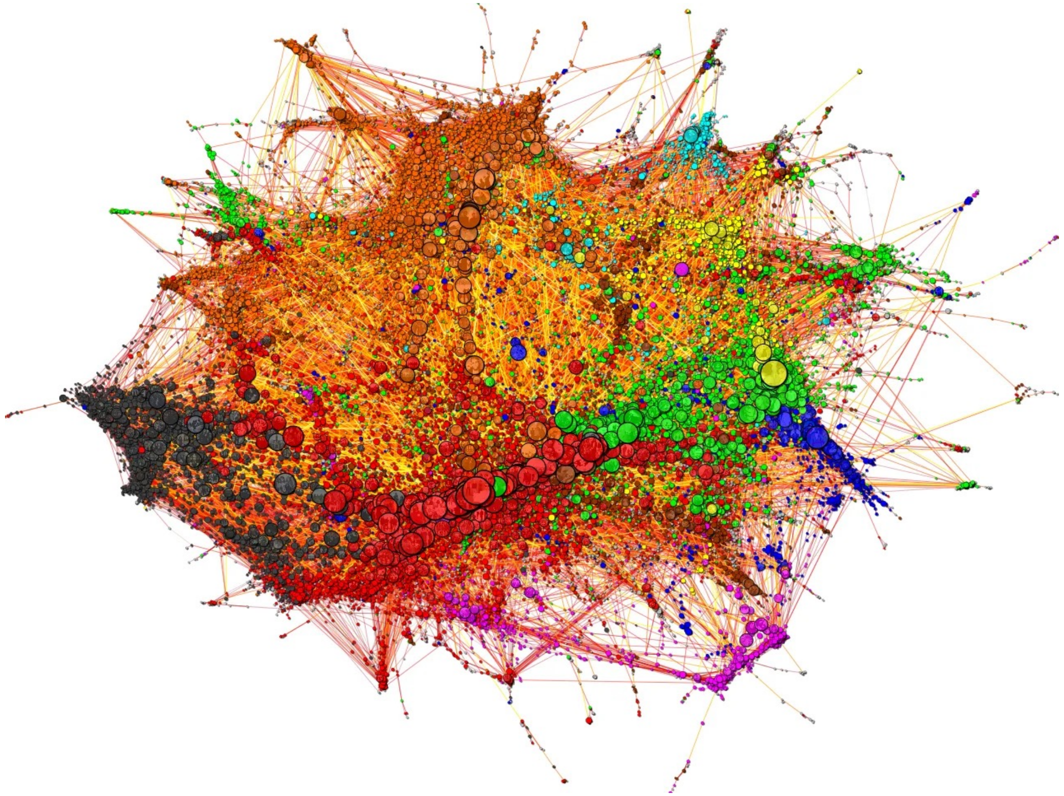

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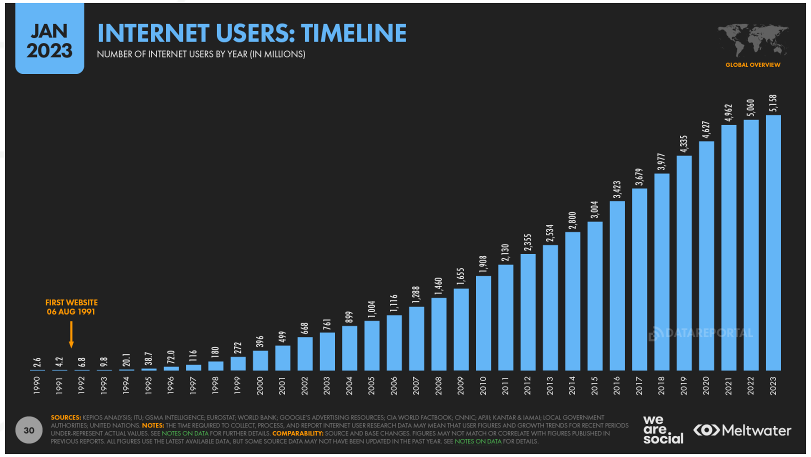

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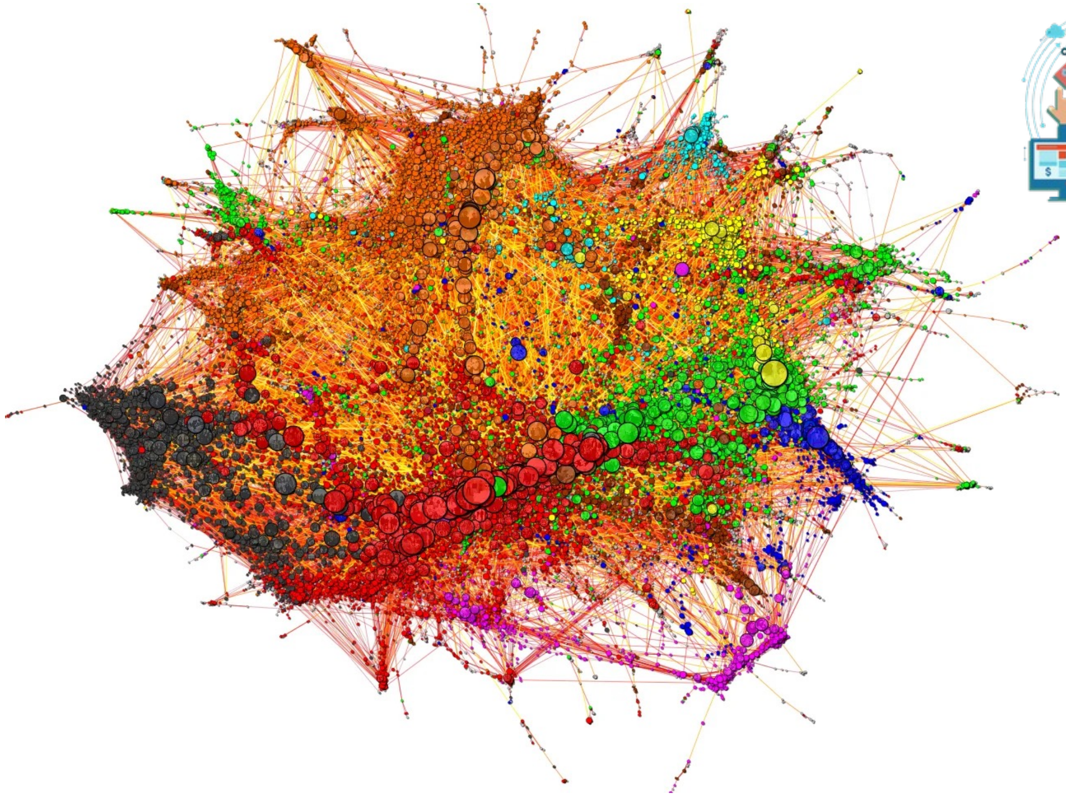

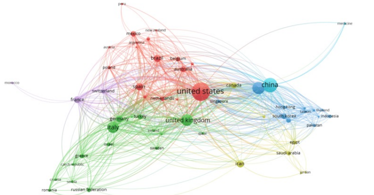

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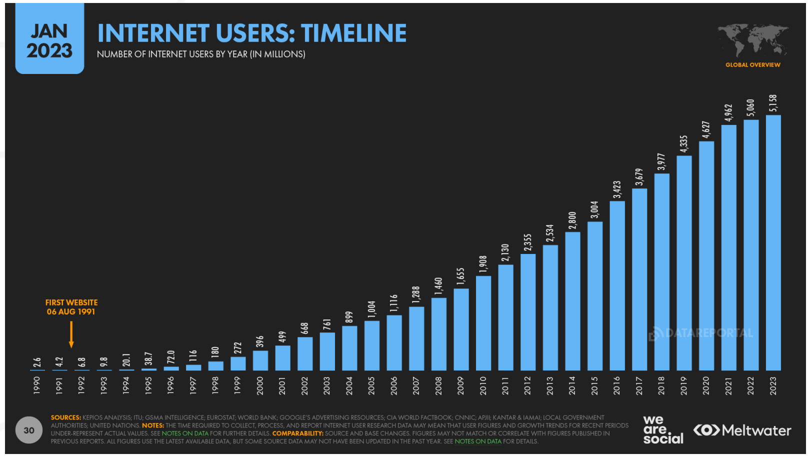

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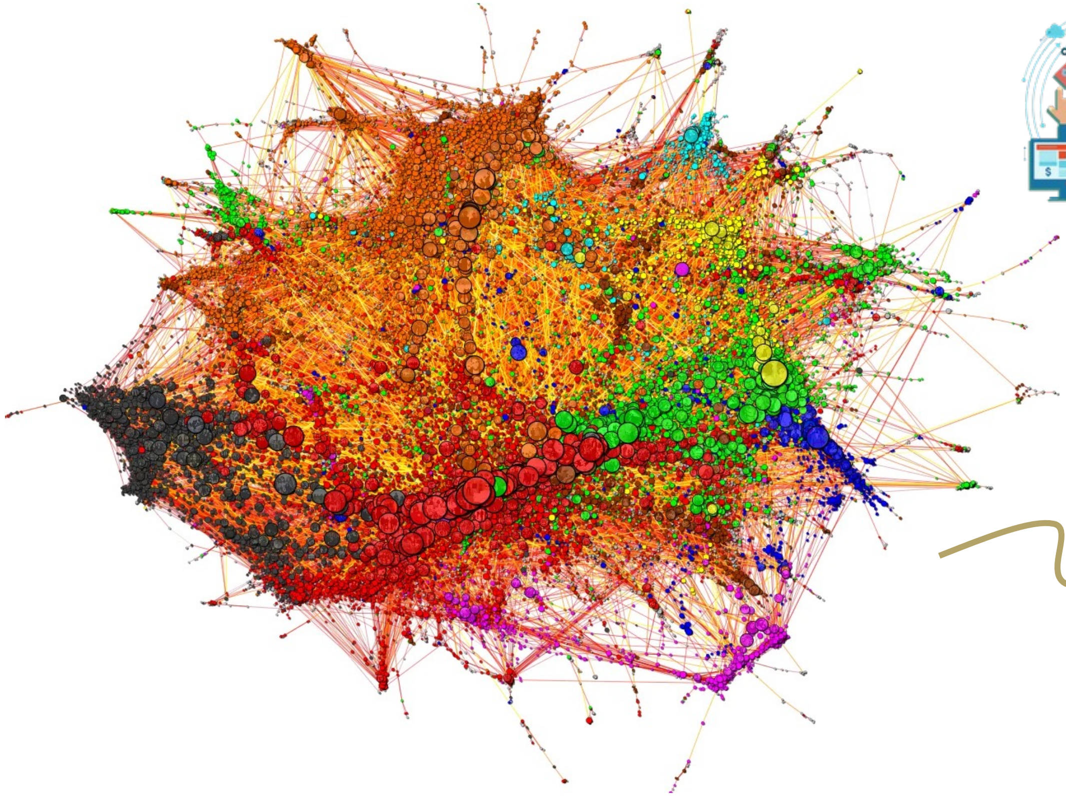

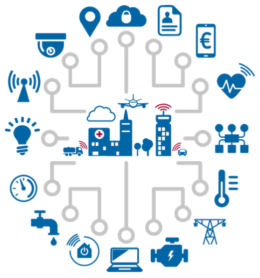

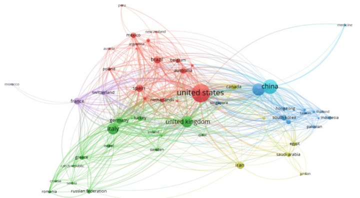

Advanced analytic tools and algorithms capable of determining the centrality and importance of network topology have become increasingly important

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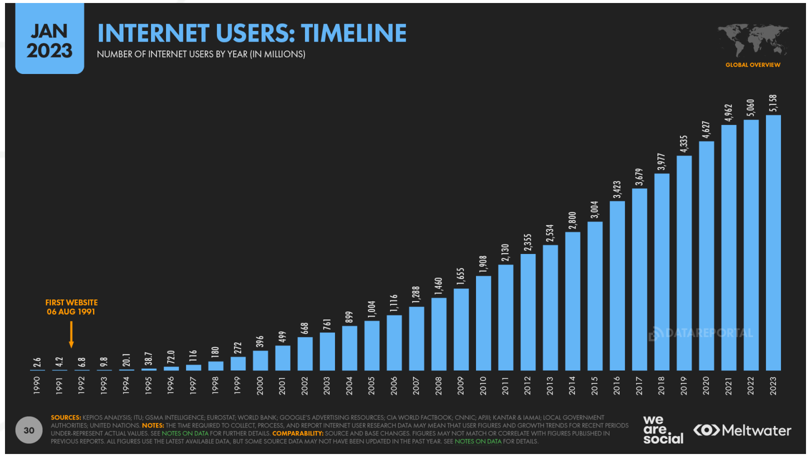

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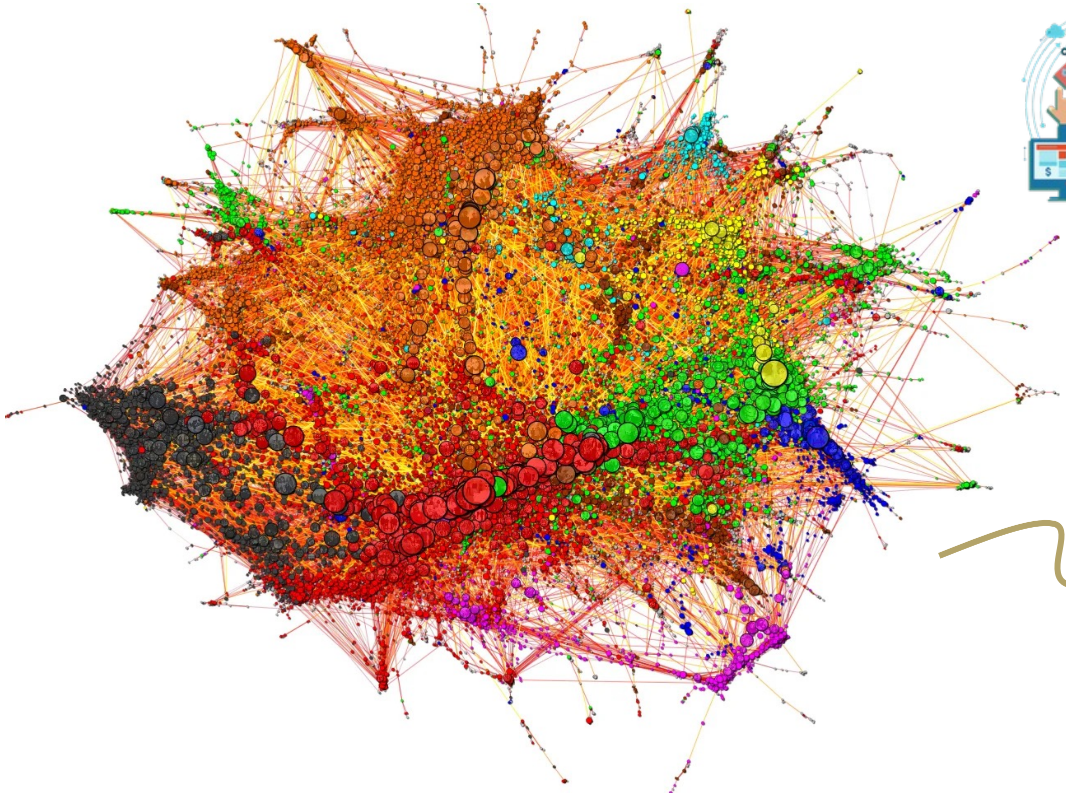

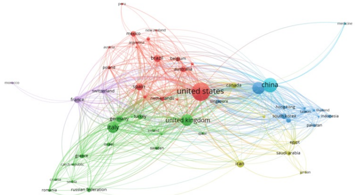

Advanced analytic tools and algorithms capable of determining the centrality and importance of network topology have become increasingly important

Effectively understanding and analyzing the critical nodes and components within these networks is paramount to:

Network Management

Security

Fault Tolerance and Resilience

Network Stability and Performance

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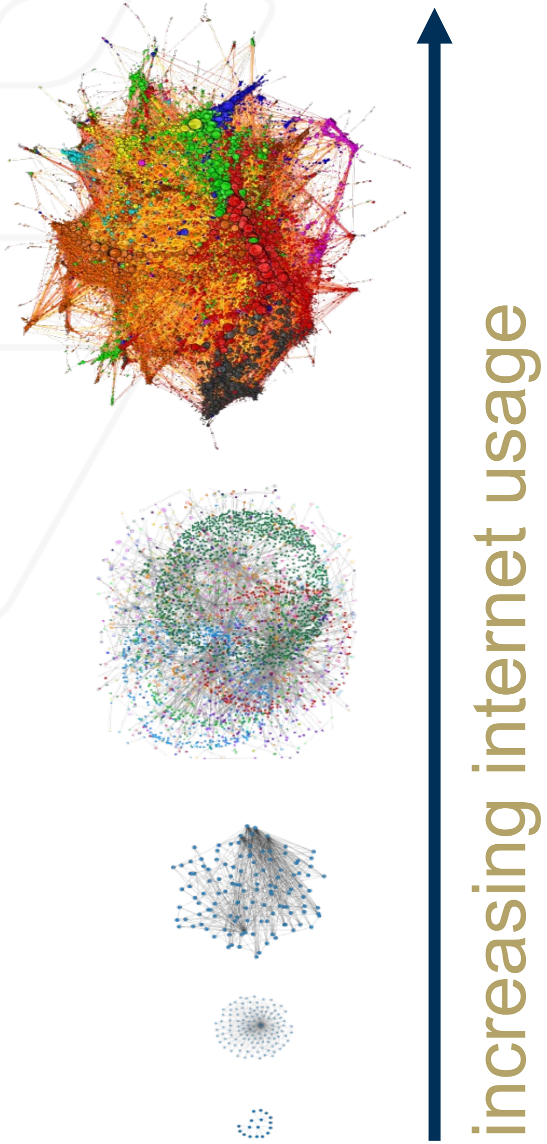
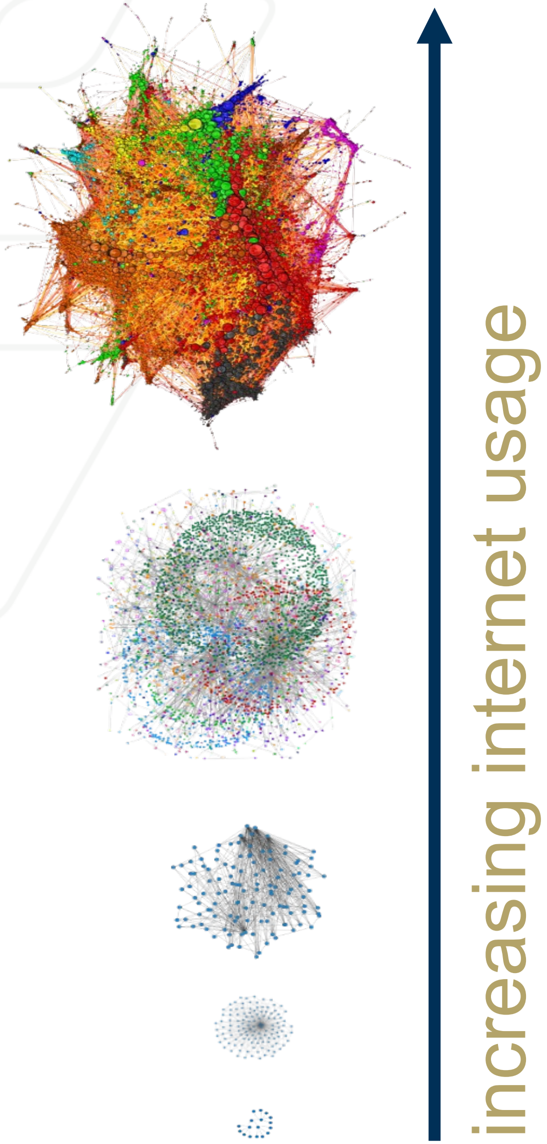
The Scalability Problem



- ❑ Efficient and accurate analysis of network topology becomes increasingly critical as internet usage rapidly increases

The Scalability Problem



Individual User

- ❑ Efficient and accurate analysis of network topology becomes increasingly critical as internet usage rapidly increases

The Scalability Problem

increasing internet usage

Individual User

Massive Corporations

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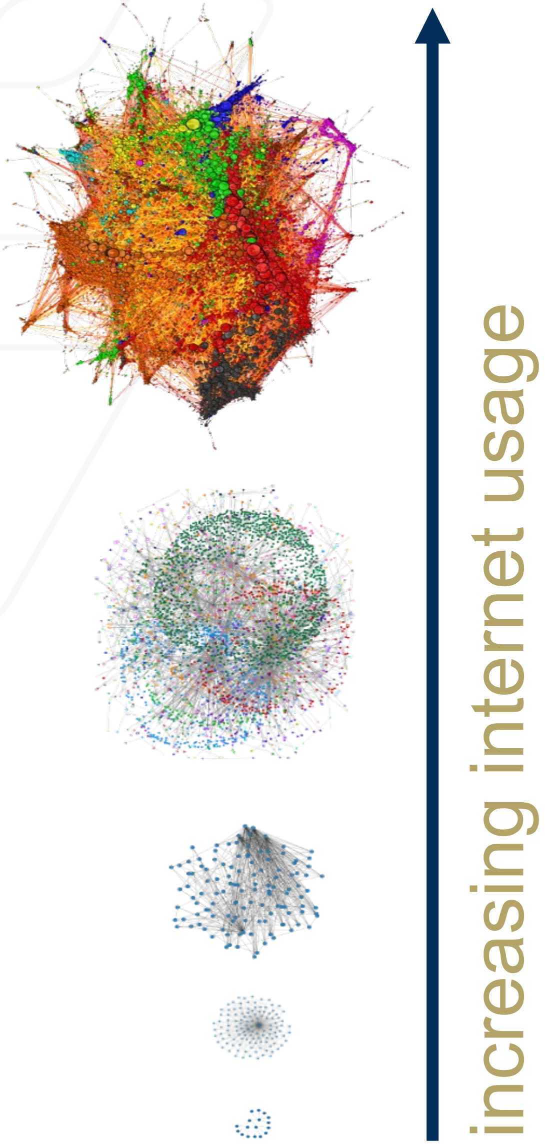

Individual User

Massive Corporations

Modern Datacenter

with hundreds of thousands of servers

- ❑ Efficient and accurate analysis of network topology becomes increasingly critical as internet usage rapidly increases

The Scalability Problem

increasing internet usage

Individual User

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DATACENTERS

growing increasingly at an exponential rate

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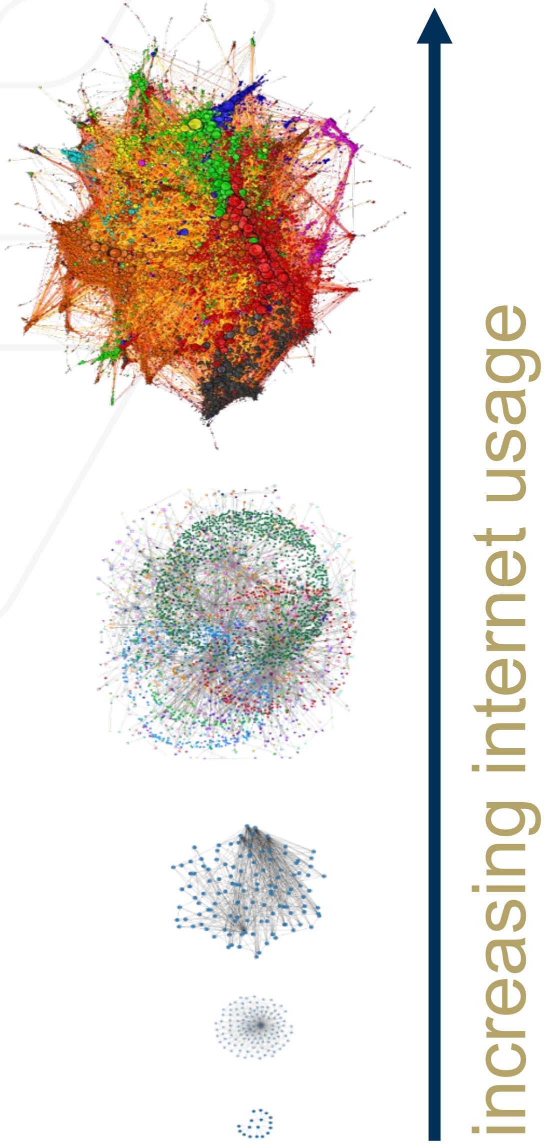
The Scalability Problem



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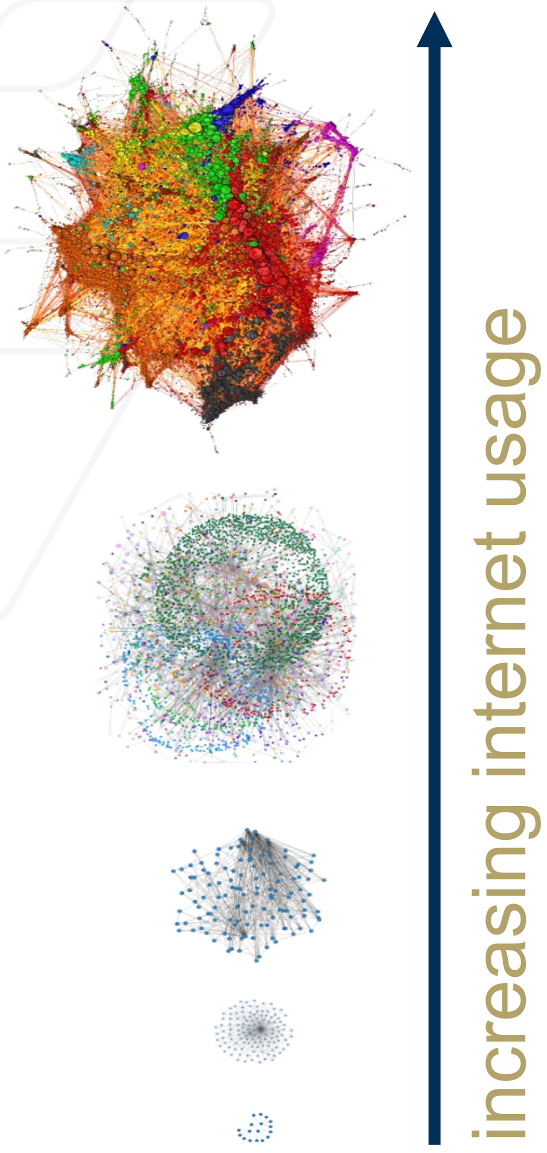
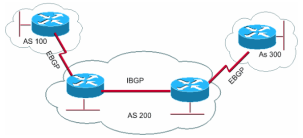



Routers

Bridges and Switches

127.0.0.1
172.16.0.9
192.0.0.7
IPs


ASes


Repeaters and Hubs


NICs

BILLIONS OF DEVICES

The Scalability Problem

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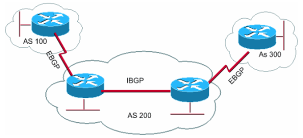

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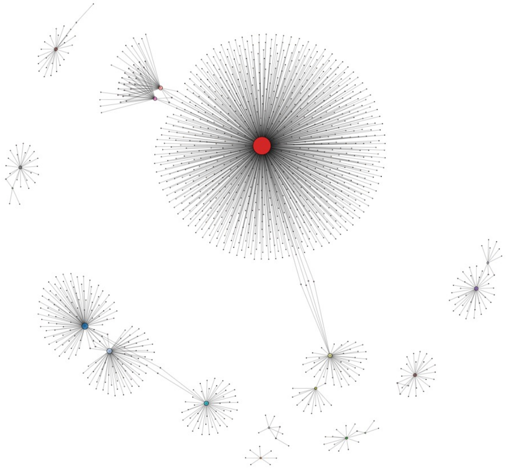
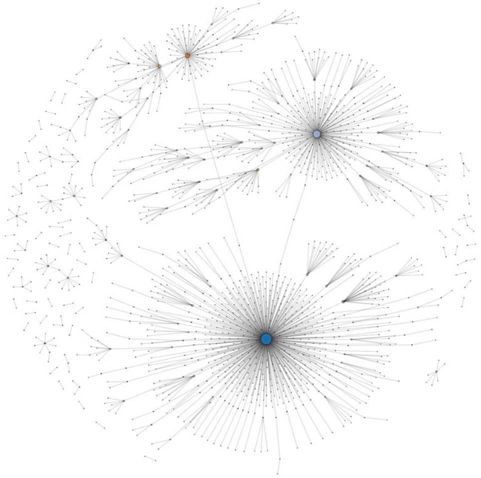
BILLIONS OF DEVICES

LARGER MAGNITUDE OF CONTINUOUS INTERACTIONS

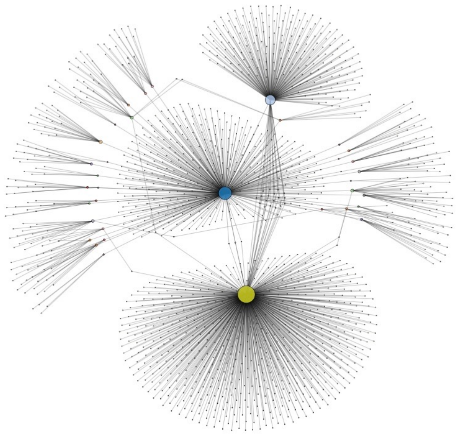
increasing internet usage



(a) Exchanges across Routers



(b) Exchanges across IPs



(c) Exchanges across ASes

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The Scalability Problem

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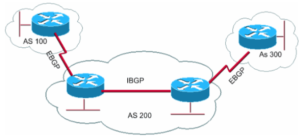

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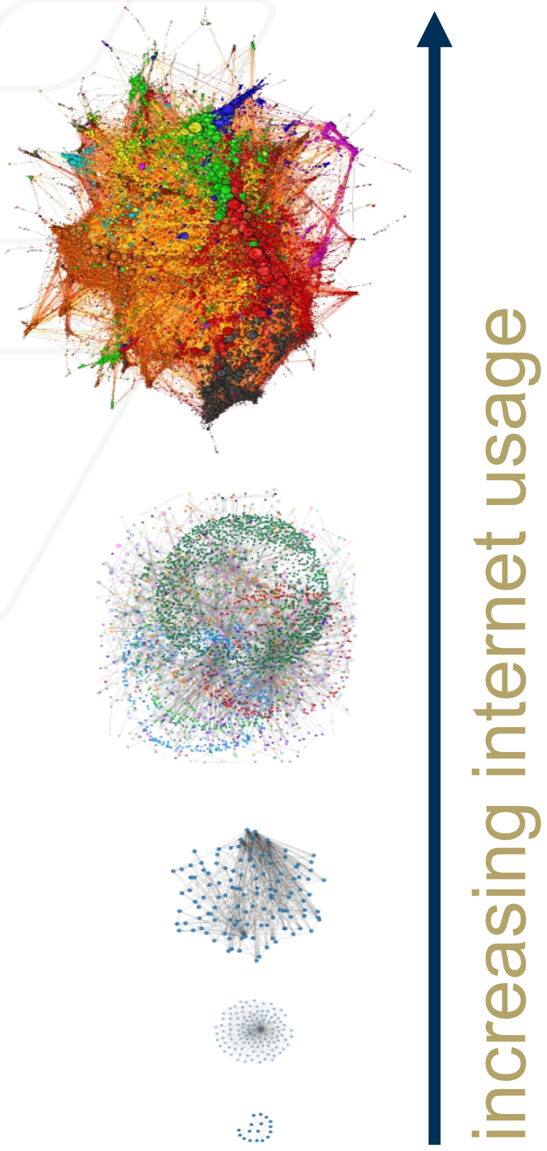
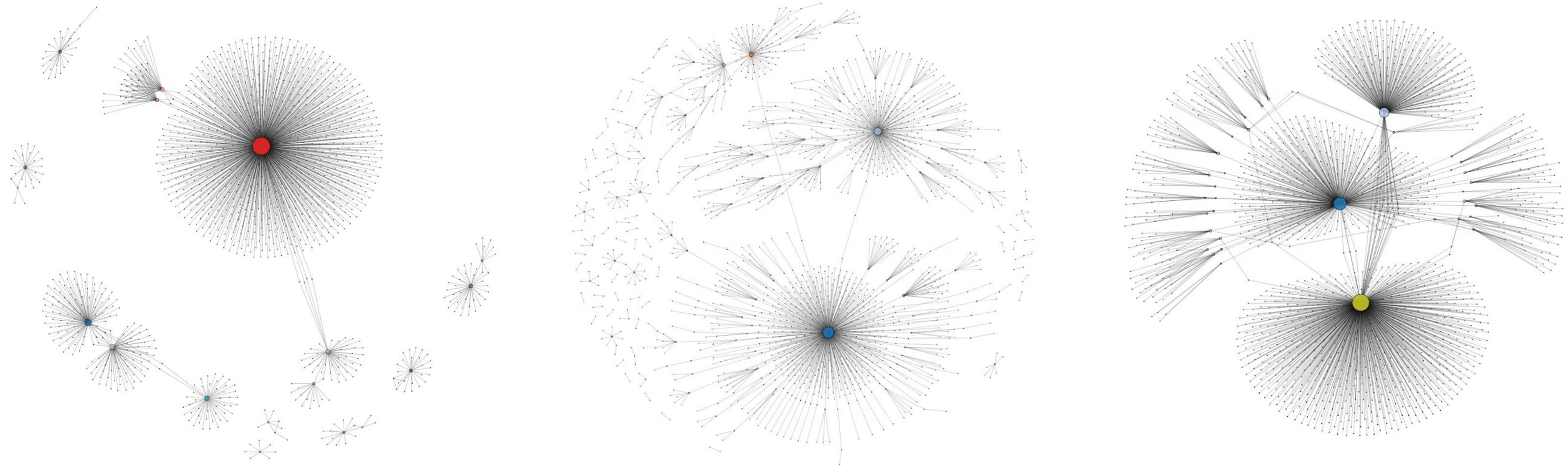
NICs



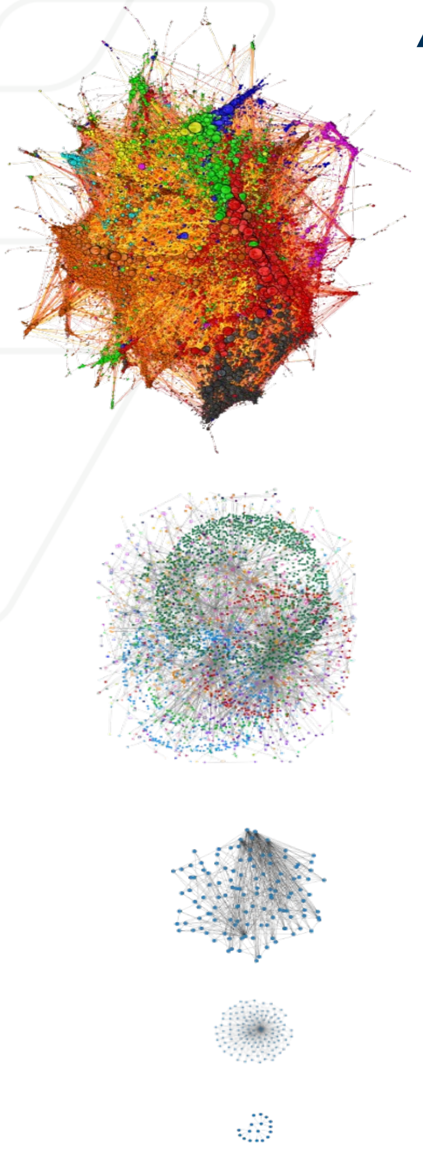
LARGER MAGNITUDE OF CONTINUOUS INTERACTIONS



(a) Exchanges across Routers (b) Exchanges across IPs (c) Exchanges across ASes

- There is a need for parallel computing resources to meet the computational and memory requirements

The Scalability Problem



increasing internet usage

Routers

Bridges and Switches

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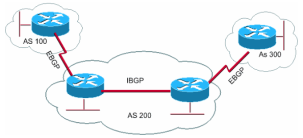

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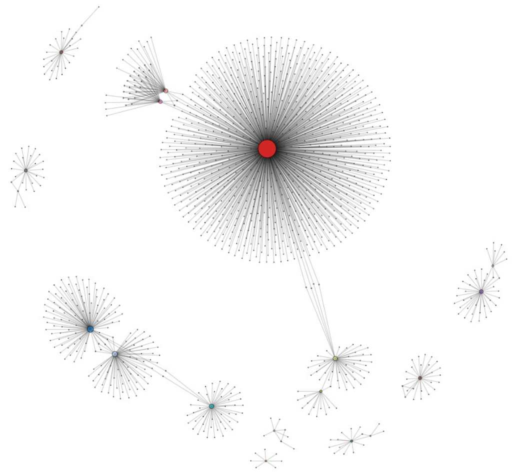

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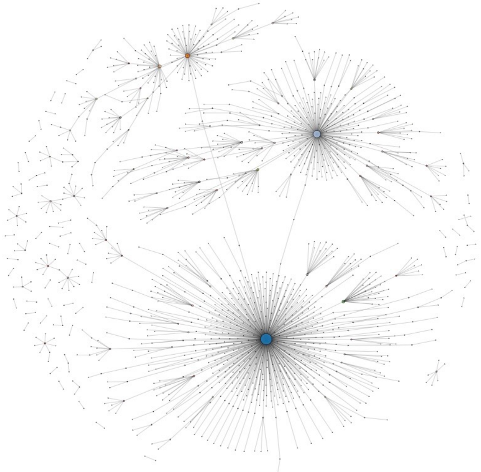

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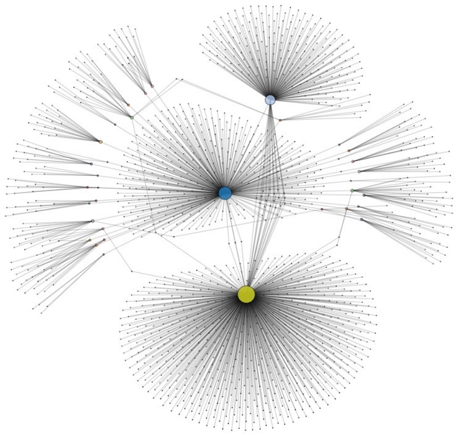

(c) Exchanges across ASes

- ❑ There is a need for parallel computing resources to meet the computational and memory requirements

It is important to develop scalable and lightweight systems to efficiently process large-scale network topologies!

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The Necessity for Large-Scale Analysis

Criticality of analyzing components within the network topology to identify sources of **vulnerabilities**, **inefficiencies**, and **possible breakdowns**, with potential impact on individual and organizational users depending on the internet for day-to-day operations

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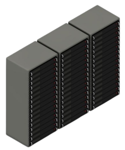

1M servers

200 datacenters

Georgia Tech

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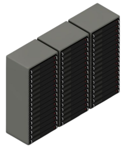

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which manages **diverse arrays of clients with unique agreements and connectivity requirements**

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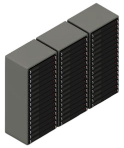

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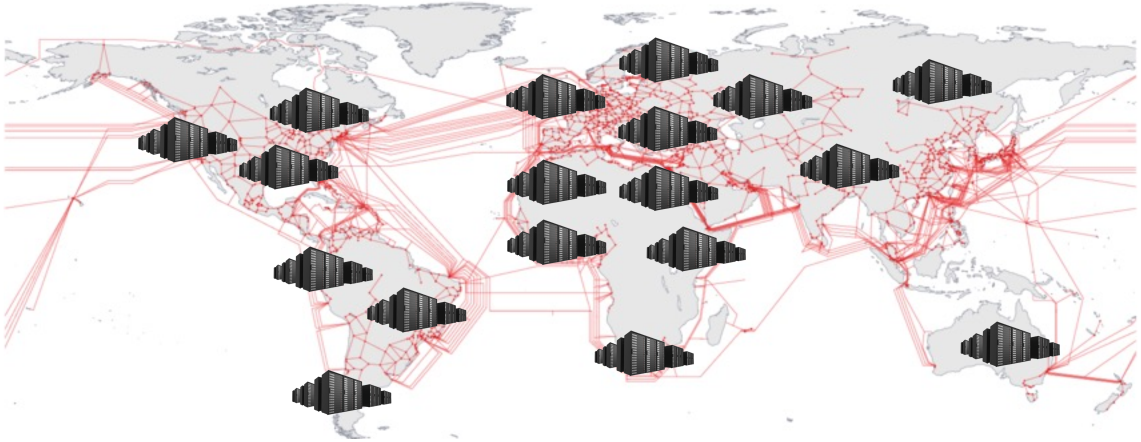

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operates **across several datacenters in multiple continents** relying on **networks of routers, switches, and computing devices**

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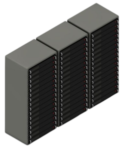

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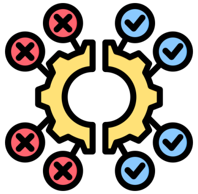

DISRUPTIONS

as a result of **performance bottlenecks**, **component failures**, or **security breaches** can have dire consequences

The 4 Challenges in Reliable Internet Provision

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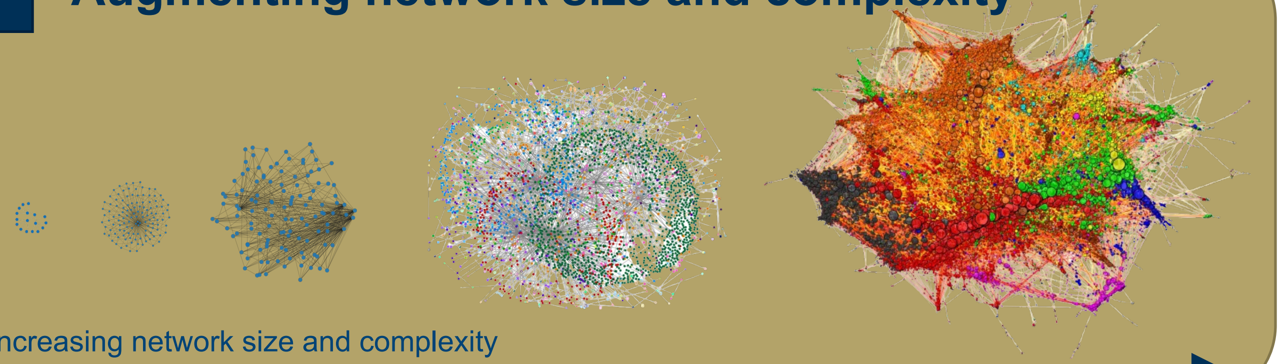
The 4 Challenges in Reliable Internet Provision

1 **Augmenting network size and complexity**



increasing network size and complexity

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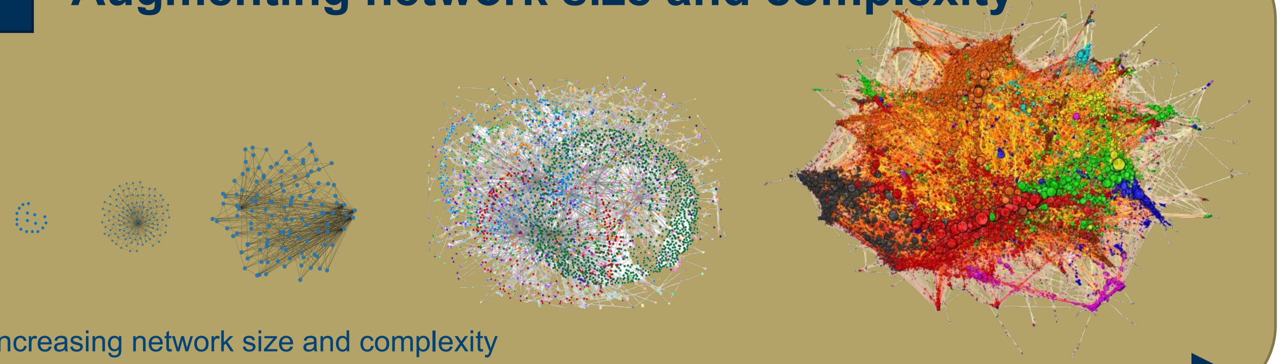
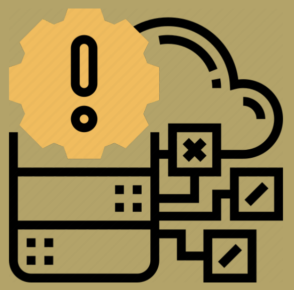


increasing network size and complexity

2 Fault tolerance and security



The 4 Challenges in Reliable Internet Provision

1 Augmenting network size and complexity

3 Real-time decision making

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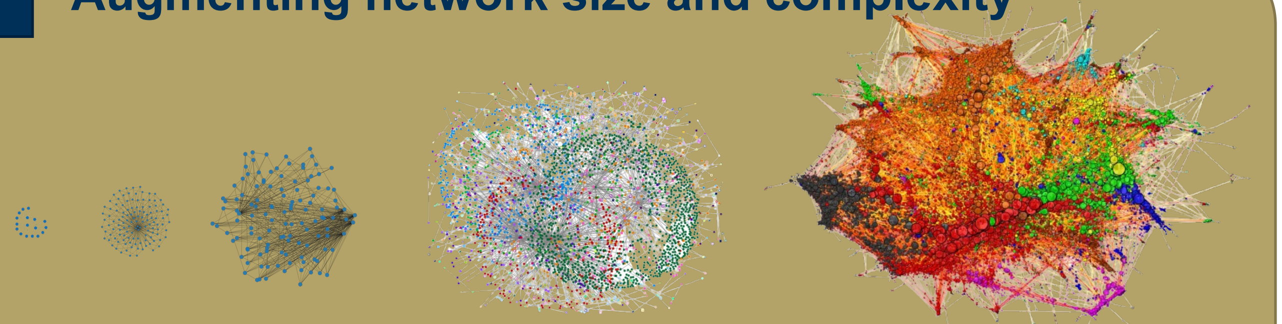

increasing network size and complexity

3 Real-time decision making

2 Fault tolerance and security

4 Energy considerations

The 4 Challenges in Reliable Internet Provision

1 Augmenting network size and complexity

3 Real-time decision making

2 Fault tolerance and security

4 Energy considerations

This paper studies the scalability of our novel algorithm to overcome the inherent challenges of internet provision by performing large-scale network topology analysis!

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Current Approaches are *NOT Efficient* for Scalable and Distributed Processing

Current approaches [2],[5],[6],[7],[8],[9] ...

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are designed and optimized for **smaller scale networks and graphs**

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CHALLENGE

Makes it difficult to process the expansive and intricate dynamic web of interconnected devices constituting the modern internet

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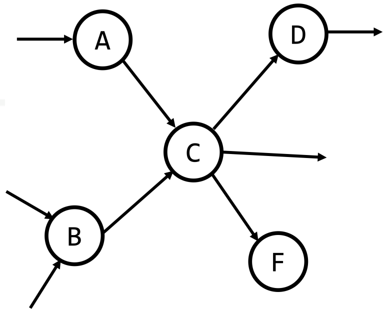
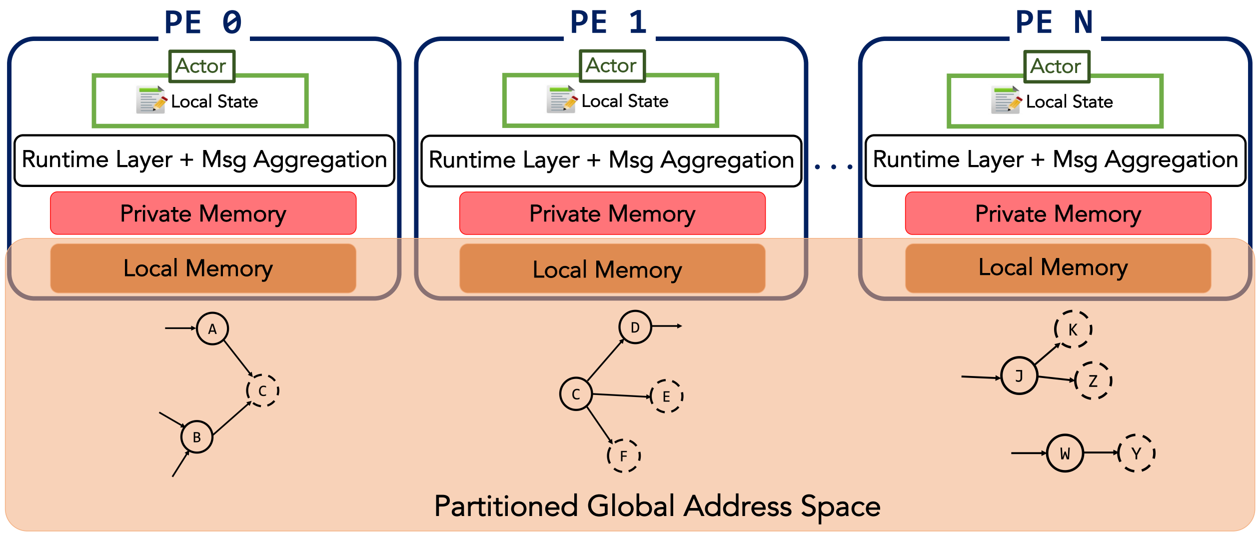
Backend Actor-based Scalable Architecture

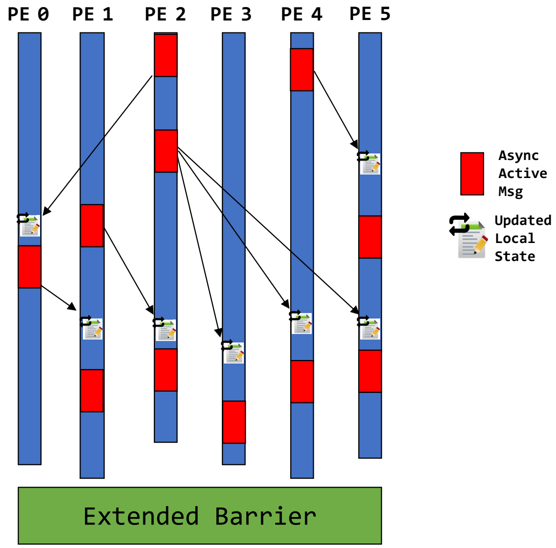
Sample Graph



Distributed Actor Runtime



Execution Model



- Presents a lightweight, asynchronous computation model
- Utilizes fine-grained asynchronous actor messages to express point-to-point remote operations
- Treats actors as primitives of computation, where actors are inherently isolated and share no mutable state
- Actors process messages sequentially within its mailbox, thereby avoiding data races and synchronization

NOTE: “Actor” and “Selector” will be used interchangeably

Distributed, Asynchronous, and Scalable Actor-Based Centrality for Internet Network Topology Analysis

Tailored for internet network topology analysis at a massive scale

We leverage the inherent formations of triangles to explore the structural importance of individual nodes and the intricate relationships among interconnected entities

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Triangle Centrality:
finds the important (central) nodes within a graph based on the concentration of triangles surrounding each node

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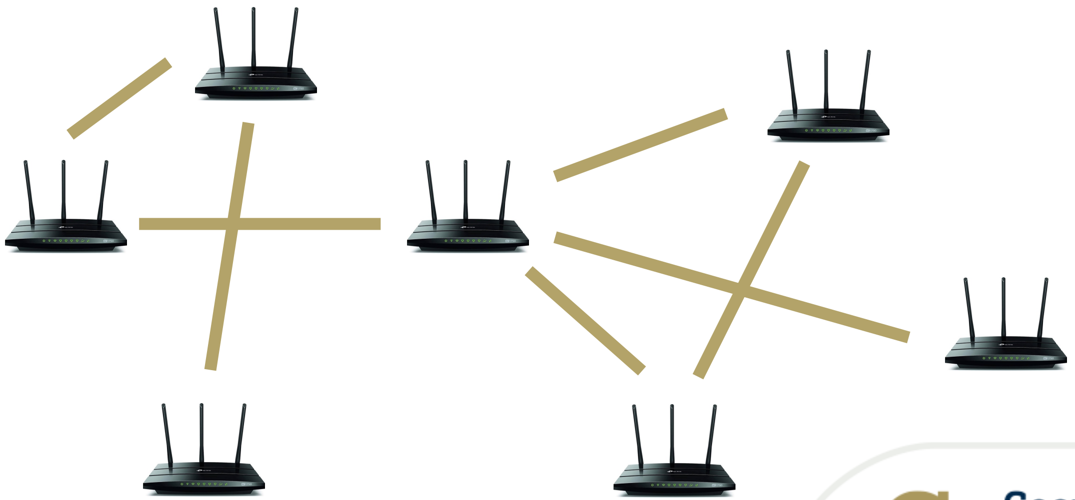
If a HW comp. is connected to two other HW comps., and these two other HW comps. as well are connected, then the trio of comps. is more cohesive



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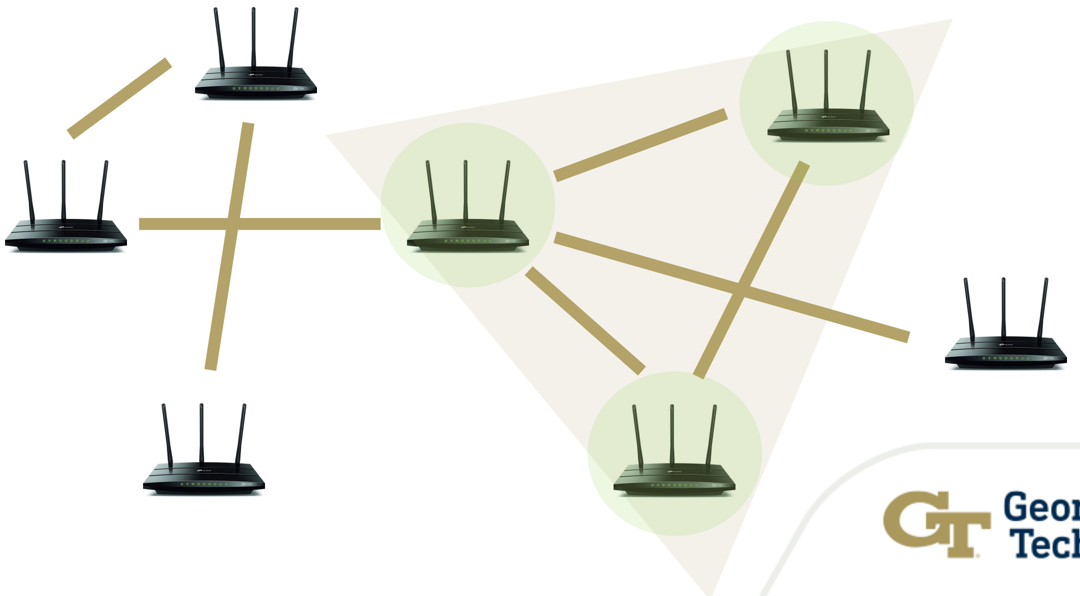

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That concentration of triangles is a rep. of augmented network density, permitting the flow and spread of the influence of data more rapidly through the connections

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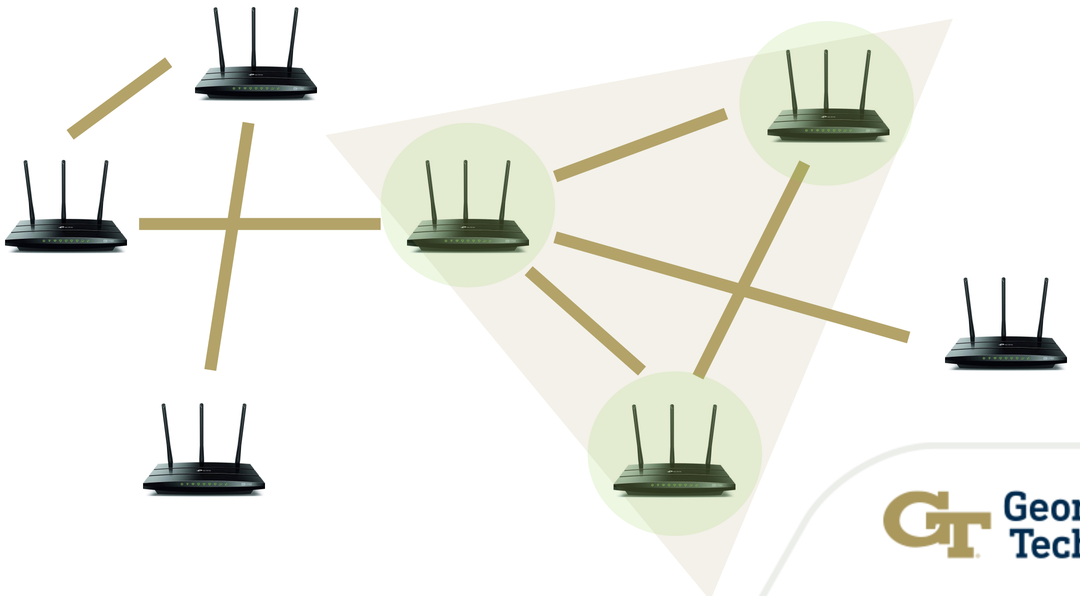

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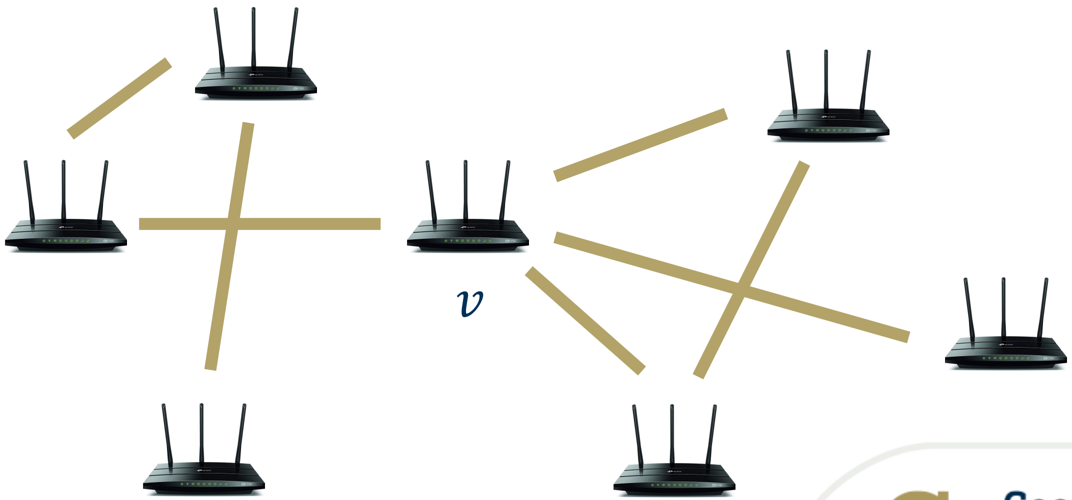
Distributed, Asynchronous, and Scalable Actor-Based Centrality for Internet Network Topology Analysis

Tailored for internet network topology analysis at a massive scale

Given an undirected network of entities, a graph $G = (V, E)$ with $|V|$ **vertices** $|E|$ **edges**

where

If a HW comp. is connected to two other HW comps., and these two other HW comps. as well are connected, then the trio of comps. is more cohesive



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$N(v)$ **is the set of neighbors of** v

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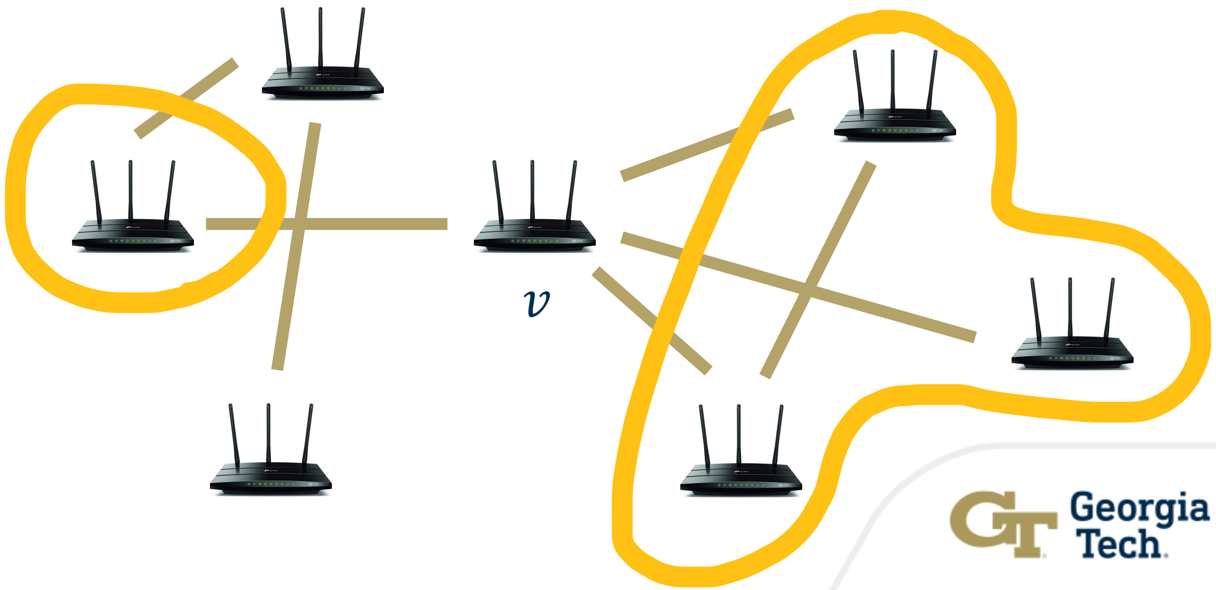

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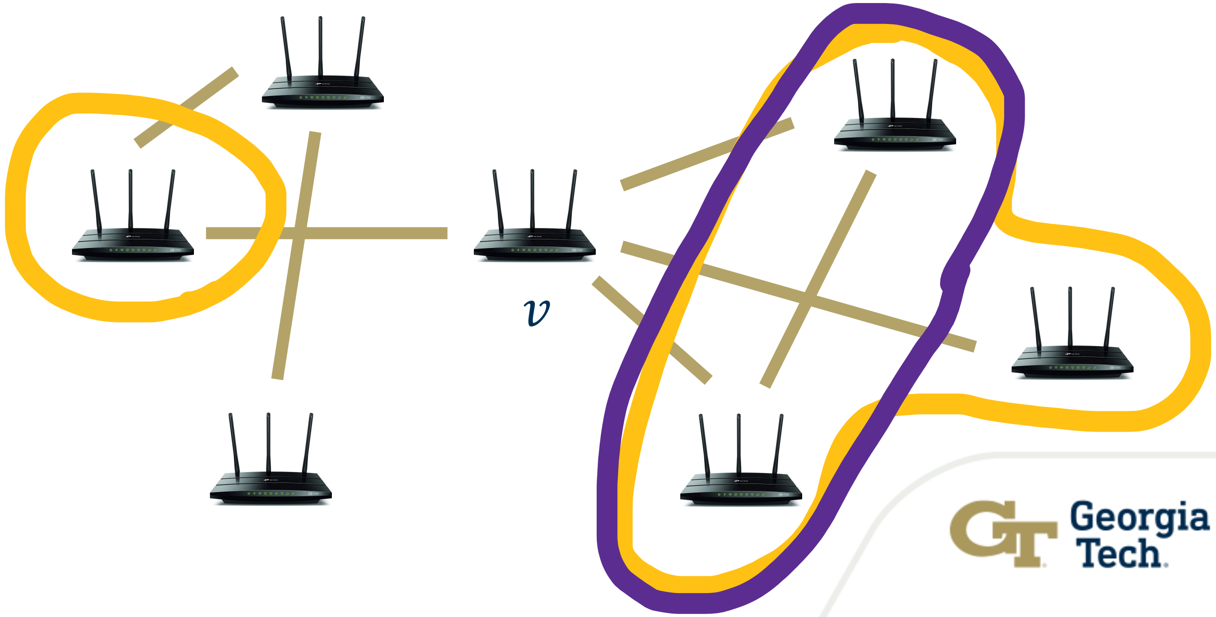

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$N_\Delta^+(v)$ **is the closed set including** v

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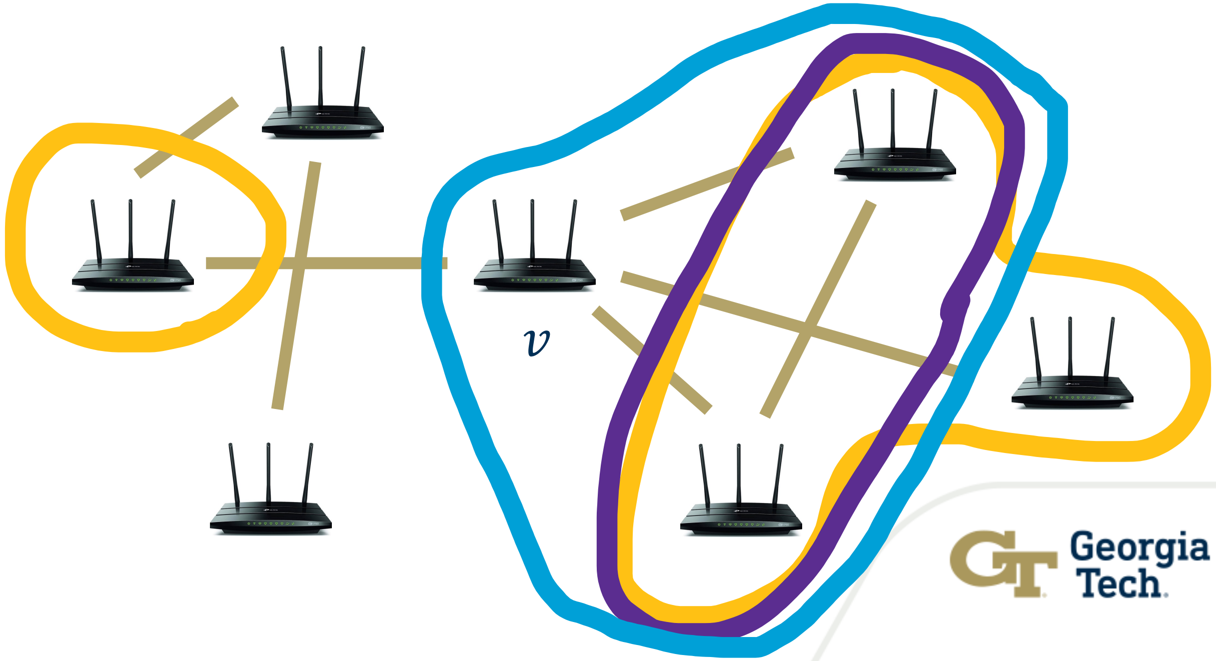

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$\Delta(v)$ **is the triangle count of** v

$\Delta(G)$ **is the triangle count of** G

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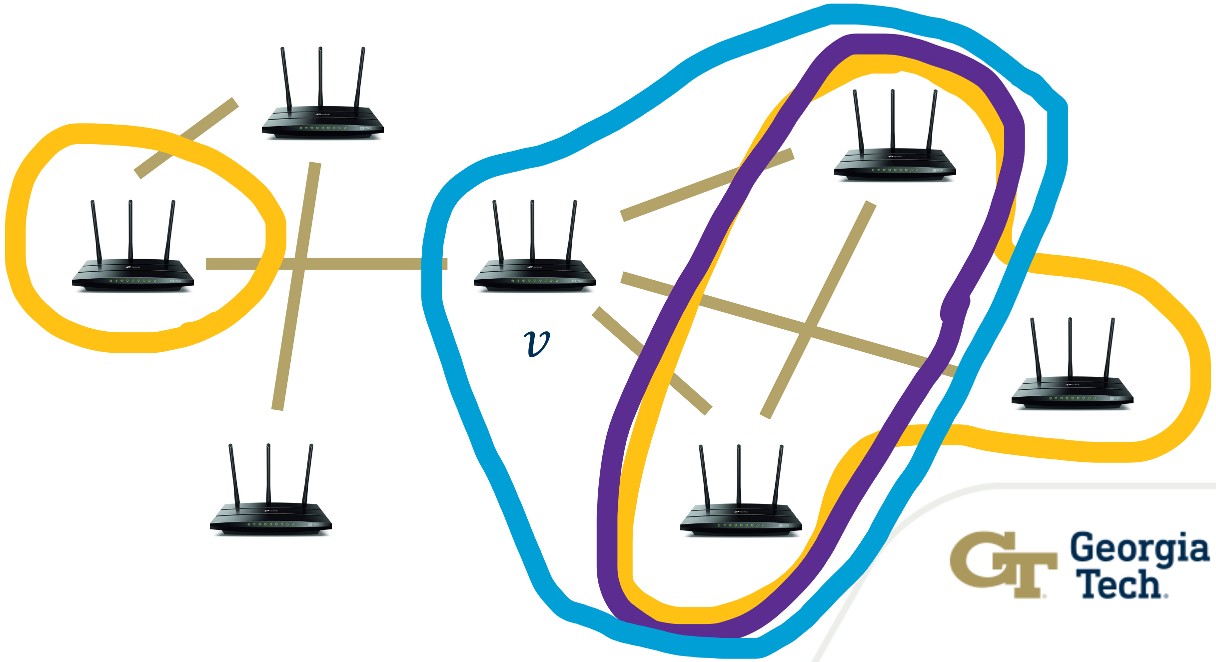

Distributed, Asynchronous, and Scalable Actor-Based Centrality for Internet Network Topology Analysis

Tailored for internet network topology analysis at a massive scale

Given an undirected network of entities, a graph $G = (V, E)$ with **$|V|$ vertices** **$|E|$ edges**

where

$N(v)$ is the set of neighbors of v

$N_\Delta(v)$ is the set of neighbors in triangles with v

$N_\Delta^+(v)$ is the closed set including v

$\Delta(v)$ is the triangle count of v

$\Delta(G)$ is the triangle count of G

$$TC(v) = \frac{\overbrace{\frac{1}{3}\sum_{u \in N_\Delta^+(v)} \Delta(u)}^{\text{sum of } \Delta \text{ for triangle neighbors}} + \overbrace{\sum_{w \in \{N(v) \setminus N_\Delta(v)\}} \Delta(w)}^{\text{sum of } \Delta \text{ for non-triangle neighbors}}}{\Delta(G)}$$

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Distributed, Asynchronous, and Scalable Actor-Based Centrality for Internet Network Topology Analysis

function $\textsc{TriCentActor}(L)$ ▷ Perform the main computation
  $\Delta(G) = \textsc{TriCountActor}(L)$ ▷ Compute global tricount
  for $\{l_{vu} \in \hat{L}\}$ **do**
    if $\{u \in N_\Delta(v)\}$ **then** ▷ Compute $\dfrac{\frac{1}{3}\sum_{u \in N_\Delta^+(v)} \Delta(u)}{\Delta(G)}$
▷ Send an active message to process1 (non-blocking)
      $Actor_p.\text{send}(1, \textsc{FindOwner}(L_u), u, v, \Delta(G), \frac{1}{3})$
    else ▷ Compute $\dfrac{\sum_{u \in \{N(v) \setminus N_\Delta(v)\}} \Delta(u)}{\Delta(G)}$
      $Actor_p.\text{send}(1, \textsc{FindOwner}(L_u), u, v, \Delta(G), 1)$
    $TC(v)$ += $\frac{1}{3}\Delta(v)/\Delta(G)$
  $\textsc{Wait}()$ ▷ Wait for the completion of local send/recv
  return TC
function $\textsc{TriCentActorProcess1}(u, v, \Delta(G), mult)$
▷ The process1 message handler
  $m_{tc} \leftarrow mult * \Delta(u)/\Delta(G)$
▷ Send an active message to process2 (non-blocking)
  $Actor_p.\text{send}(2, \textsc{FindOwner}(L_v), v, m_{tc})$
function $\textsc{TriCentActorProcess2}(v, m_{tc})$
▷ The process2 message handler
  $TC(v)$ += m_{tc}

Notation: Let r_p be the local rank, $\hat{L}$ be the local rows of L owned by r_p, c be the local counter owned by r_p, $Actor_p$ denote the actor instance that is running on r_p, N_Δ be the local array of lists holding set of neighbors in triangles with local rows owned by r_p, TC be the local rows of the triangle centrality matrix owned by r_p, $\Delta(G)$ be the global triangle count.

`send` **Semantics:** `Actor.send(proc handler, rank, packet)`

Distributed, Asynchronous, and Scalable Actor-Based Centrality for Internet Network Topology Analysis

function TriCentActor(L) ▷ Perform the main computation
  $\Delta(G) = $ TriCountActor(L) ▷ Compute global tricount
  for $\{l_{vu} \in \hat{L}\}$ **do**
    if $\{u \in N_\Delta(v)\}$ **the**
  ▷ Send an active message to
      $Actor_p$.send(1,F
    else
      $Actor_p$.send(1,F
    $TC(v)$ += $\frac{1}{3}\Delta(v)/$
  Wait() ▷
  return TC
function TriCentActorP
  ▷ The process1 message han
  $m_{tc} \leftarrow mult * \Delta(u)/\Delta$
  ▷ Send an active message to
  $Actor_p$.send(2,FindOw
function TriCentActorP
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Notation: Let r_p be the local rank, $\hat{L}$ be the local rows of L owned by r_p, c be the local counter owned by r_p, $Actor_p$ denote the actor instance that is running on r_p, N_Δ be the local array of lists holding set of neighbors in triangles with local rows owned by r_p, TC be the local rows of the ... r_p, $\Delta(G)$ be the global triangle count. ...c handler, rank, packet)

```
function TriCountActor(L)
    for {l_vw, l_vu ∈ L̂, u < w < v} do
  ▷ Send an active message to process1 (non-blocking)
        Actor_p.send(1,FindOwner(L_wu), v, w, u)
    Wait()
    return AllReduce(c)
function TriCountActorProcess1(v, w, u)
    if {l_wu ∈ L̂} then
        c += 1
  ▷ Send an active message to process2 (non-blocking)
        Actor_p.send(2,FindOwner(L_v), v, w, u)
        Actor_p.send(2,FindOwner(L_w), w, v, u)
        Actor_p.send(2,FindOwner(L_u), u, v, w)
function TriCountActorProcess2(i, j, k)
    Δ(i) += 1
    N_Δ(i) ← N_Δ(i) ∪ {j, k}
function FindOwner(row)        ▷ Returns a rank responsible for row
    return row % P             ▷ 1-D Cyclic distribution
```

Distributed, Asynchronous, and Scalable Actor-Based Centrality for Internet Network Topology Analysis

function TriCentActor(L) ▷ Perform the main computation
    $\Delta(G) = $ TriCountActor(L) ▷ Compute global tricount
    for $\{l_{vu} \in \hat{L}\}$ **do**
        if $\{u \in N_\Delta(v)\}$ **the**
▷ Send an active message to
            $Actor_p$.send(1,F
        else
            $Actor_p$.send(1,F
        $TC(v)$ += $\frac{1}{3}\Delta(v)/$
    Wait() ▷
    return TC
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    $TC(v)$ += m_{tc}

function TriCountActor(L)
    for $\{l_{vw}, l_{vu} \in \hat{L}, u < w < v\}$ **do**
▷ Send an active message to process1 (non-blocking)
        $Actor_p$.send(1,FindOwner(L_{wu}), v, w, u)
    Wait()
    return AllReduce(c)
function TriCountActorProcess1(v, w, u)
    if $\{l_{wu} \in \hat{L}\}$ **then**
        c += 1
▷ Send an active message to process2 (non-blocking)
        $Actor_p$.send(2,FindOwner(L_v), v, w, u)
        $Actor_p$.send(2,FindOwner(L_w), w, v, u)
        $Actor_p$.send(2,FindOwner(L_u), u, v, w)
function TriCountActorProcess2(i, j, k)
    $\Delta(i)$ += 1
    $N_\Delta(i) \leftarrow N_\Delta(i) \cup \{j, k\}$
function FindOwner(row) ▷ Returns a rank responsible for row
    return row % P ▷ 1-D Cyclic distribution

Notation
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r_p, $\Delta(G)$ be the global triangle count.
c handler, rank, packet)

Loop through local edges and grab trio of vertices ($\{v, w, u\}$) to check for a triangle

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Distributed, Asynchronous, and Scalable Actor-Based Centrality for Internet Network Topology Analysis

function TRICENTACTOR(L) ▷ Perform the main computation
$\Delta(G)$ = TRICOUNTACTOR(L) ▷ Compute global tricount
for $\{l_{vu} \in \hat{L}\}$ **do**
if $\{u \in N_\Delta(v)\}$ **the**
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$Actor_p$.send(1,F
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$TC(v)$ += $\frac{1}{3}\Delta(v)/$
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return TC
function TRICENTACTORP
▷ The process1 message han
$m_{tc} \leftarrow mult * \Delta(u)/\Delta$
▷ Send an active message to
$Actor_p$.send(2,FINDOW
function TRICENTACTORP
▷ The process2 message han
$TC(v)$ += m_{tc}

Notation

function TRICOUNTACTOR(L)
for $\{l_{vw}, l_{vu} \in \hat{L}, u < w < v\}$ **do**
▷ Send an active message to process1 (non-blocking)
$Actor_p$.send(1,FINDOWNER(L_{wu}), v, w, u)
WAIT()
return ALLREDUCE(c)
function TRICOUNTACTORPROCESS1(v, w, u)
if $\{l_{wu} \in \hat{L}\}$ **then**
c += 1
▷ Send an active message to process2 (non-blocking)
$Actor_p$.send(2,FINDOWNER(L_v), v, w, u)
$Actor_p$.send(2,FINDOWNER(L_w), w, v, u)
$Actor_p$.send(2,FINDOWNER(L_u), u, v, w)
function TRICOUNTACTORPROCESS2(i, j, k)
$\Delta(i)$ += 1
$N_\Delta(i) \leftarrow N_\Delta(i) \cup \{j, k\}$
function FINDOWNER(row) ▷ Returns a rank responsible for row
return row % P ▷ 1-D Cyclic distribution

Loop through local edges and grab trio of vertices ($\{v, w, u\}$) to check for a triangle

Send a non-blocking fine-grained active message to remote vertex owner

MSG HANDLER

Georgia Tech

Distributed, Asynchronous, and Scalable Actor-Based Centrality for Internet Network Topology Analysis

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Notation
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function TRICOUNTACTOR(L)
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Loop through local edges and grab trio of vertices ($\{v, w, u\}$) to check for a triangle

Send a non-blocking fine-grained active message to remote vertex owner

MSG HANDLER

If triangle present, increment local counter and send non-blocking fine-grained active messages to each of v, w, u to update their vertex triangle count and triangle neighbor lists

MSG HANDLER

Distributed, Asynchronous, and Scalable Actor-Based Centrality for Internet Network Topology Analysis

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Notation

function TriCountActor(L)
 for $\{l_{vw}, l_{vu} \in \hat{L}, u < w < v\}$ **do**
 ▷ Send an active message to process1 (non-blocking)
 $Actor_p$.send(1,FindOwner(L_{wu}), v, w, u)
 Wait()
 return AllReduce(c)
function TriCountActorProcess1(v, w, u)
 if $\{l_{wu} \in \hat{L}\}$ **then**
 c += 1
 ▷ Send an active message to process2 (non-blocking)
 $Actor_p$.send(2,FindOwner(L_v), v, w, u)
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Loop through local edges and grab trio of vertices ($\{v, w, u\}$) to check for a triangle

Send a non-blocking fine-grained active message to remote vertex owner

MSG HANDLER

Await completion of all local sends and receives

If triangle present, increment local counter and send non-blocking fine-grained active messages to each of v, w, u to update their vertex triangle count and triangle neighbor lists

MSG HANDLER

Distributed, Asynchronous, and Scalable Actor-Based Centrality for Internet Network Topology Analysis

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function TRICOUNTACTORPROCESS2(i, j, k)
    Δ(i) += 1
    N_Δ(i) ← N_Δ(i) ∪ {j, k}
function FINDOWNER(row)          ▷ Returns a rank responsible for row
    return row % P               ▷ 1-D Cyclic distribution
```

Loop through local edges and grab trio of vertices ($\{v, w, u\}$) to check for a triangle

Send a non-blocking fine-grained active message to remote vertex owner

MSG HANDLER

If triangle present, increment local counter and send non-blocking fine-grained active messages to each of v, w, u to update their vertex triangle count and triangle neighbor lists

MSG HANDLER

Await completion of all local sends and receives

Returns global reduced triangle count

Distributed, Asynchronous, and Scalable Actor-Based Centrality for Internet Network Topology Analysis

function TRICENTACTOR(L) ▷ Perform the main computation
  $\Delta(G) = $ TRICOUNTACTOR(L) ▷ Compute global tricount
  for $\{l_{vu} \in \hat{L}\}$ **do**
    if $\{u \in N_{\Delta}(v)\}$ **then** ▷ Compute $\frac{\frac{1}{3}\sum_{u \in N_{\Delta}^{+}(v)} \Delta(u)}{\Delta(G)}$
      ▷ Send an active message to process1 (non-blocking)
      $Actor_p$.send(1,FINDOWNER(L_u)$, u, v, \Delta(G), \frac{1}{3}$)
    else ▷ Compute $\frac{\sum_{u \in \{N(v) \setminus N_{\Delta}(v)\}} \Delta(u)}{\Delta(G)}$
      $Actor_p$.send(1,FINDOWNER(L_u)$, u, v, \Delta(G), 1$)
    $TC(v)$ += $\frac{1}{3}\Delta(v)/\Delta(G)$
  WAIT() ▷ Wait for the completion of local send/recv
  return TC

function TRICENTACTORPROCESS1($u, v, \Delta(G), mult$)
  ▷ The process1 message handler
  $m_{tc} \leftarrow mult * \Delta(u)/\Delta(G)$
  ▷ Send an active message to process2 (non-blocking)
  $Actor_p$.send(2,FINDOWNER(L_v)$, v, m_{tc}$)

function TRICENTACTORPROCESS2(v, m_{tc})
  ▷ The process2 message handler
  $TC(v)$ += m_{tc}

Distributed, Asynchronous, and Scalable Actor-Based Centrality for Internet Network Topology Analysis

function TRICENTACTOR(L) ▷ Perform the main computation
  $\Delta(G)$ = TRICOUNTACTOR(L) ▷ Compute global tricount
  for $\{l_{vu} \in \hat{L}\}$ **do**
    if $\{u \in N_\Delta(v)\}$ **then** ▷ Compute $\frac{\frac{1}{3}\sum_{u \in N^+_\Delta(v)} \Delta(u)}{\Delta(G)}$
  ▷ Send an active message to process1 (non-blocking)
      $Actor_p$.send(1,FINDOWNER(L_u), $u, v, \Delta(G), \frac{1}{3}$)
    else ▷ Compute $\frac{\sum_{u \in \{N(v) \setminus N_\Delta(v)\}} \Delta(u)}{\Delta(G)}$
      $Actor_p$.send(1,FINDOWNER(L_u), $u, v, \Delta(G), 1$)
    $TC(v)$ += $\frac{1}{3}\Delta(v)/\Delta(G)$
  WAIT() ▷ Wait for the completion of local send/recv
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function TRICENTACTORPROCESS1($u, v, \Delta(G), mult$)
  ▷ The process1 message handler
  $m_{tc} \leftarrow mult * \Delta(u)/\Delta(G)$
  ▷ Send an active message to process2 (non-blocking)
  $Actor_p$.send(2,FINDOWNER(L_v), v, m_{tc})
function TRICENTACTORPROCESS2(v, m_{tc})
  ▷ The process2 message handler
  $TC(v)$ += m_{tc}

Sum of the Δ for the triangle neighbors
Send non-blocking message to remote vertex owner

Distributed, Asynchronous, and Scalable Actor-Based Centrality for Internet Network Topology Analysis

function TRICENTACTOR(L) ▷ Perform the main computation
  $\Delta(G) =$ TRICOUNTACTOR(L) ▷ Compute global tricount
  for $\{l_{vu} \in \hat{L}\}$ **do**
    if $\{u \in N_\Delta(v)\}$ **then** ▷ Compute $\frac{\frac{1}{3}\sum_{u \in N_\Delta^+(v)} \Delta(u)}{\Delta(G)}$
  ▷ Send an active message to process1 (non-blocking)
      $Actor_p$.send(1,FINDOWNER(L_u)$, u, v, \Delta(G), \frac{1}{3}$)
    else ▷ Compute $\frac{\sum_{u \in \{N(v) \setminus N_\Delta(v)\}} \Delta(v)}{\Delta(G)}$
      $Actor_p$.send(1,FINDOWNER(L_u)$, u, v, \Delta(G), 1$)
    $TC(v) \mathrel{+}= \frac{1}{3}\Delta(v)/\Delta(G)$
  WAIT() ▷ Wait for the completion of local ser... v
  return TC
function TRICENTACTORPROCESS1($u, v, \Delta(G), mult$)
  ▷ The process1 message handler
  $m_{tc} \leftarrow mult * \Delta(u)/\Delta(G)$
  ▷ Send an active message to process2 (non-blocking)
  $Actor_p$.send(2,FINDOWNER(L_v)$, v, m_{tc}$)
function TRICENTACTORPROCESS2(v, m_{tc})
  ▷ The process2 message handler
  $TC(v) \mathrel{+}= m_{tc}$

Sum of the Δ for the triangle neighbors
Send non-blocking message to remote vertex owner

Sum of the Δ for the non-triangle neighbors
Send non-blocking message to remote vertex owner

MSG HANDLER

Distributed, Asynchronous, and Scalable Actor-Based Centrality for Internet Network Topology Analysis

function TRICENTACTOR(L) ▷ Perform the main computation
  $\Delta(G) =$ TRICOUNTACTOR(L) ▷ Compute global tricount
  for $\{l_{vu} \in \hat{L}\}$ **do**
    if $\{u \in N_\Delta(v)\}$ **then** ▷ Compute $\frac{\frac{1}{3}\sum_{u \in N_\Delta^+(v)} \Delta(u)}{\Delta(G)}$
  ▷ Send an active message to process1 (non-blocking)
      $Actor_p$.send(1,FINDOWNER(L_u)$, u, v, \Delta(G), \frac{1}{3}$)
    else ▷ Compute $\frac{\sum_{u \in \{N(v) \setminus N_\Delta(v)\}} \Delta(v)}{\Delta(G)}$
      $Actor_p$.send(1,FINDOWNER(L_u)$, u, v, \Delta(G), 1$)
    $TC(v)$ += $\frac{1}{3}\Delta(v)/\Delta(G)$
  WAIT() ▷ Wait for the completion of local ser...v
  return TC
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  ▷ The process1 message handler
  $m_{tc} \leftarrow mult * \Delta(u)/\Delta(G)$
  ▷ Send an active message to process2 (non-blocking)
  $Actor_p$.send(2,FINDOWNER(L_v)$, v, m_{tc}$)
function TRICENTACTORPROCESS2(v, m_{tc})
  ▷ The process2 message handler
  $TC(v)$ += m_{tc}

Sum of the Δ for the triangle neighbors
Send non-blocking message to remote vertex owner

Sum of the Δ for the non-triangle neighbors
Send non-blocking message to remote vertex owner

Addition of the vertex within the final triangle centrality

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Distributed, Asynchronous, and Scalable Actor-Based Centrality for Internet Network Topology Analysis

function TRICENTACTOR(L) ▷ Perform the main computation

$\Delta(G)$ = TRICOUNTACTOR(L) ▷ Compute global tricount

for $\{l_{vu} \in \hat{L}\}$ **do**

if $\{u \in N_{\Delta}(v)\}$ **then** ▷ Compute $\frac{\frac{1}{3}\sum_{u \in N_{\Delta}^{+}(v)} \Delta(u)}{\Delta(G)}$

▷ Send an active message to process1 (non-blocking)

$Actor_p$.send(1,FINDOWNER(L_u), $u, v, \Delta(G), \frac{1}{3}$)

else ▷ Compute $\frac{\sum_{u \in \{N(v) \setminus N_{\Delta}(v)\}} \Delta(v)}{\Delta(G)}$

$Actor_p$.send(1,FINDOWNER(L_u), $u, v, \Delta(G), 1$)

$TC(v)$ += $\frac{1}{3}\Delta(v)/\Delta(G)$

WAIT() ▷ Wait for the completion of local ser…v

return TC

function TRICENTACTORPROCESS1($u, v, \Delta(G), mult$)

▷ The process1 message handler

$m_{tc} \leftarrow mult * \Delta(u)/\Delta(G)$

▷ Send an active message to process2 (non-blocking)

$Actor_p$.send(2,FINDOWNER(L_v), v, m_{tc})

function TRICENTACTORPROCESS2(v, m_{tc})

▷ The process2 message handler

$TC(v)$ += m_{tc}

Sum of the Δ for the triangle neighbors

Send non-blocking message to remote vertex owner

Sum of the Δ for the non-triangle neighbors

Send non-blocking message to remote vertex owner

Addition of the vertex within the final triangle centrality

MSG HANDLER

Do the calculation depending on packet variables and send a non-blocking message to v to increment final triangle centrality

MSG HANDLER

Distributed, Asynchronous, and Scalable Actor-Based Centrality for Internet Network Topology Analysis

function TriCentActor(L) ▷ Perform the main computation
 $\Delta(G) =$ TriCountActor(L) ▷ Compute global tricount
 for $\{l_{vu} \in \hat{L}\}$ **do**
  if $\{u \in N_\Delta(v)\}$ **then** ▷ Compute $\frac{\frac{1}{3}\sum_{u \in N^+_\Delta(v)} \Delta(u)}{\Delta(G)}$
 ▷ Send an active message to process1 (non-blocking)
   $Actor_p$.send(1,FindOwner(L_u), $u, v, \Delta(G), \frac{1}{3}$)
  else ▷ Compute $\frac{\sum_{u \in \{N(v) \setminus N_\Delta(v)\}} \Delta(v)}{\Delta(G)}$
   $Actor_p$.send(1,FindOwner(L_u), $u, v, \Delta(G), 1$)
  $TC(v)$ += $\frac{1}{3}\Delta(v)/\Delta(G)$
 Wait() ▷ Wait for the completion of local ser... ...v
 return TC
function TriCentActorProcess1($u, v, \Delta(G), mult$)
 ▷ The process1 message handler
 ...)
 ...ocess2 (non-blocking)
 ...R(L_v), v, m_{tc})
 ...CESS2(v, m_{tc})
 ▷ The process2 message handler
 $TC(v)$ += m_{tc}

Sum of the Δ for the triangle neighbors
Send non-blocking message to remote vertex owner

Sum of the Δ for the non-triangle neighbors
Send non-blocking message to remote vertex owner

Addition of the vertex within the final triangle centrality

MSG HANDLER

Await completion of all local sends and receives

Do the calculation depending on packet variables and send a non-blocking message to v to increment final triangle centrality

MSG HANDLER

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Distributed, Asynchronous, and Scalable Actor-Based Centrality for Internet Network Topology Analysis

function TRICENTACTOR(L) ▷ Perform the main computation

$\Delta(G)$ = TRICOUNTACTOR(L) ▷ Compute global tricount

for $\{l_{vu} \in \hat{L}\}$ **do**

if $\{u \in N_\Delta(v)\}$ **then** ▷ Compute $\frac{\frac{1}{3}\sum_{u \in N^+_\Delta(v)} \Delta(u)}{\Delta(G)}$

▷ Send an active message to process1 (non-blocking)

$Actor_p$.send(1,FINDOWNER(L_u), $u, v, \Delta(G), \frac{1}{3}$)

else ▷ Compute $\frac{\sum_{u \in \{N(v) \setminus N_\Delta(v)\}} \Delta(v)}{\Delta(G)}$

$Actor_p$.send(1,FINDOWNER(L_u), $u, v, \Delta(G), 1$)

$TC(v)$ += $\frac{1}{3}\Delta(v)/\Delta(G)$

WAIT() ▷ Wait for the completion of local se…

return TC

function TRICENT…($u, v, \Delta(G), m_{tc}$)

▷ The process1 message handler

…)

…ocess2 (non-blocking)

…R(L_v), v, m_{tc})

…CESS2(v, m_{tc})

▷ The process2 message handler

$TC(v)$ += m_{tc}

Sum of the Δ for the triangle neighbors

Send non-blocking message to remote vertex owner

Sum of the Δ for the non-triangle neighbors

Send non-blocking message to remote vertex owner

Addition of the vertex within the final triangle centrality

Return triangle centrality

MSG HANDLER

Do the calculation depending on packet variables and send a non-blocking message to v to increment final triangle centrality

MSG HANDLER

Await completion of all local sends and receives

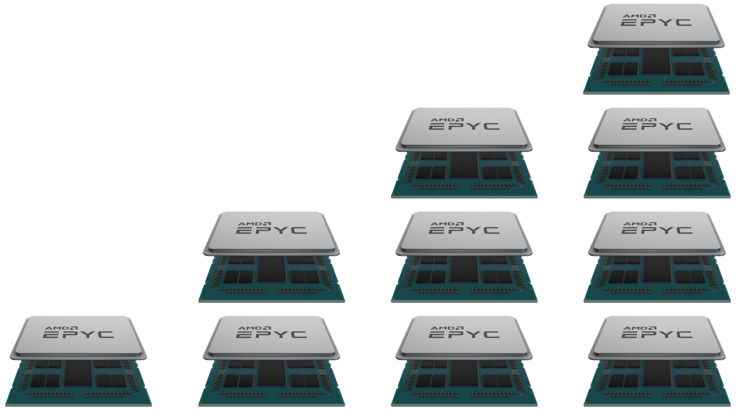
Georgia Tech

Experimental Setup and Architecture

- Experiments conducted on the CPU nodes of
  - The **Perlmutter Supercomputer** at the National Energy Research Scientific Computing Center (NERSC)
    - Each CPU node: 2x AMD EPYC 7763 (Milan) CPUs, 64 physical cores per CPU, 512 GB memory
  - The **HPC PACE Cluster** at Georgia Tech
    - Each CPU node: Dual Intel Xeon Gold 6226 CPUs, 24 total physical cores, 192 GB memory
- We present results using speedup of execution time compared to single core
- We use four large-scale internet network datasets:
  - A **Routers Network Dataset** $(|V| = 191K, |E| = 608K)$
  - An **IP Addresses Network Dataset** $(|V| = 2.3M, |E| = 21.6M)$
  - An **Autonomous Systems Network Dataset** $(|V| = 1.7M, |E| = 11.1M)$
  - A **Synthetic Network Dataset** $($100K rows/core for weak scaling, $|V| = 205M$, $|E| = 13.9B$ at largest scale)
- Results for **different dimensions of scalability** are presented

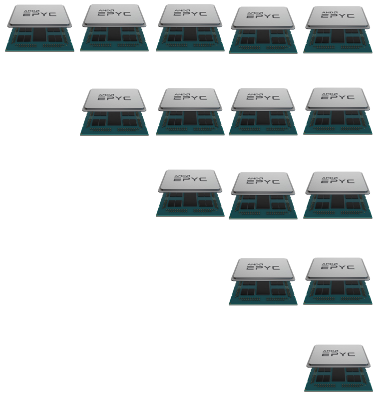
Dimensions of Scalability

(1) SCALE-OUT



increasing #nodes (<u>SCALE-OUT</u>, from 1 to 2,048 cores)

(2) SCALE-UP

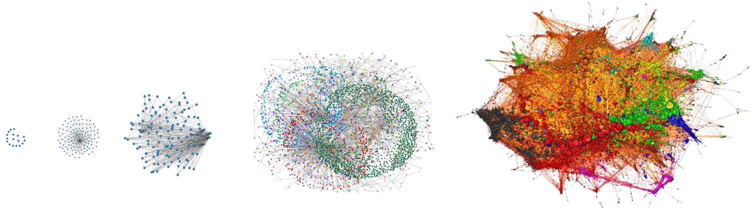


increasing #cores
per node
(<u>SCALE-UP</u>,
from 1
core/node to
128 cores/node)

HARDWARE SCALABILITY

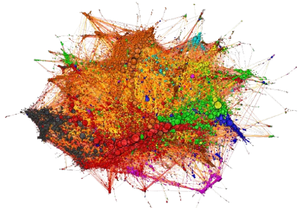
DATASET SCALABILITY

(1) WEAK SCALING



increasing graph size (synthetic dataset, 100K vertices per core)

(2) STRONG SCALING



constant graph size
(Routers dataset, IP dataset, ASes dataset)

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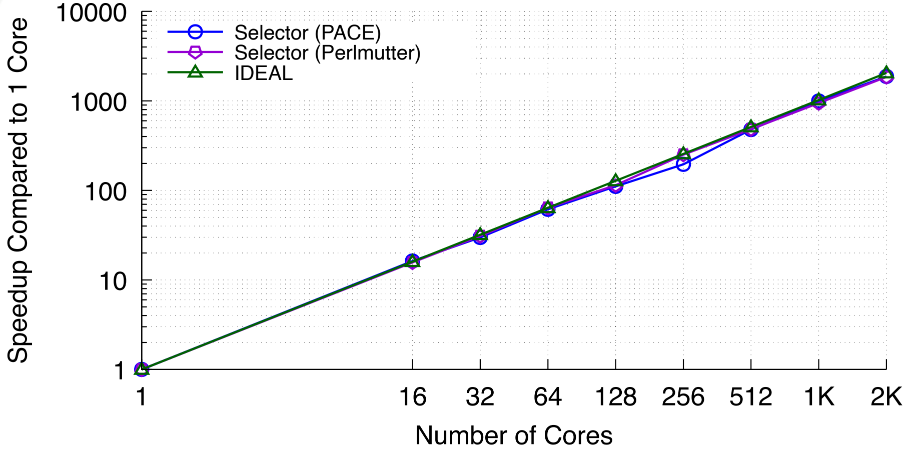
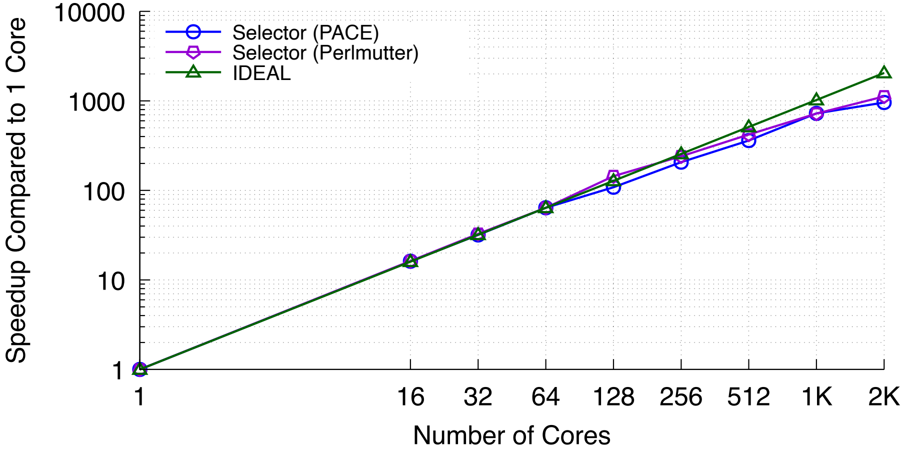
Performance Results: Scalability for SCALE-OUT

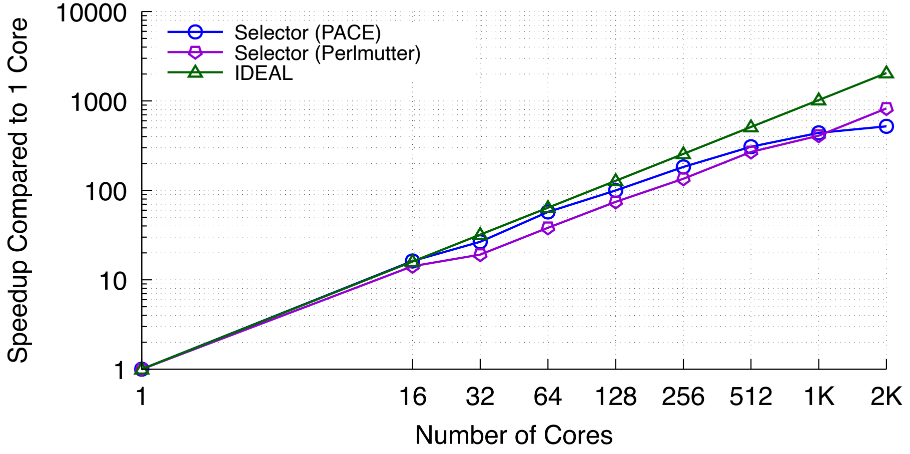
Routers Dataset
Strong Scaling



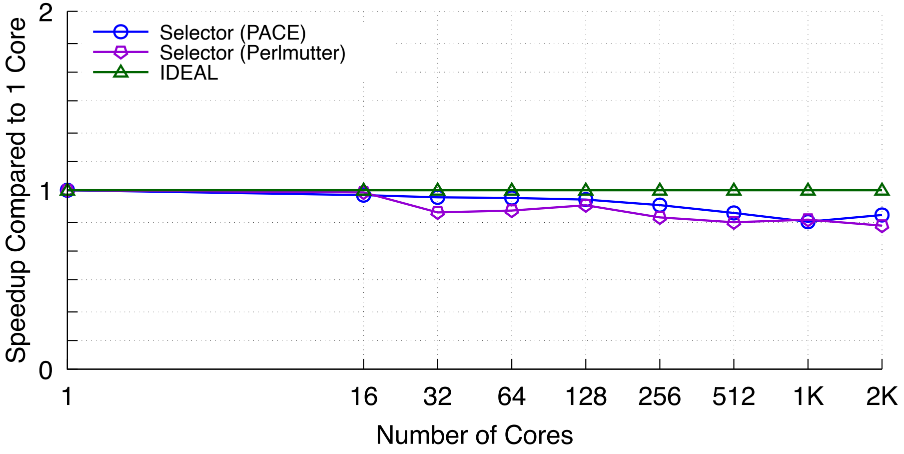
IPs Dataset
Strong Scaling



ASes Dataset
Strong Scaling



Synthetic Dataset
Weak Scaling



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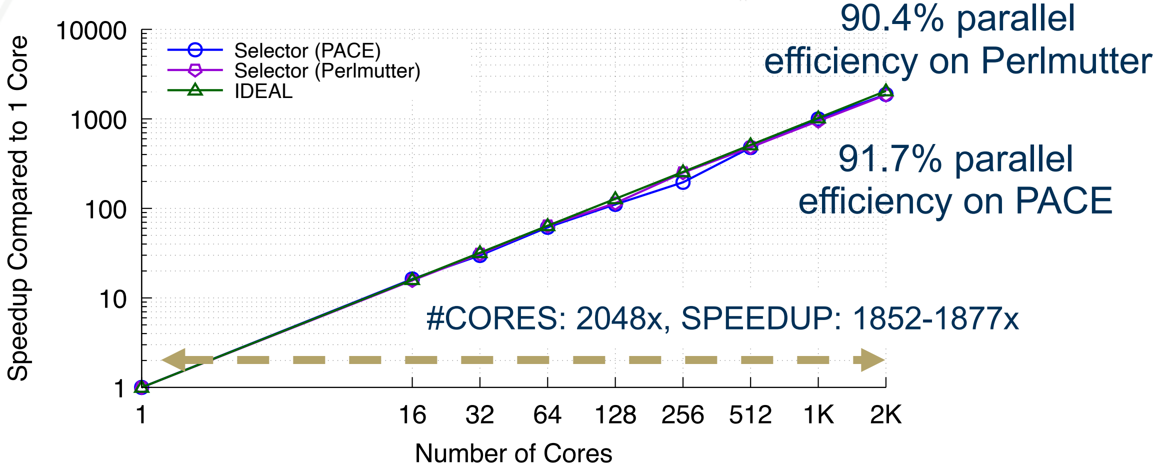
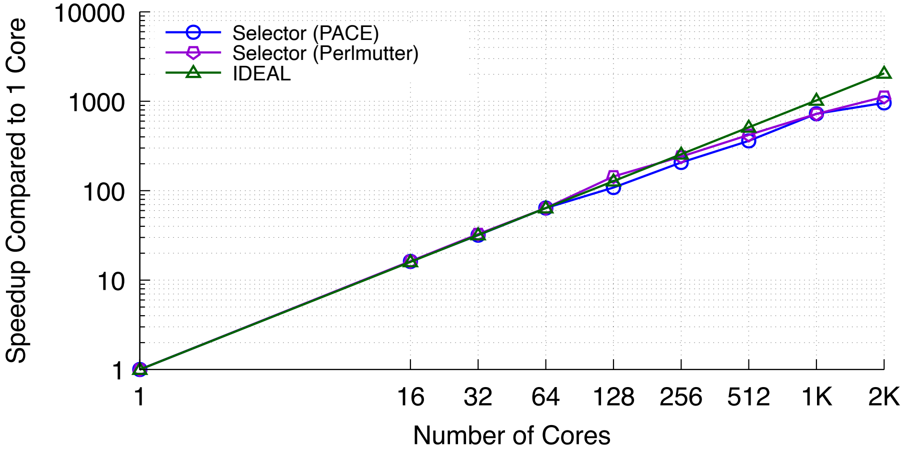
Performance Results: Scalability for SCALE-OUT

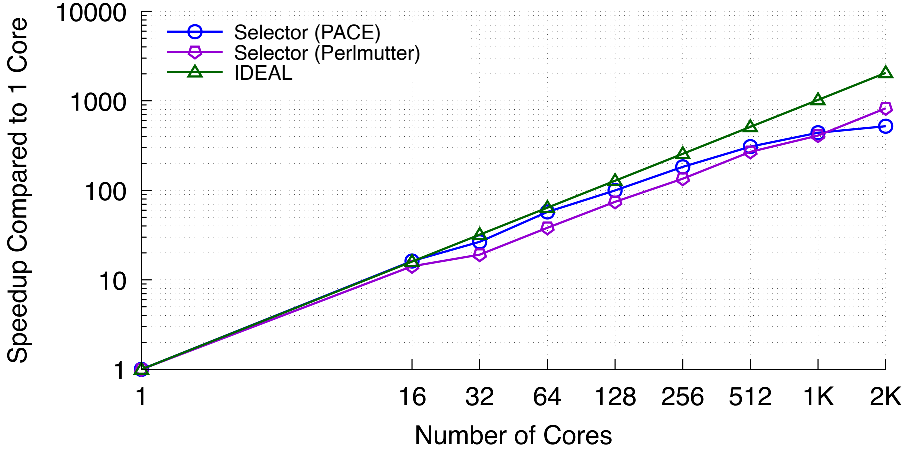
Routers Dataset
Strong Scaling



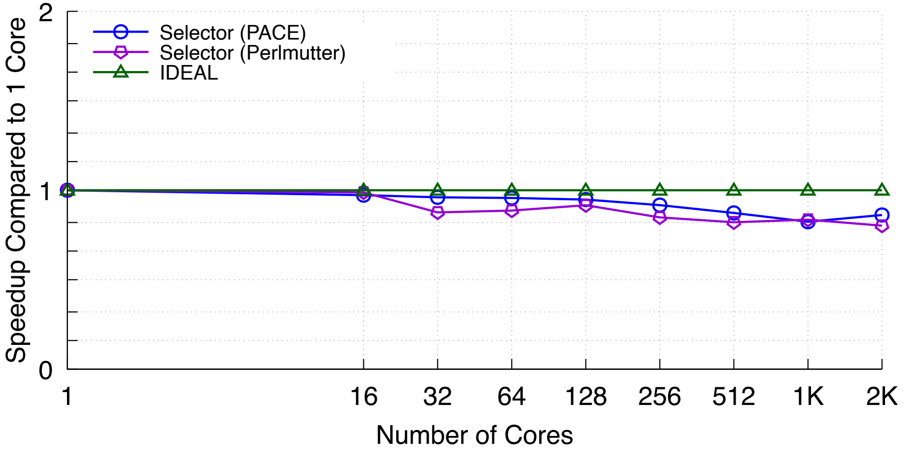
IPs Dataset
Strong Scaling



ASes Dataset
Strong Scaling



Synthetic Dataset
Weak Scaling



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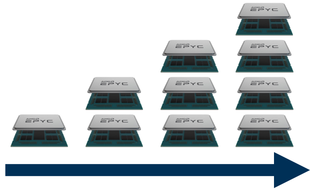
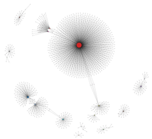
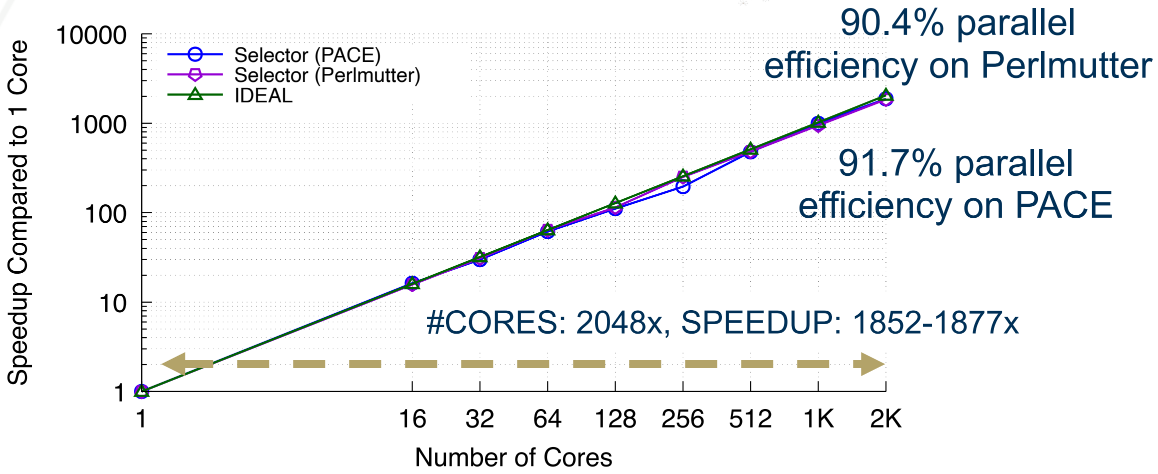
Performance Results: Scalability for SCALE-OUT

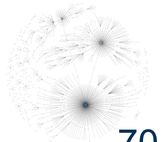


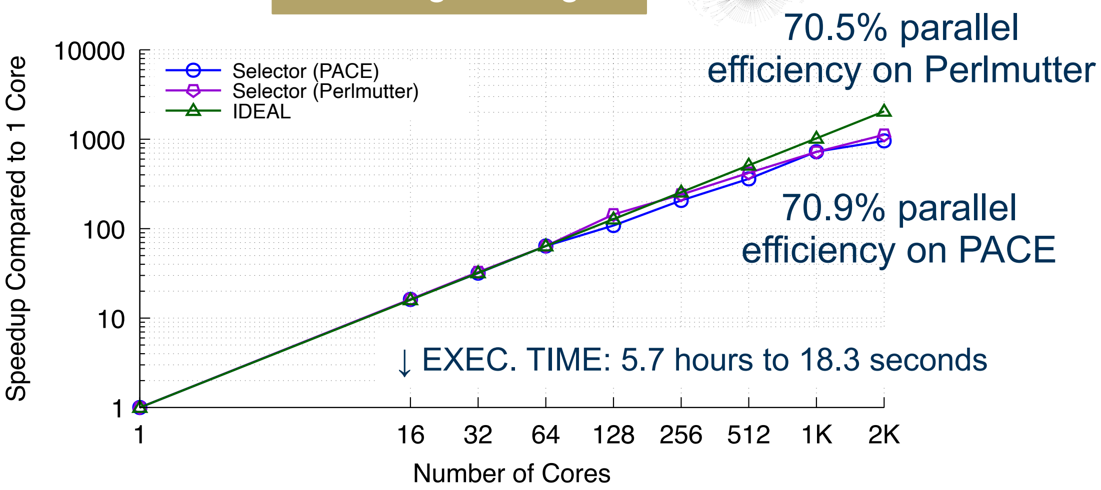
Routers Dataset
Strong Scaling



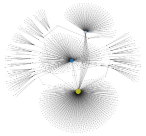


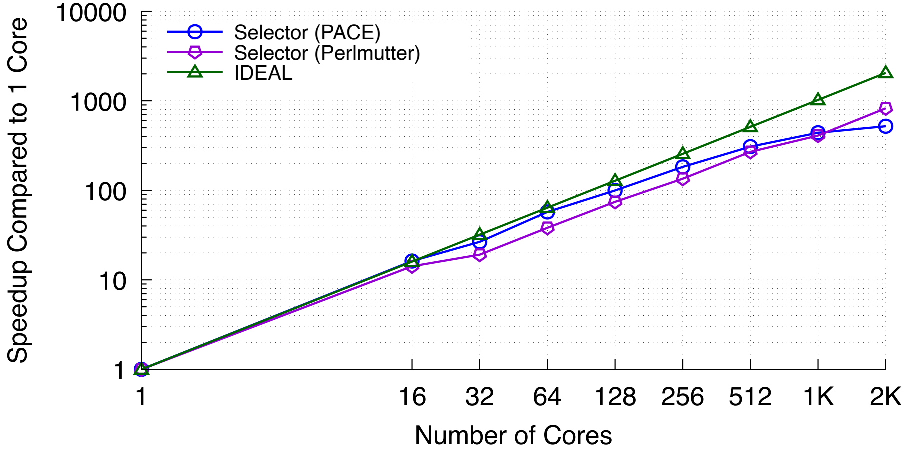
IPs Dataset
Strong Scaling



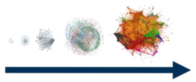


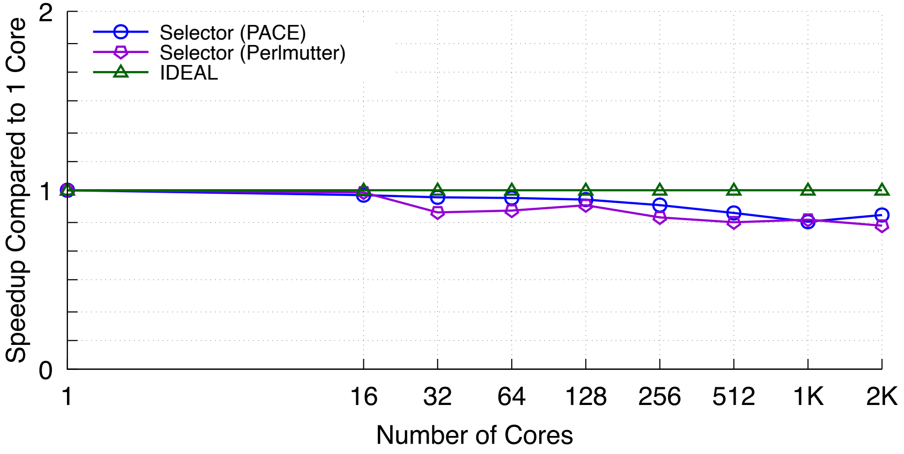
ASes Dataset
Strong Scaling





Synthetic Dataset
Weak Scaling





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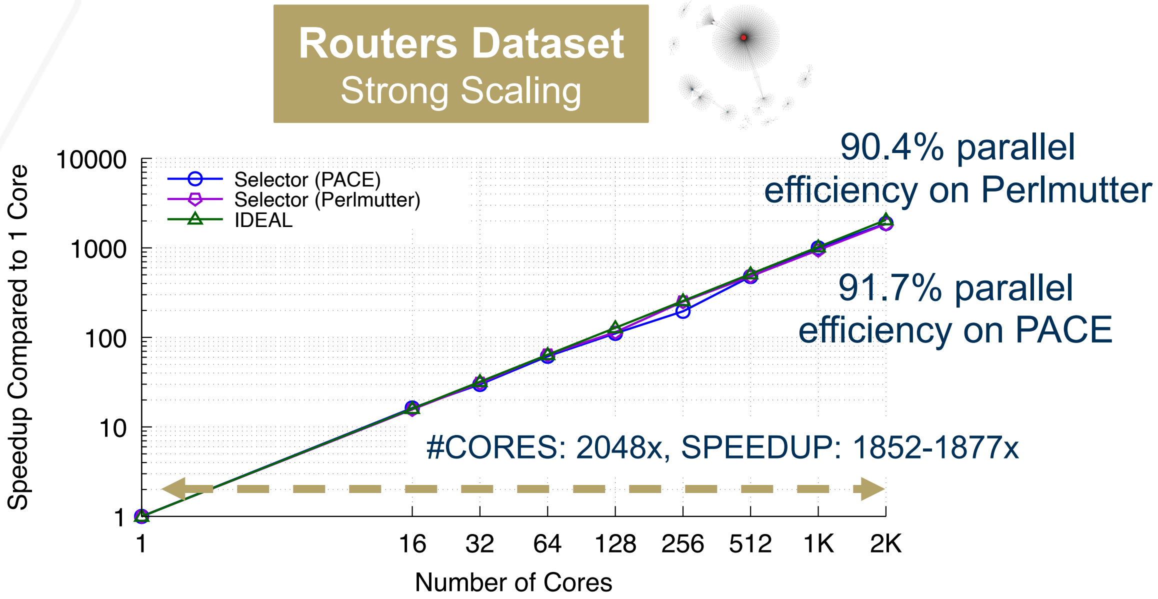
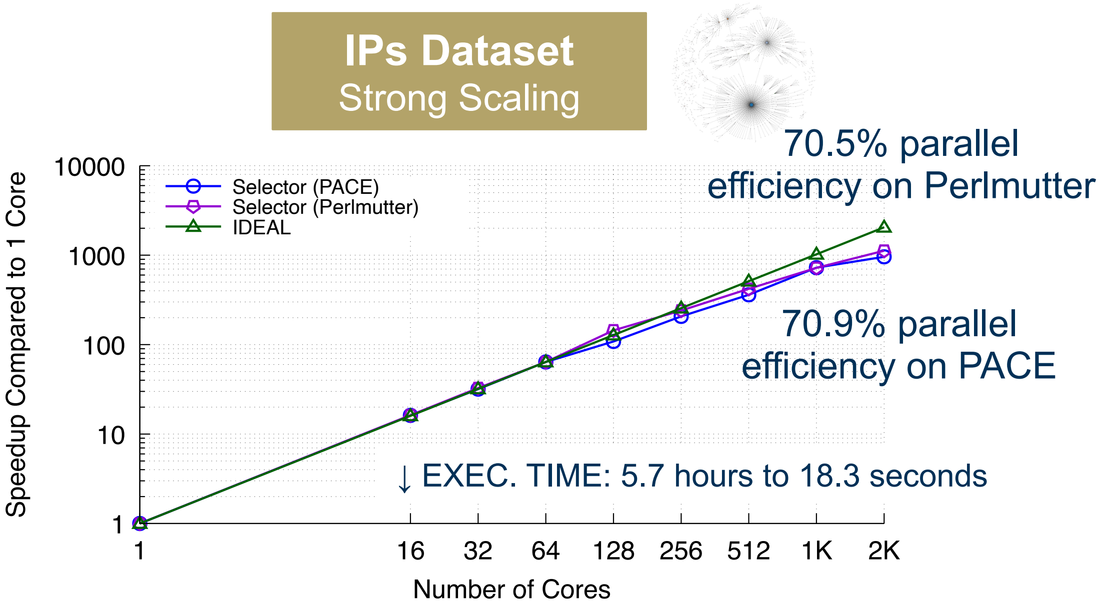
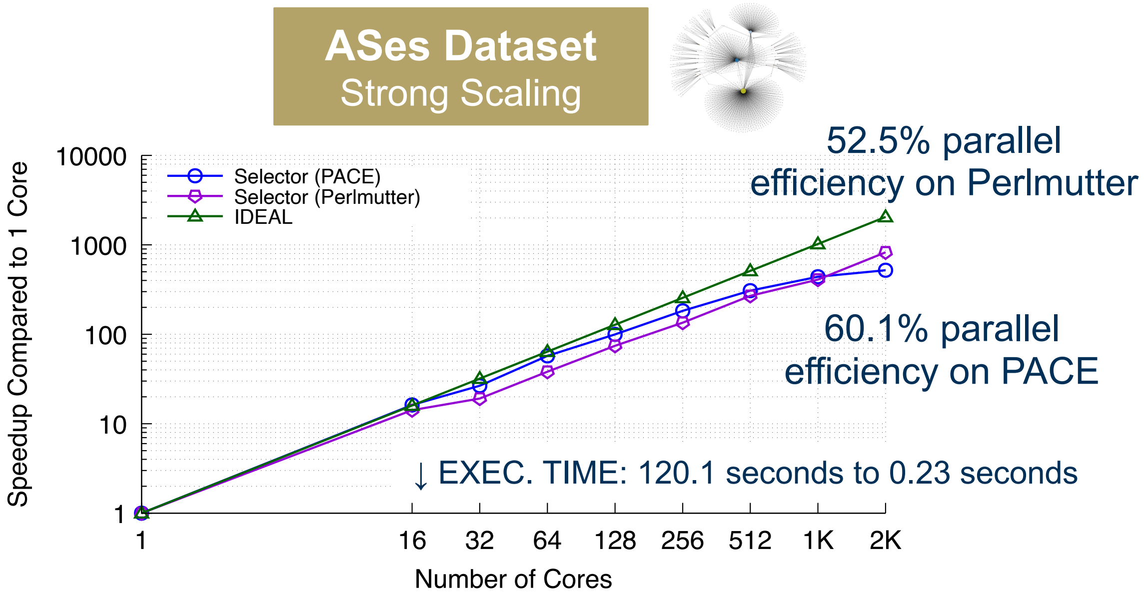
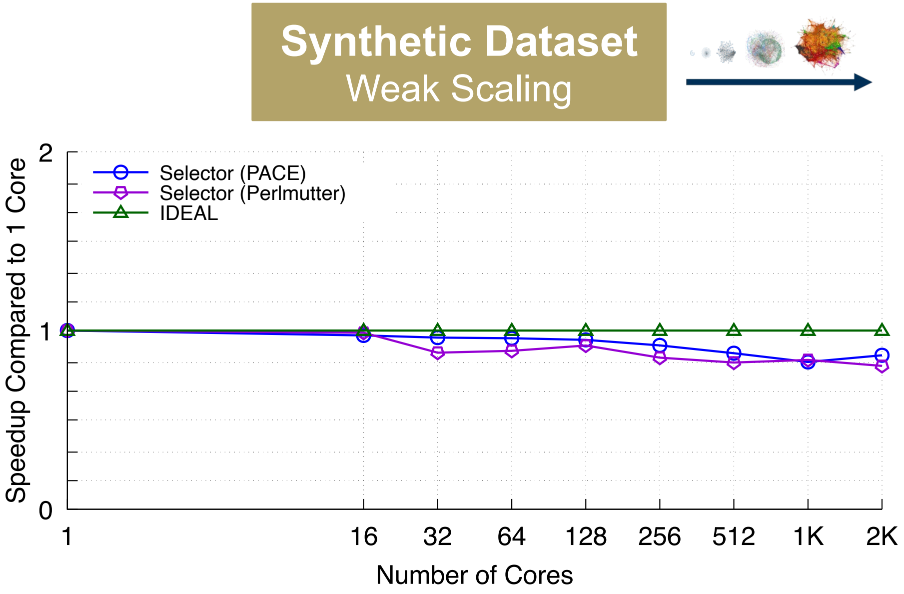
Performance Results: Scalability for SCALE-OUT









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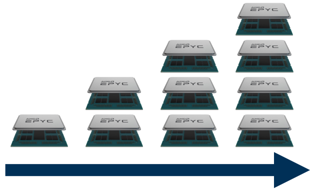
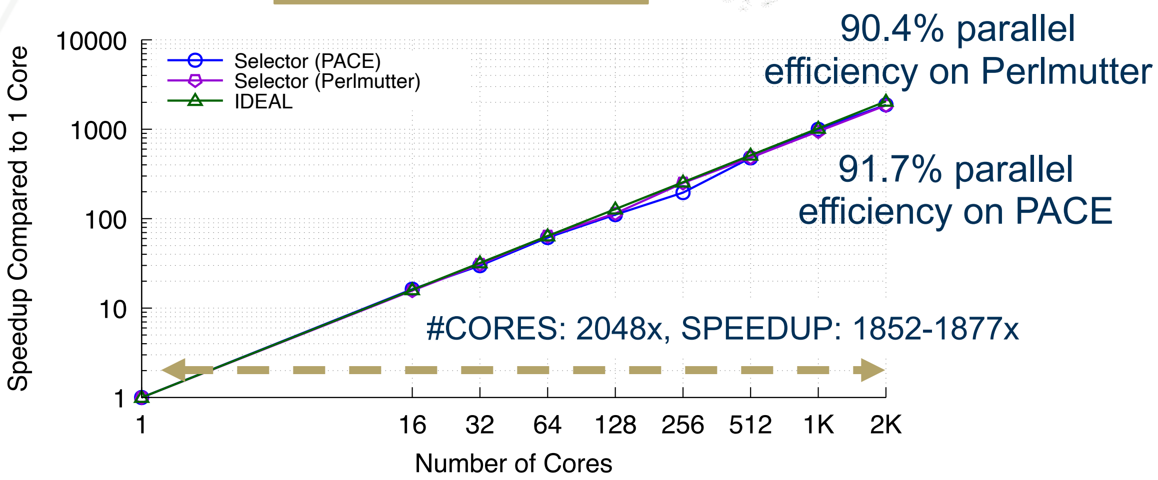
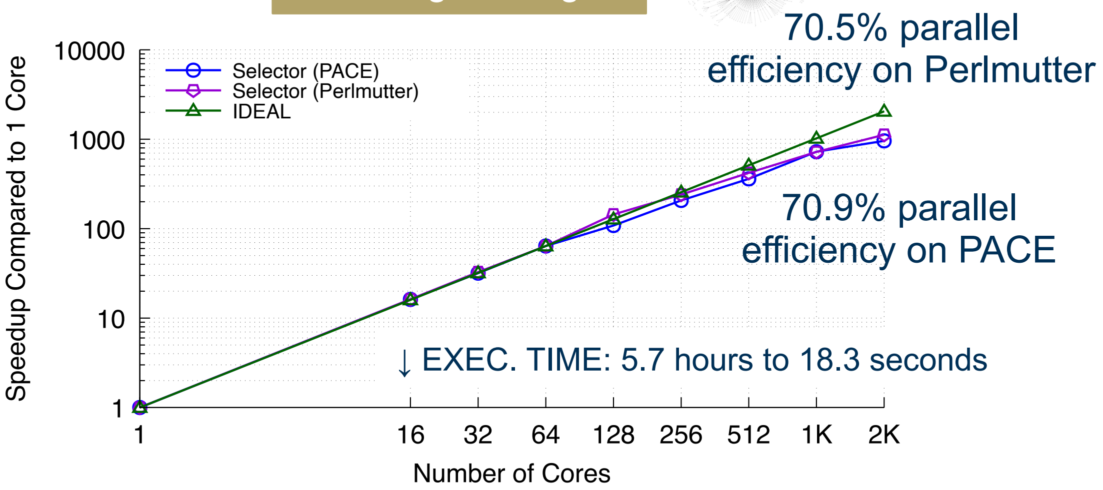
Performance Results: Scalability for SCALE-OUT



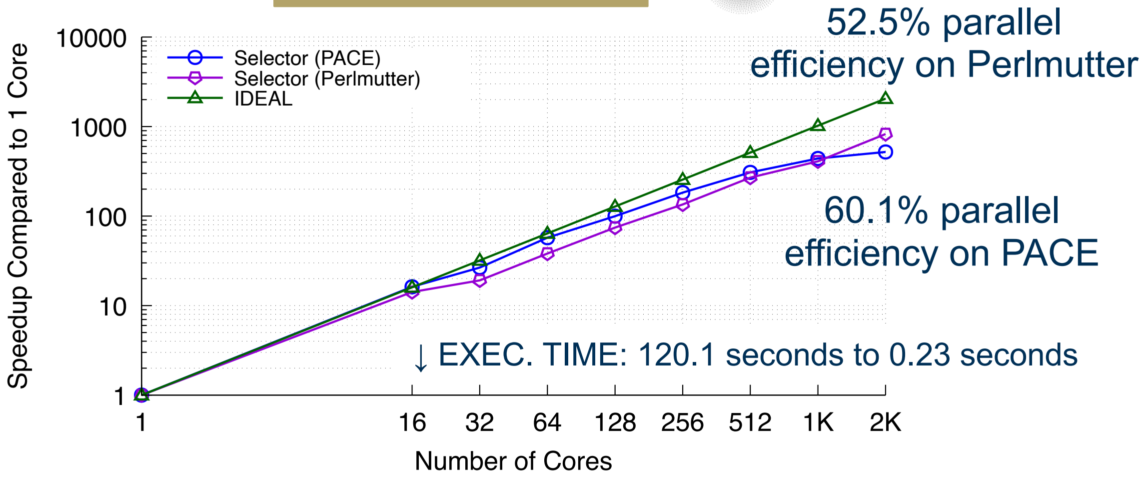
Routers Dataset
Strong Scaling



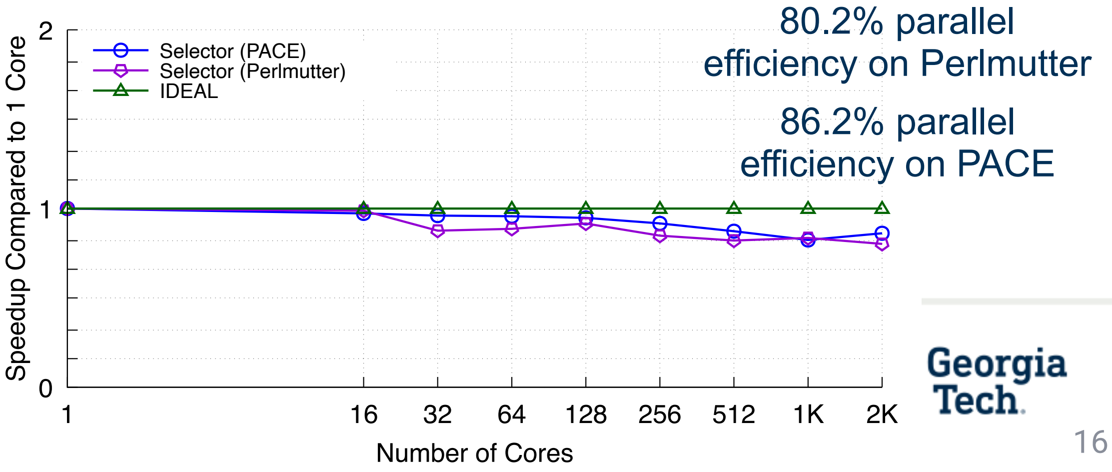
IPs Dataset
Strong Scaling



ASes Dataset
Strong Scaling



Synthetic Dataset
Weak Scaling



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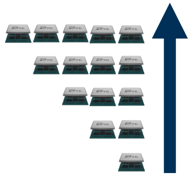
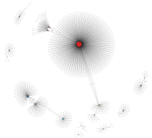
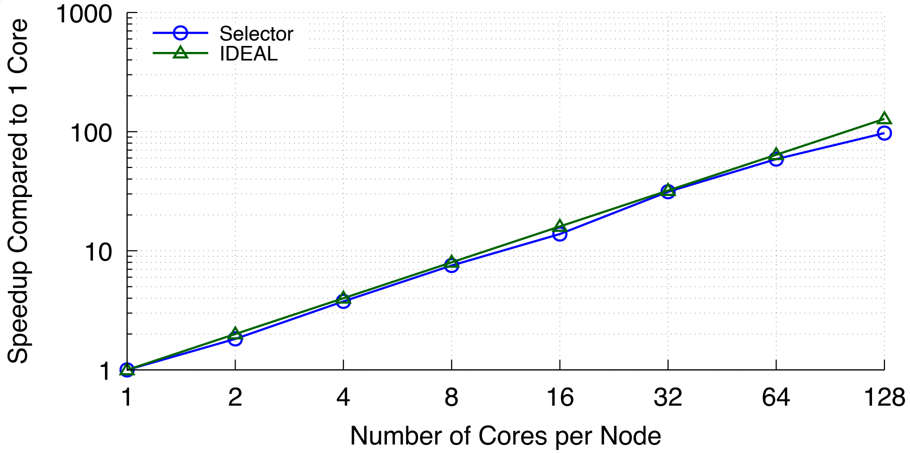


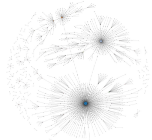
Performance Results: Scalability for SCALE-UP

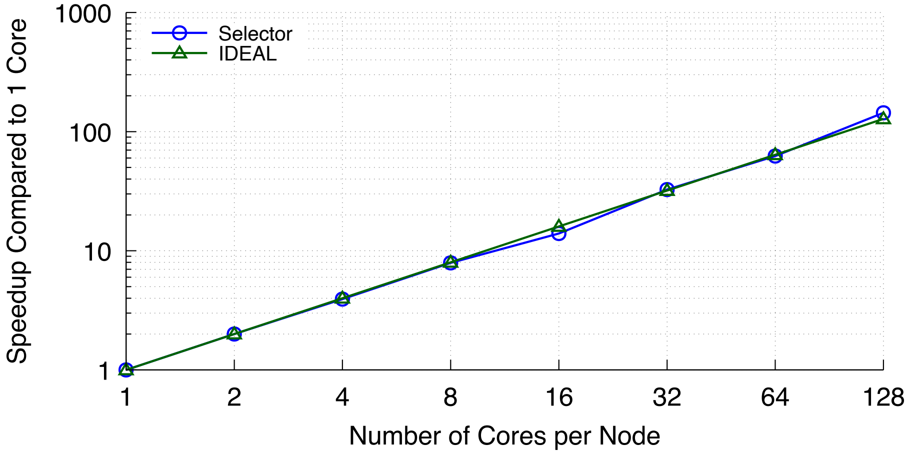
Routers Dataset
Strong Scaling



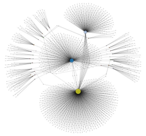


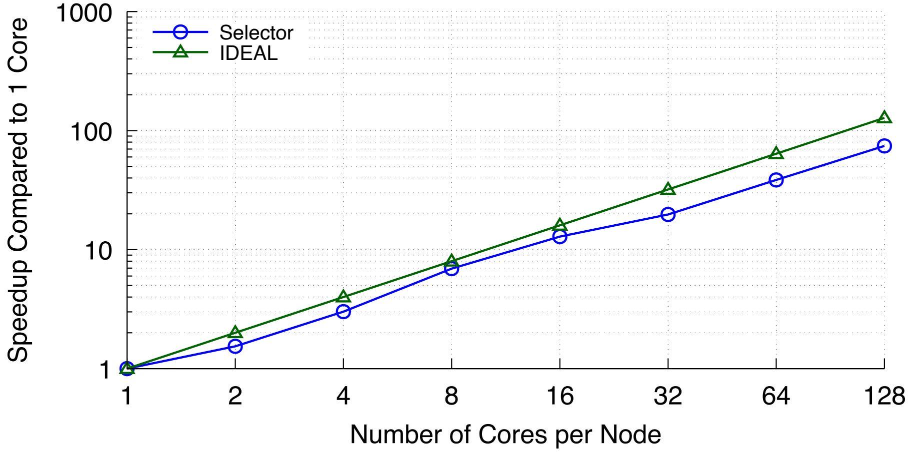
IPs Dataset
Strong Scaling



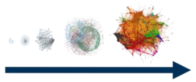


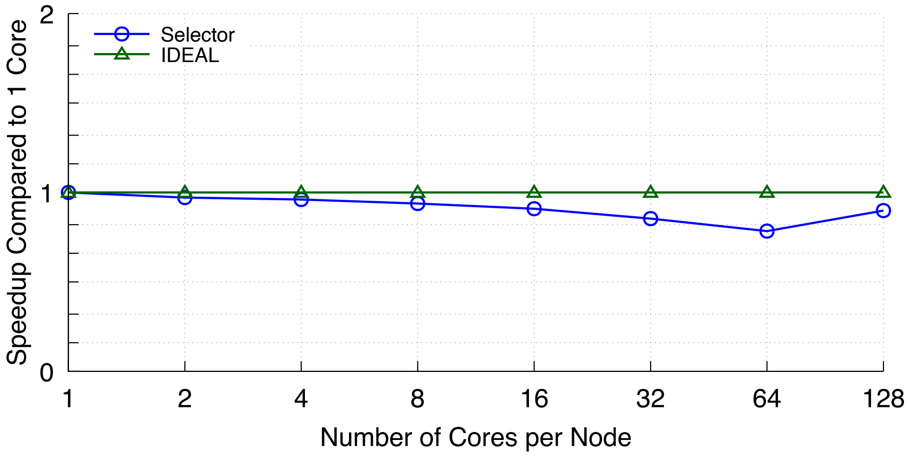
ASes Dataset
Strong Scaling





Synthetic Dataset
Weak Scaling





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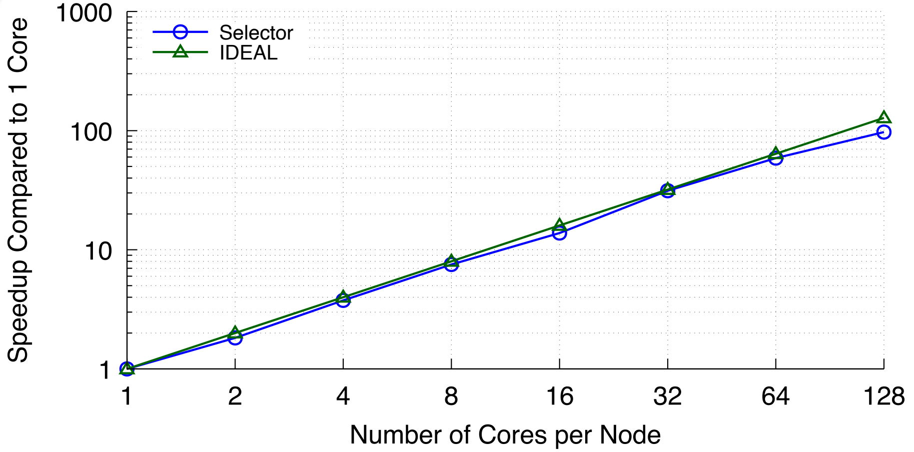
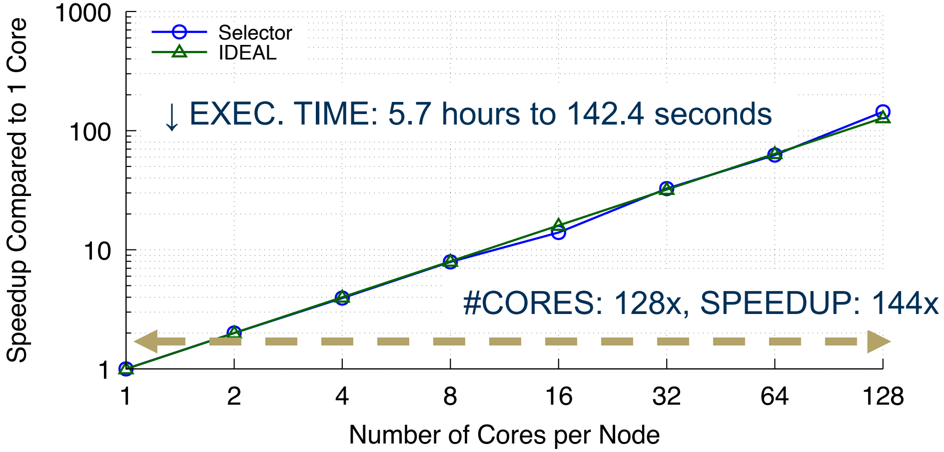
Performance Results: Scalability for SCALE-UP

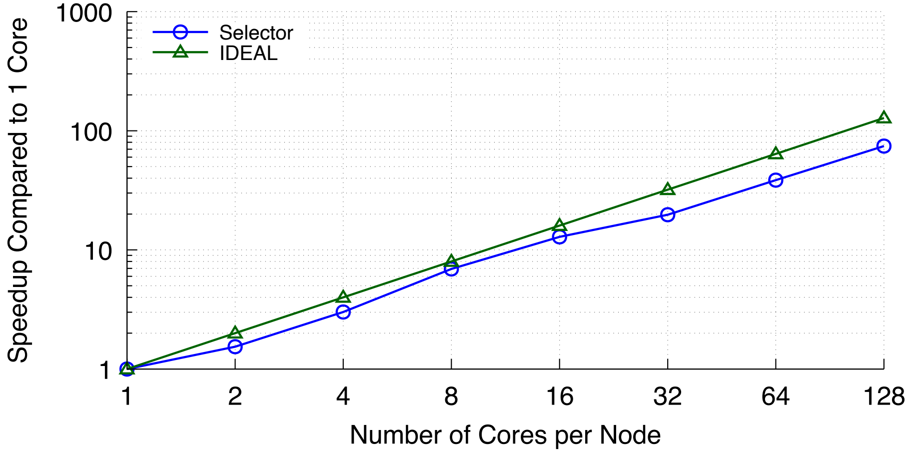
Routers Dataset
Strong Scaling



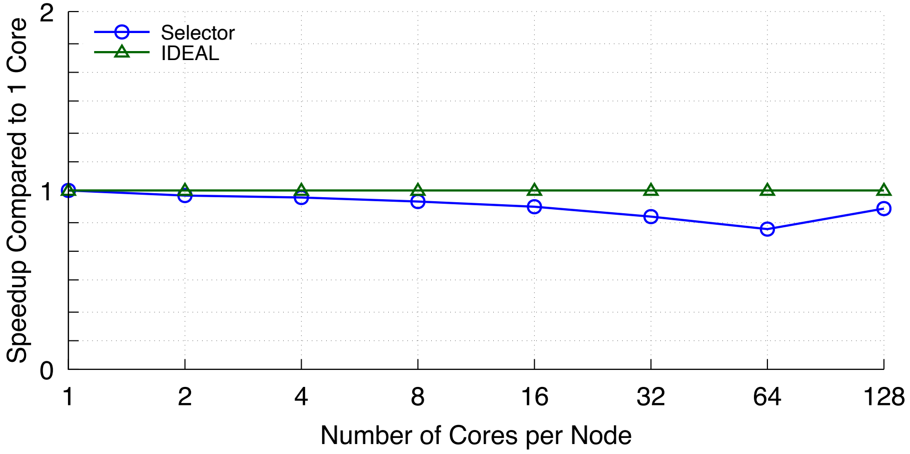
IPs Dataset
Strong Scaling



ASes Dataset
Strong Scaling



Synthetic Dataset
Weak Scaling



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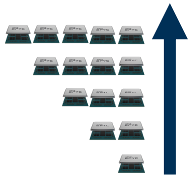
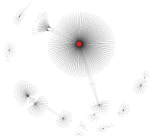
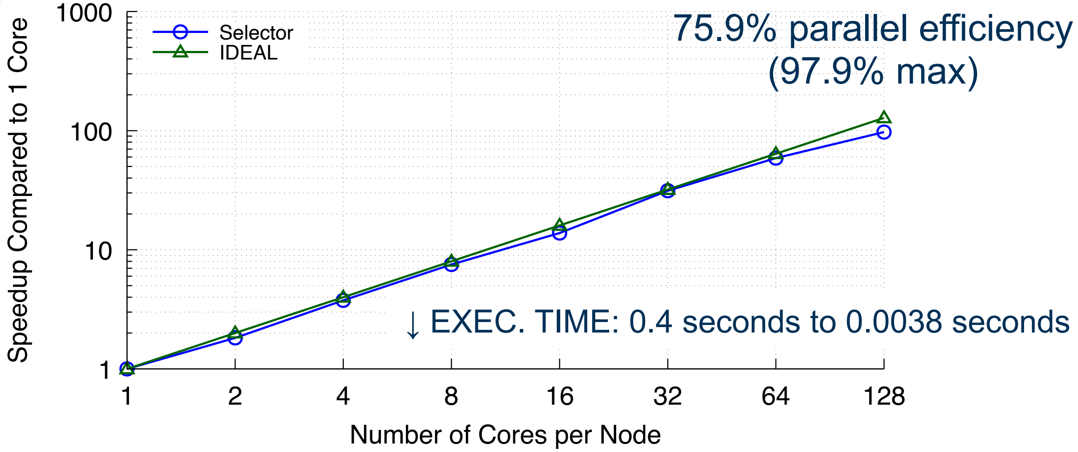
Performance Results: Scalability for SCALE-UP

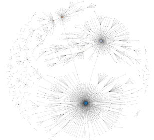


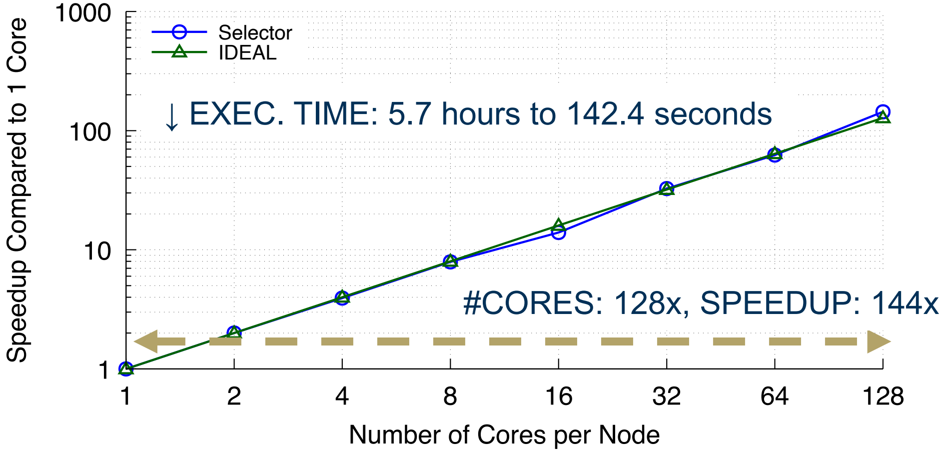
Routers Dataset
Strong Scaling



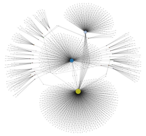


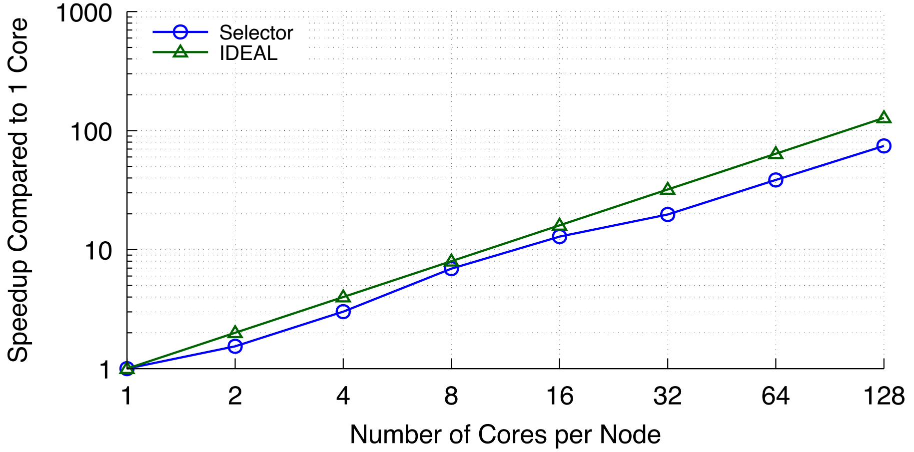
IPs Dataset
Strong Scaling



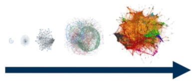


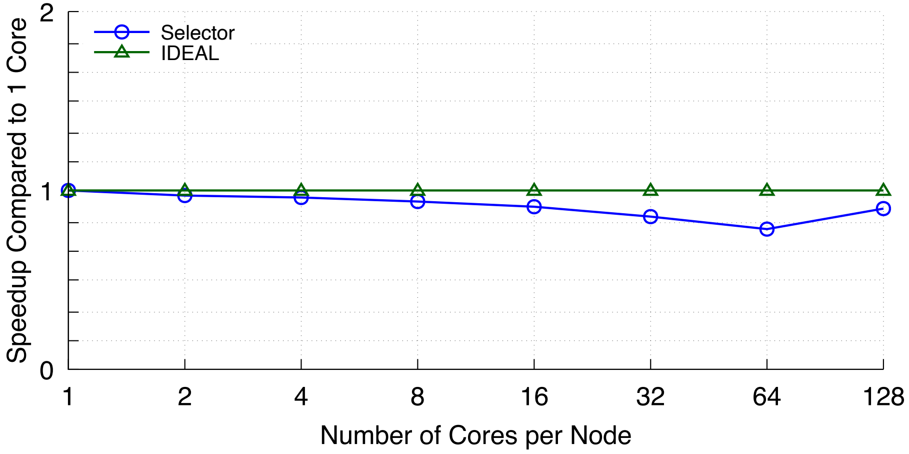
ASes Dataset
Strong Scaling





Synthetic Dataset
Weak Scaling





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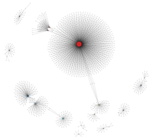
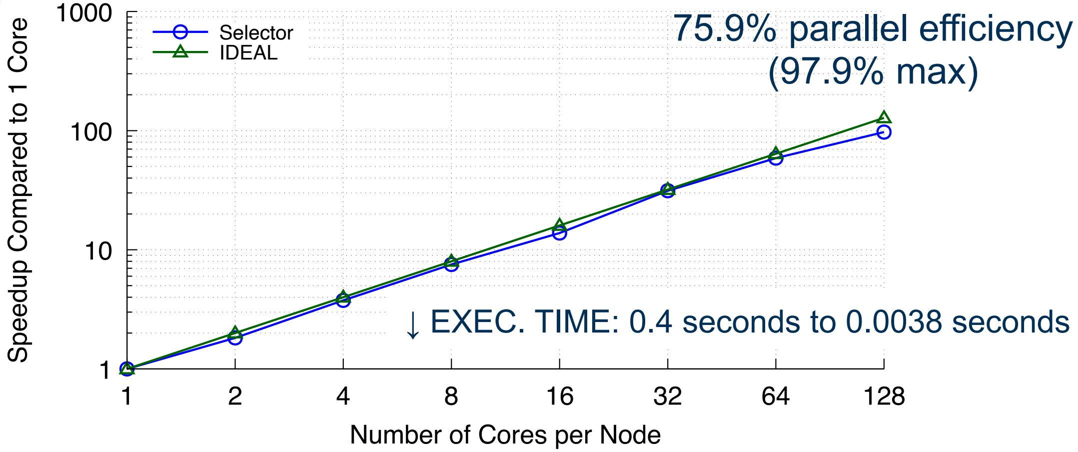
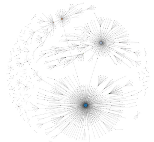
Performance Results: Scalability for SCALE-UP

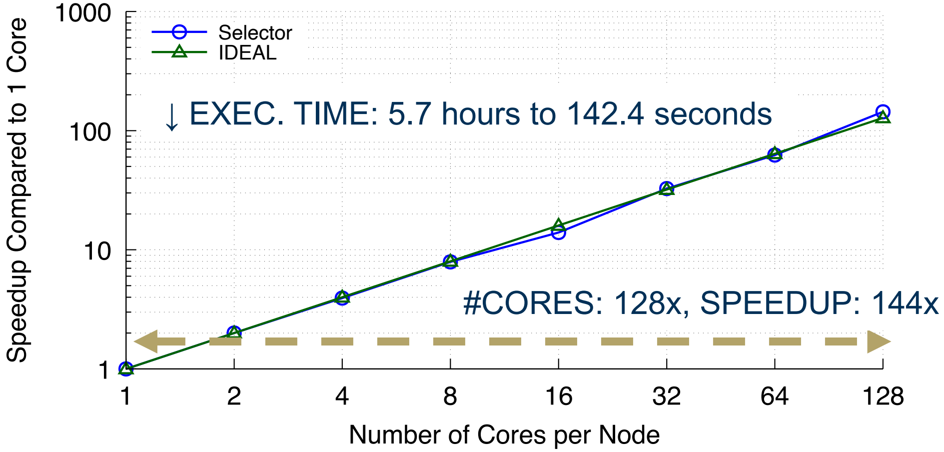
Routers Dataset
Strong Scaling



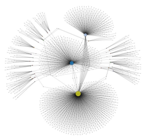


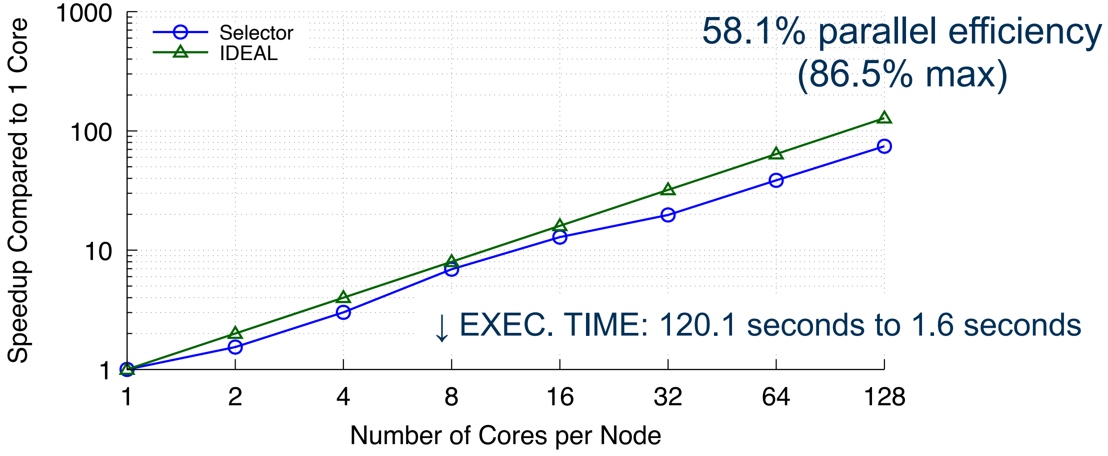
IPs Dataset
Strong Scaling



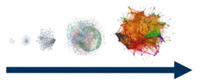


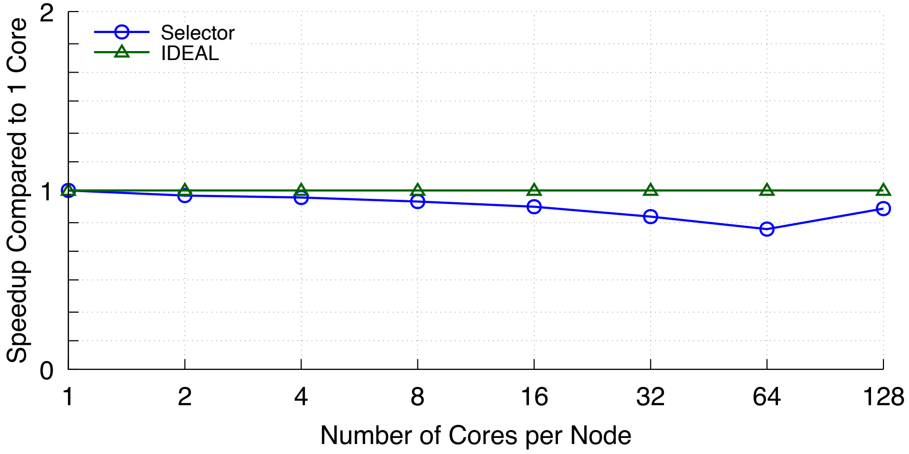
ASes Dataset
Strong Scaling





Synthetic Dataset
Weak Scaling





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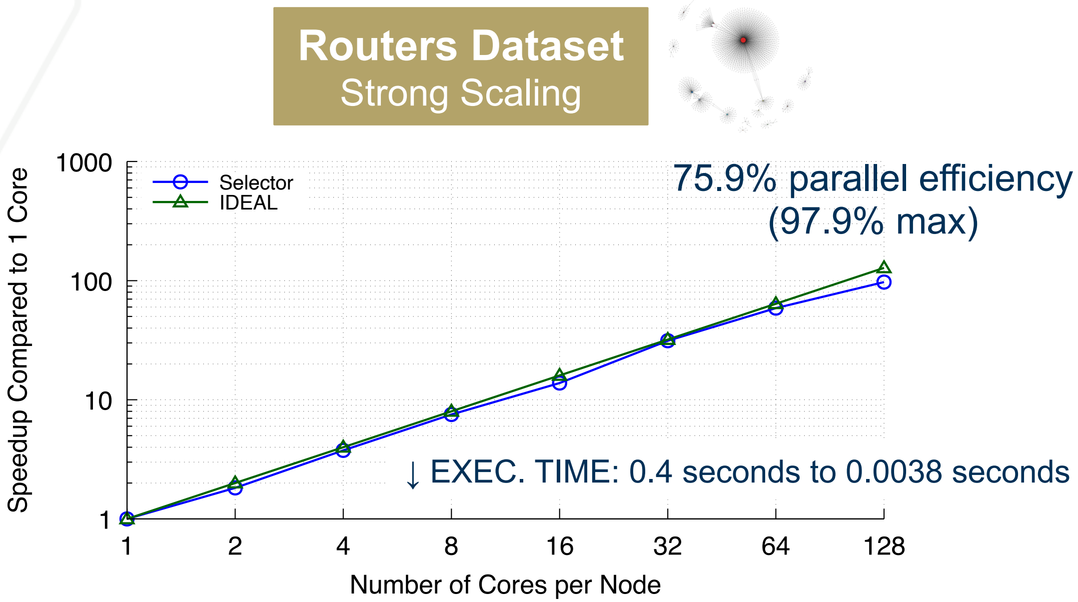
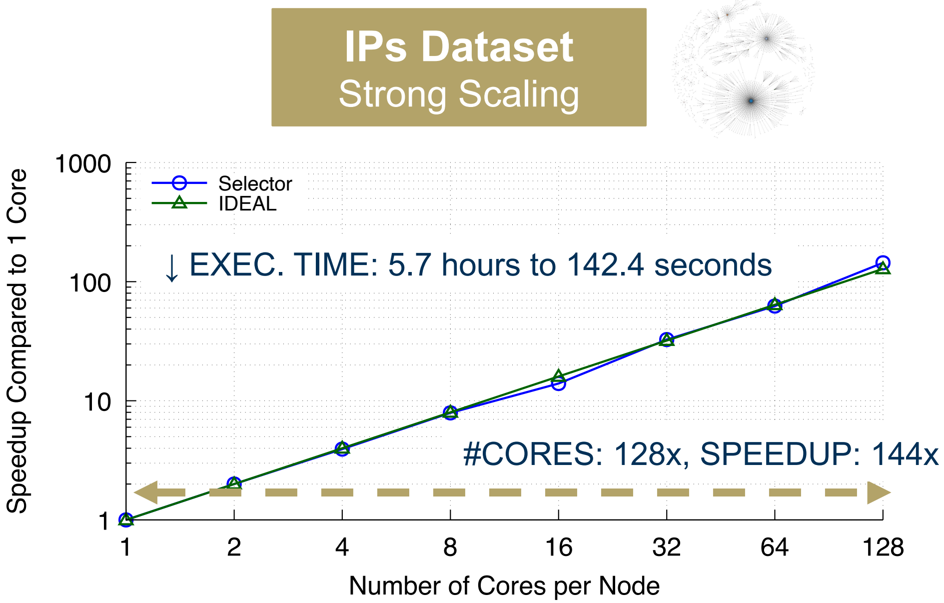
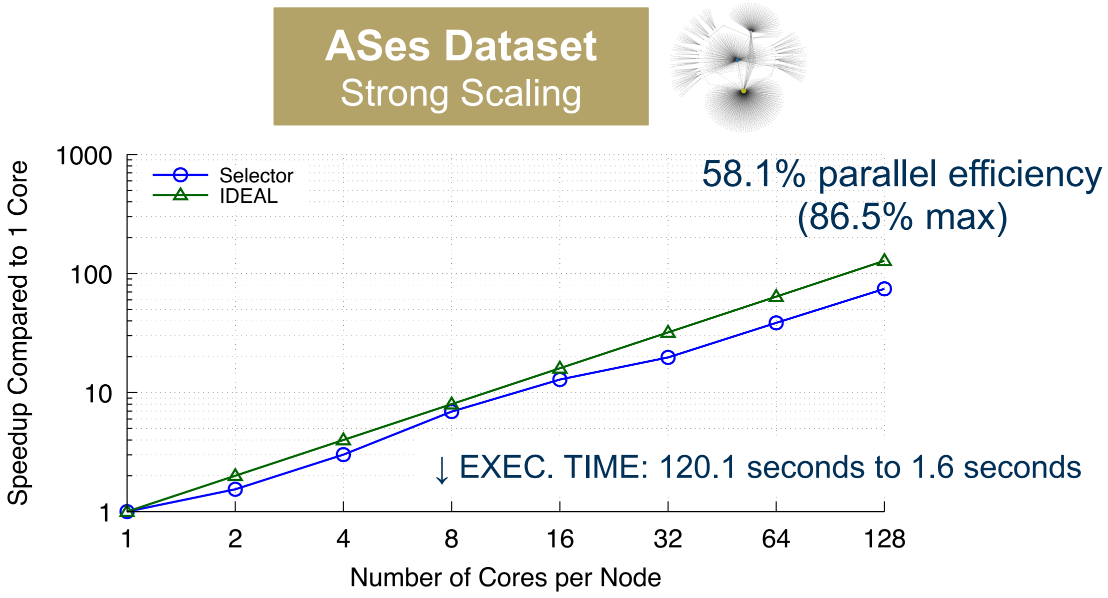
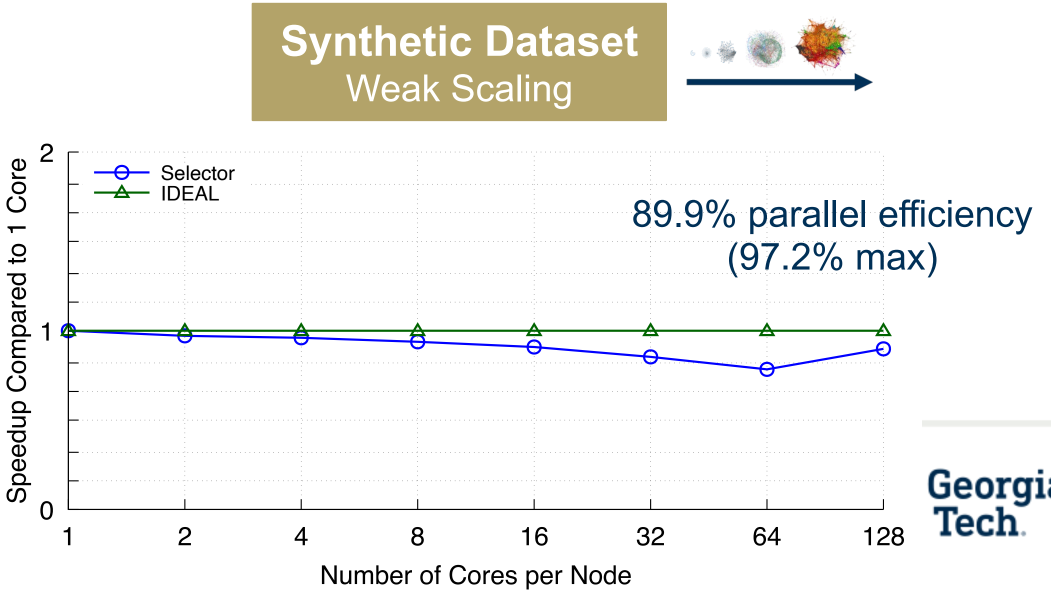
Performance Results: Scalability for SCALE-UP









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Contrasting to Related Approaches

- We contrast with respect to **performance on the large-scale synthetic dataset (weak scaling) in the `SCALE-OUT` dimension** on the Perlmutter Supercomputer
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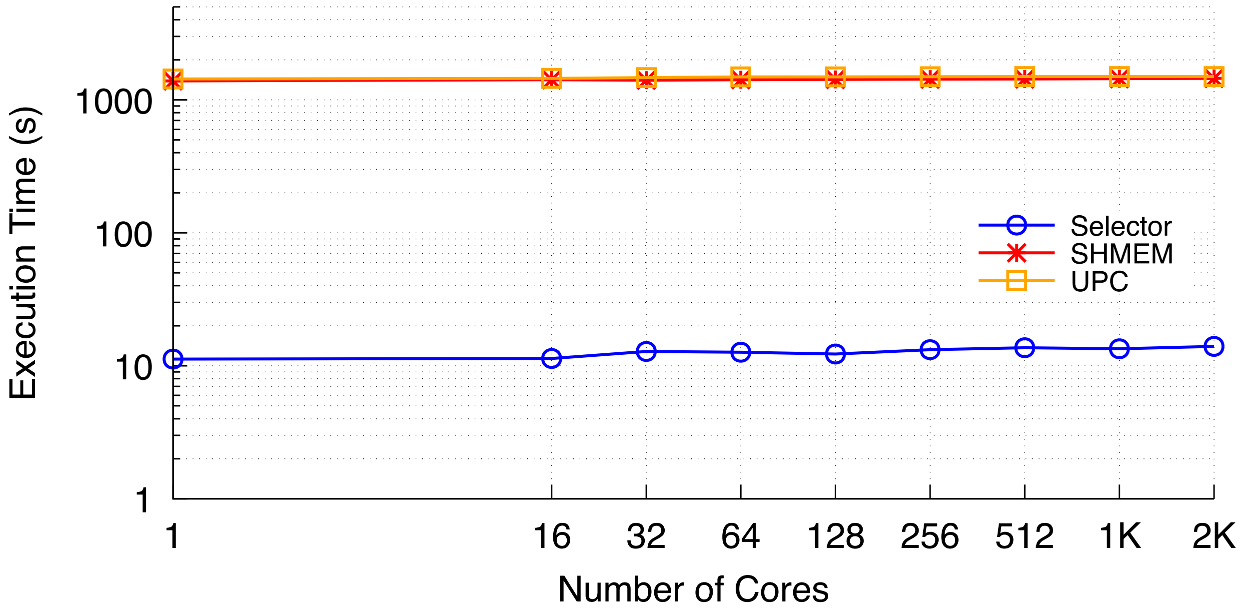

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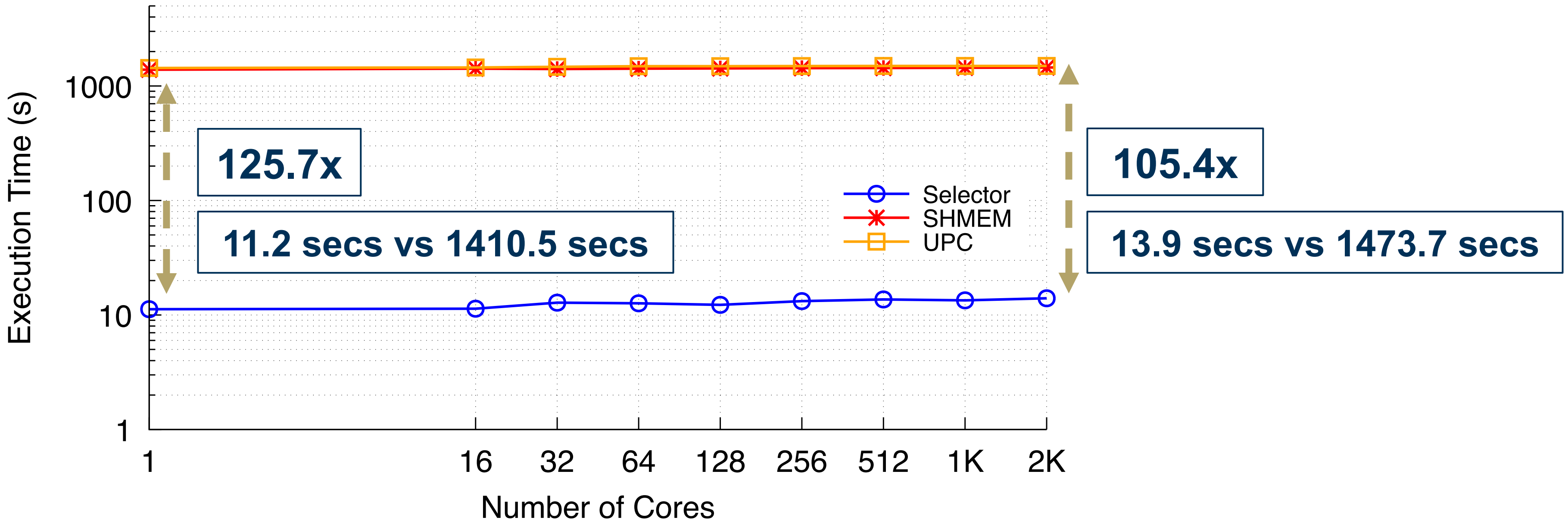

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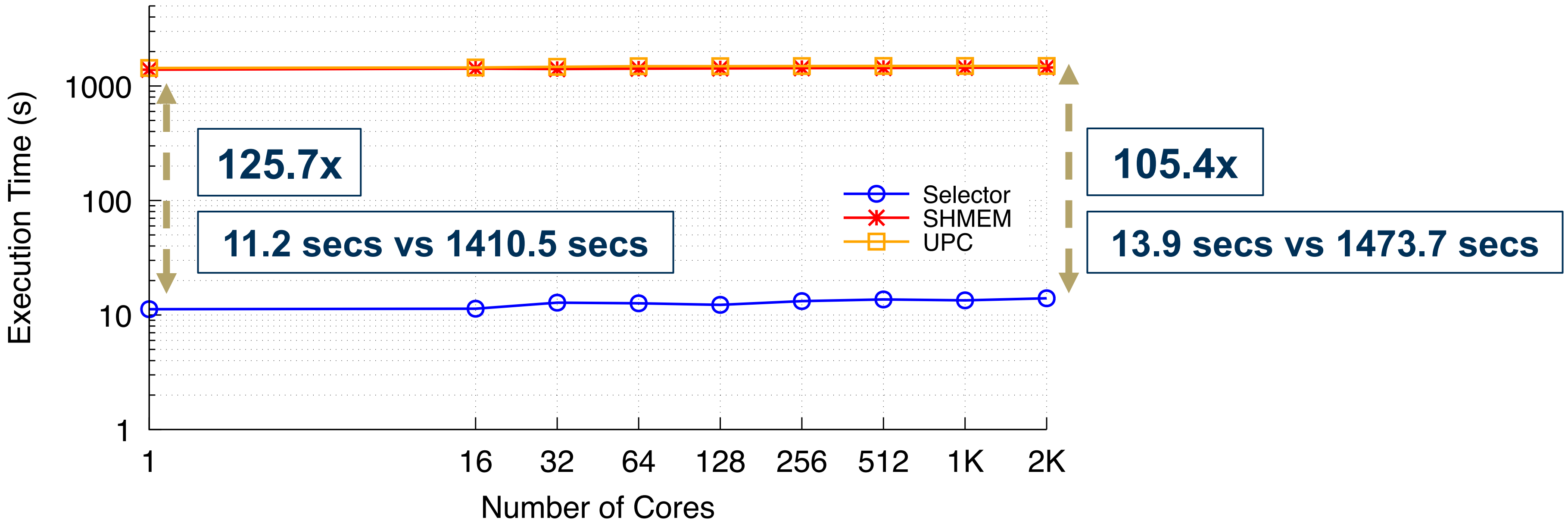

Attributed to the distributed and async. characteristics of our centrality algorithm as well as the efficient backend runtime

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5. Our algorithm can be extended to other domains

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DEMO

A Distributed, Asynchronous Algorithm for Large-Scale Internet Network Topology Analysis

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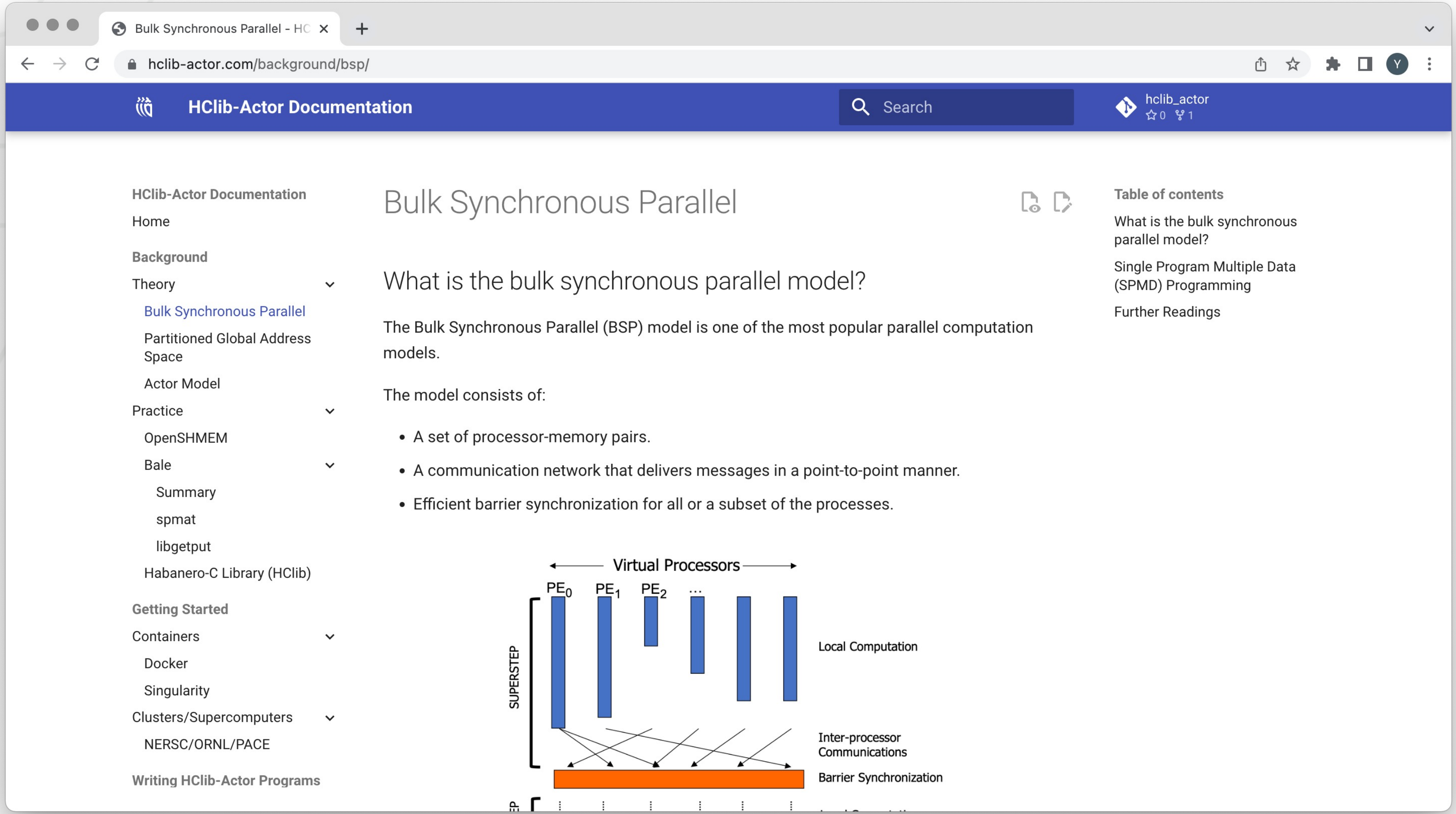
You can try this at home… Just visit hclib-actor.com !



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Youssef Elmougy, Akihiro Hayashi, and Vivek Sarkar

Habanero Extreme Scale Software Research Lab
Georgia Institute of Technology

Thank you for your attention!

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