Hacking pgvector for performance

sednai

Daniel Krefl
Sednai

$1.$2 @ sedn.ai

@ Swiss PGDay 2025

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AERO

Sponsor

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Aero aims to complement the efforts of the *EU Processor Initiative (EPI)* project by developing the open-source software ecosystem required to not only improve the efficiency of the EPI hardware but also accelerate and ease the processor's integration into the cloud.

Funded by the European Union

UK Research and Innovation

Project funded by

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

Funded by the European Union. Views and opinions are however those of the author(s) only and do not necessarily reflect those of the European Union or the HaDEA. Neither the European Union nor the granting authority can be held responsible for them. Project number: 101092850.

AERO has also received funding from UKRI under grants no. 10048318 and 10048915, and the Swiss State Secretariat for Education, Research, and Innovation.

Intro

Aero aims to complement the efforts of the *EU Processor Initiative (EPI)* project by developing the open-source software ecosystem required to not only improve the efficiency of the EPI hardware but also accelerate and ease the processor's integration into the cloud.

Target platform: RHEA 1

HPC and AI processor

European high-performance energy-efficient processor (ARM based), dedicated to high performance computing, and designed to work with third-party accelerators, see [https://sipearl.com/]

RHEA images kindly provided by SIPEARL

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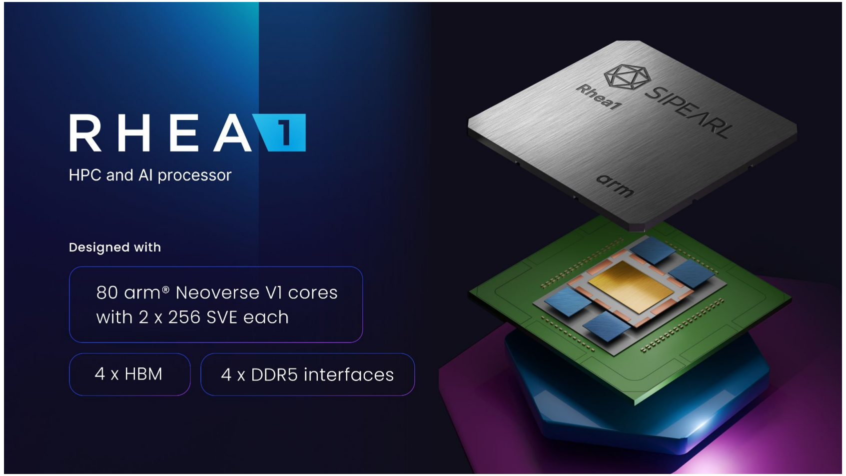

[https://sipearl.com/]

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Intro

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AERO

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Objectives: *[https://aero-project.eu/about/]*

- *Managed Programming Languages*
- *Native Programming Languages & Runtimes*
- *OS, drivers & virtualization support*
- *State-of-the-art cloud deployments*
- *Hardware acceleration for performance & security*
- *Adoption of the EU cloud ecosystem*

Intro

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Use cases / pilots:

- *Automotive Digital Twins with IoT-Cloud Interoperability*
- *High Performance Algorithms for Space Exploration (Gaia)*
- *HPC/Cloud Database Acceleration for Scientific Computing*

ICCS UBITECH SIPEARL PIERER INNOVATION Red Hat FORTH Università di Pisa Virtual Open Systems Université de Genève sednai Manchester 1824 The University of Manchester codeplay

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... GAIA ...

Gaia

Gaia was a space based astronomy telescope of ESA operational 2014-2025.

Gaia has made more than three trillion observations of two billion stars and other objects throughout our Milky Way galaxy and beyond, mapping their motions, luminosity, temperature and composition.

Scientific objectives:

- *First 3d map of our galaxy*
- *Insides on the origin and formation of our galaxy*
- *Detection of diverse variable phenomena*
- *Many more … see* [https://www.cosmos.esa.int/web/gaia/science]

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Data and compute challenge:

- *Petabyte scale*
- *~ 10 Billion photometric time series*
- *~ 5 Billion spectra time series*

Gaia

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Variability analysis @ Geneva:

- *All data stored in a distributed PostgreSQL database*
- *Compute where data is located, as far as possible.*
- *PostgreSQL XC -> XL -> TBase lineage*
- *6 nodes, each with 1 TB RAM and a Nvidia A100*

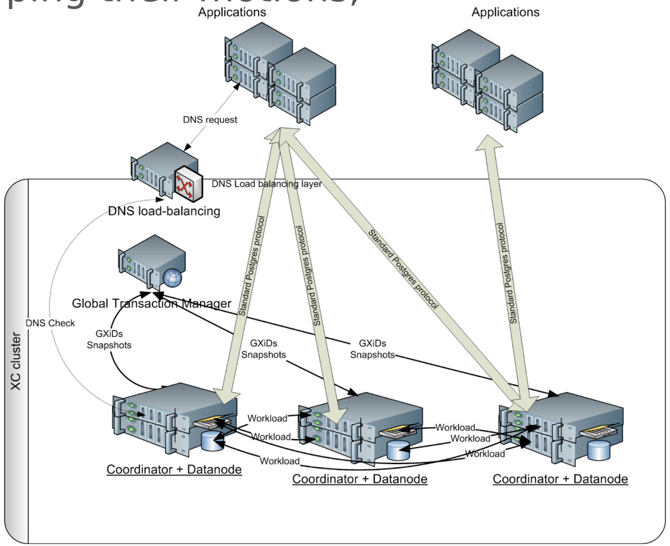

Figure provided by K. Nienartowicz

Intro

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Intertwined Gaia+SED pilots:

- *Process efficiently constantly increasing volumes of data.*

→ - *Enable GPU computations directly within the database*

- *Optimize data and compute pipeline for RHEA*

Intro

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Intertwined Gaia+SED pilots:

- *Process efficiently constantly increasing volumes of data.*

→ - *Enable GPU computations directly within the database*

Example: Hack to GPU accelerate a Postgres vector index

(WARNING: This will be more technical …)

... VECTOR SEARCH ...

Vector Search

Motivation

Many data analysis algorithms require a nearest neighbour search in a D-dim space.
Often just referred to as *Vector Search*.

Vector Search

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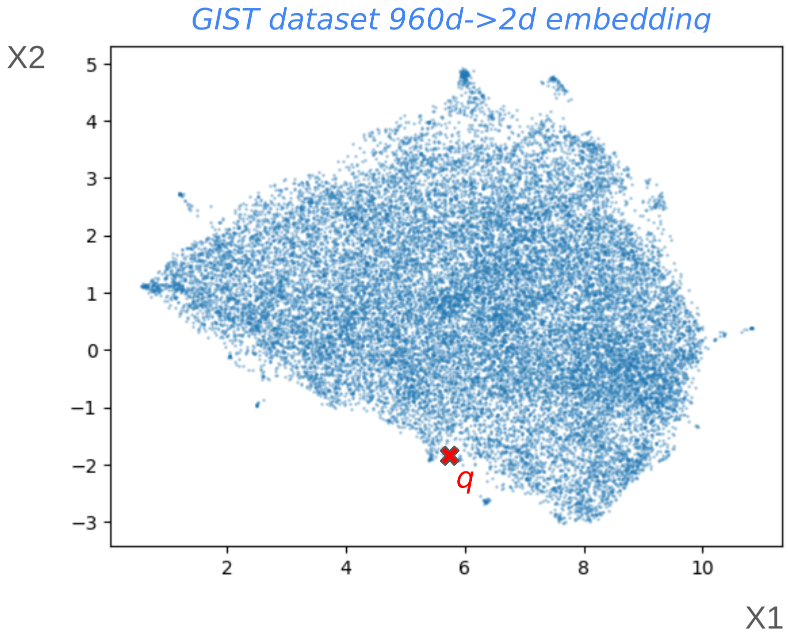
For a query point *q* :

What are its *k* nearest neighbors?



Vector Search

Motivation

Many data analysis algorithms require a nearest neighbour search in a D-dim space. Often just referred to as *Vector Search*.

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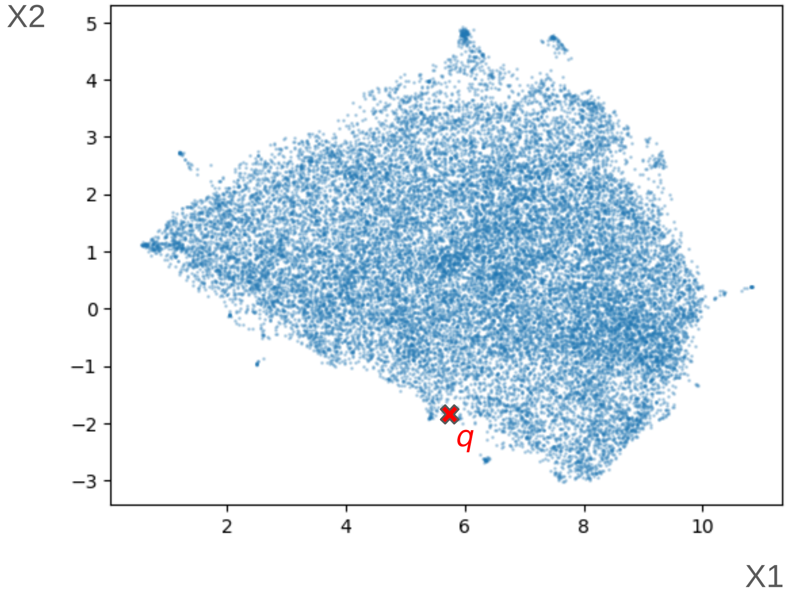
Note:

Growing interest due to ML / AI generated vector embeddings.

For instance: Document retrieval.

GIST dataset 960d->2d embedding



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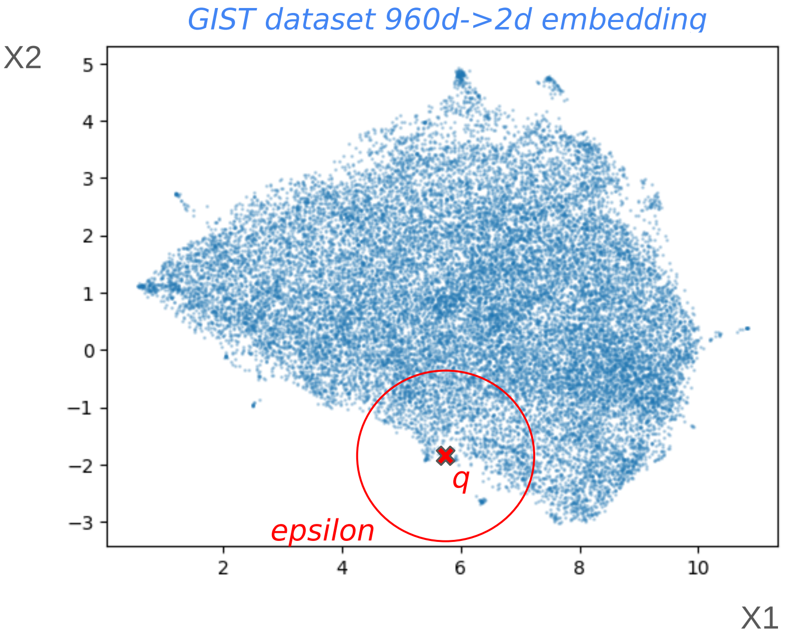
What are its *k* nearest neighbors?

What points are close by ?



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For a query point *q :*

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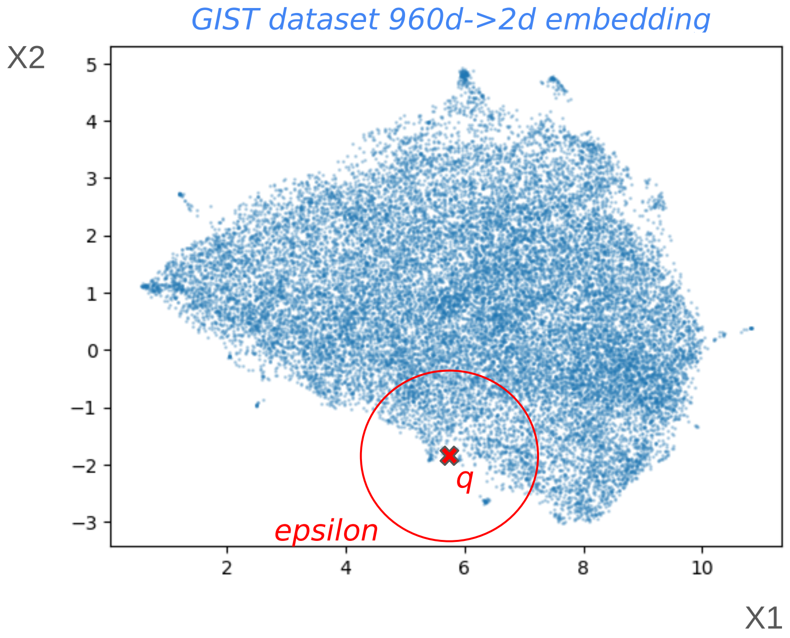
Note:

Of interest for classical unsupervised learning algorithms.

kNN, *DBSCAN*, ...

→ Application to Gaia data



Vector Search

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Motivation

Many data analysis algorithms require a nearest neighbour search in a D-dim space.
Often just referred to as *Vector Search*.

BUT:

Requires for each query point N distance calculations + ranking.
(With N the number of datapoints in the dataset)

How to scale to large datasets ?

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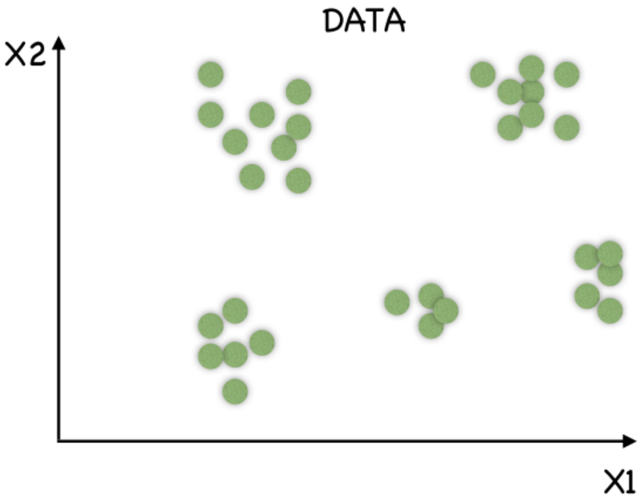
Approximate Nearest Neighbour search

Several flavours exist, but *IVFFLAT* is the conceptually simplest algorithm.



Vector Search

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Approximate Nearest Neighbour search

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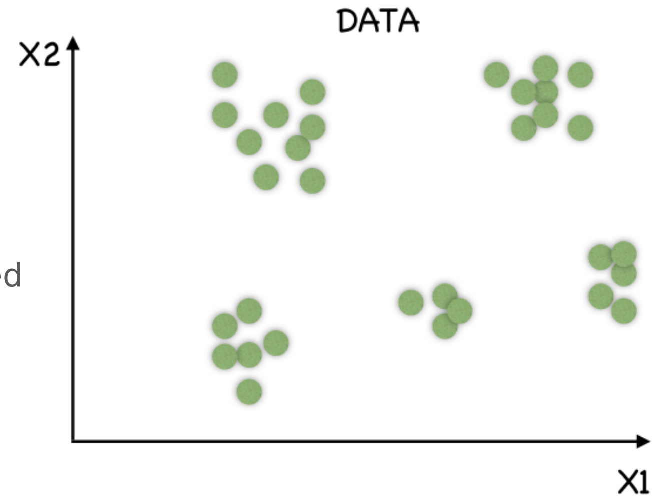
InVerted File Flat Index

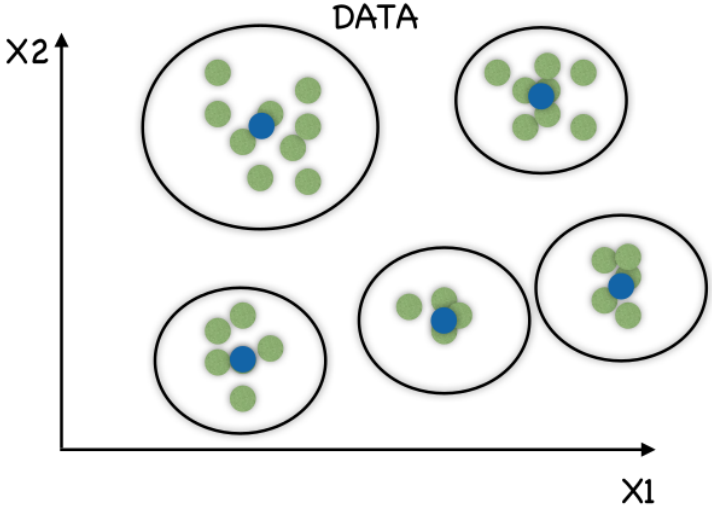
This talk: Mainly inference will be discussed



Approximate Nearest Neighbour search

Several flavours exist, but *IVFFLAT* is the conceptually simplest algorithm.

- Build vector index on dataset via K-means clustering
- Index each datapoint to the closest cluster (centroid)



Vector Search

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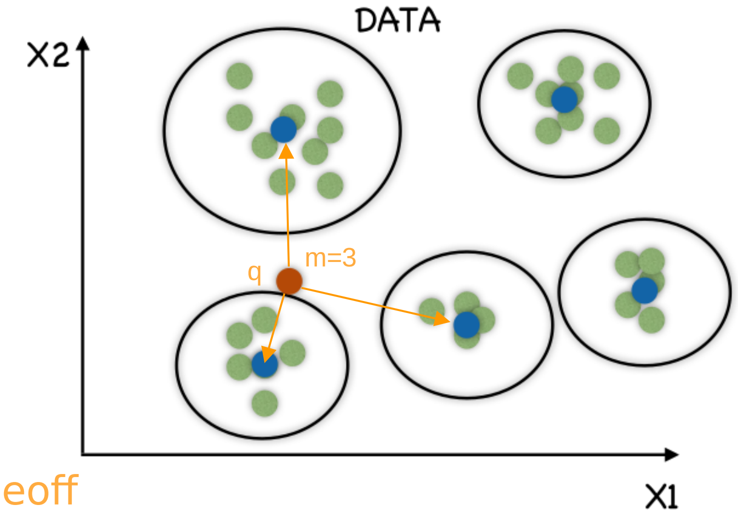
IVFFLAT inference

Several flavours exist, but *IVFFLAT* is the conceptually simplest algorithm.

- Build vector index on dataset via K-means clustering
- Index each datapoint to the closest cluster (centroid)
- Evaluate query point *q* only against cluster members of the *m* nearest centroids.



→ Recall / Performance tradeoff

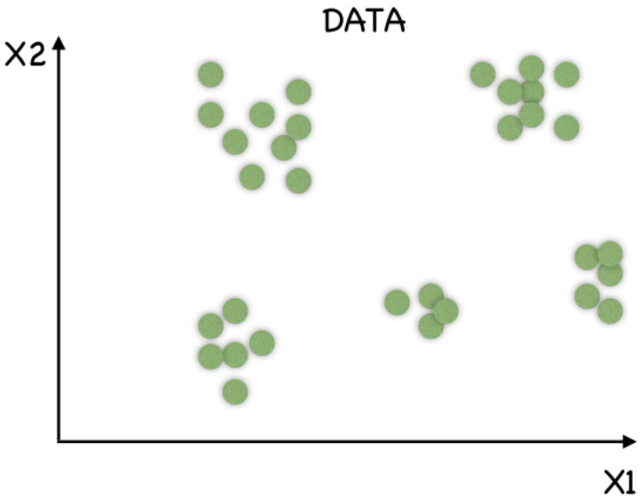
BUT:

- Strongly depends on distribution of data
- Insert requires re-computation of clustering

Vector Search

Approximate Nearest Neighbour search

A bit more conceptually challenging is *HNSW*. But nowadays preferred algorithm due to generally better recall / performance behavior.



[Malkov and Yashunin, 2016]

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Hierarchical navigable small world

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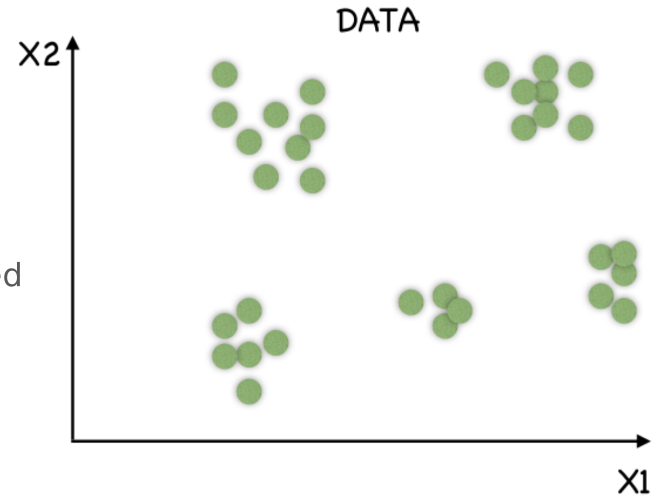

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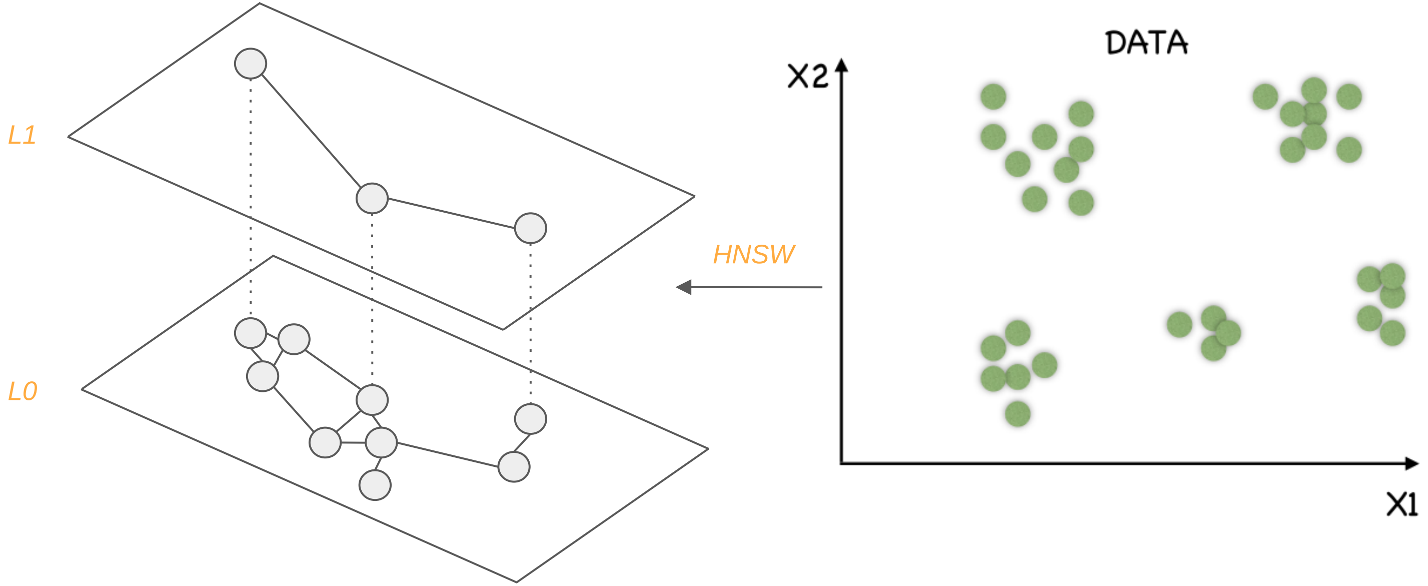

Multi-layered graph
(figure is simplified, usually many more layers)

[Malkov and Yashunin, 2016]

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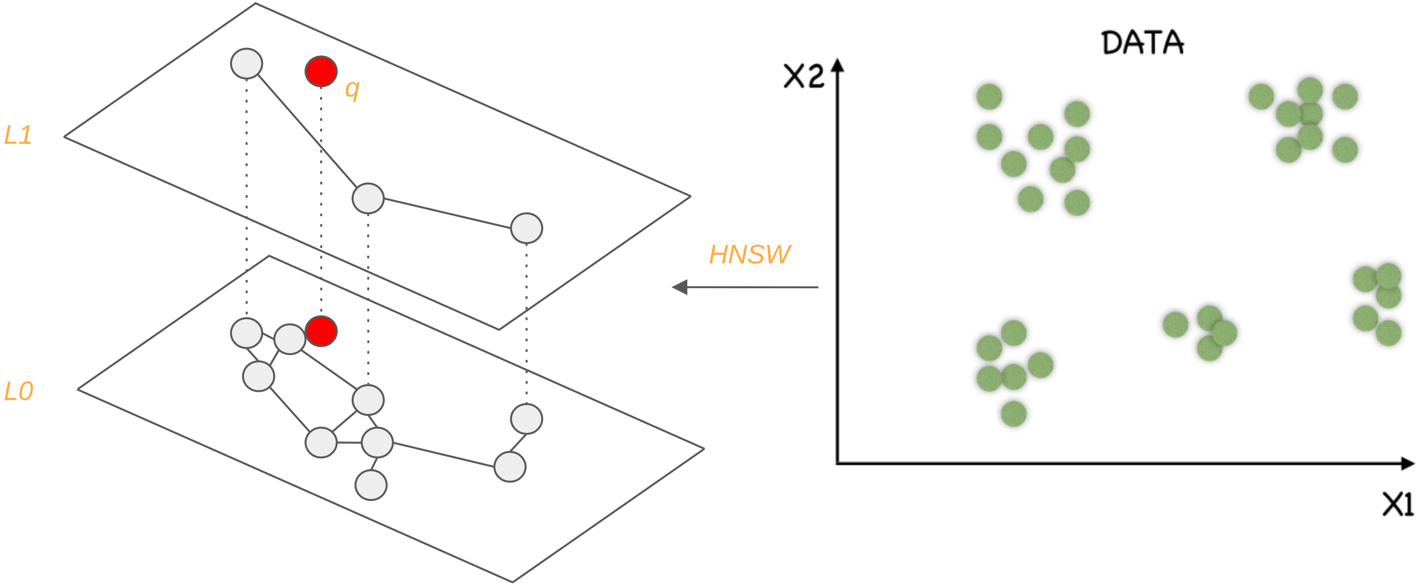

Search via greedy graph traversal

(keeping closest k visited nodes along the way)

[Malkov and Yashunin, 2016]

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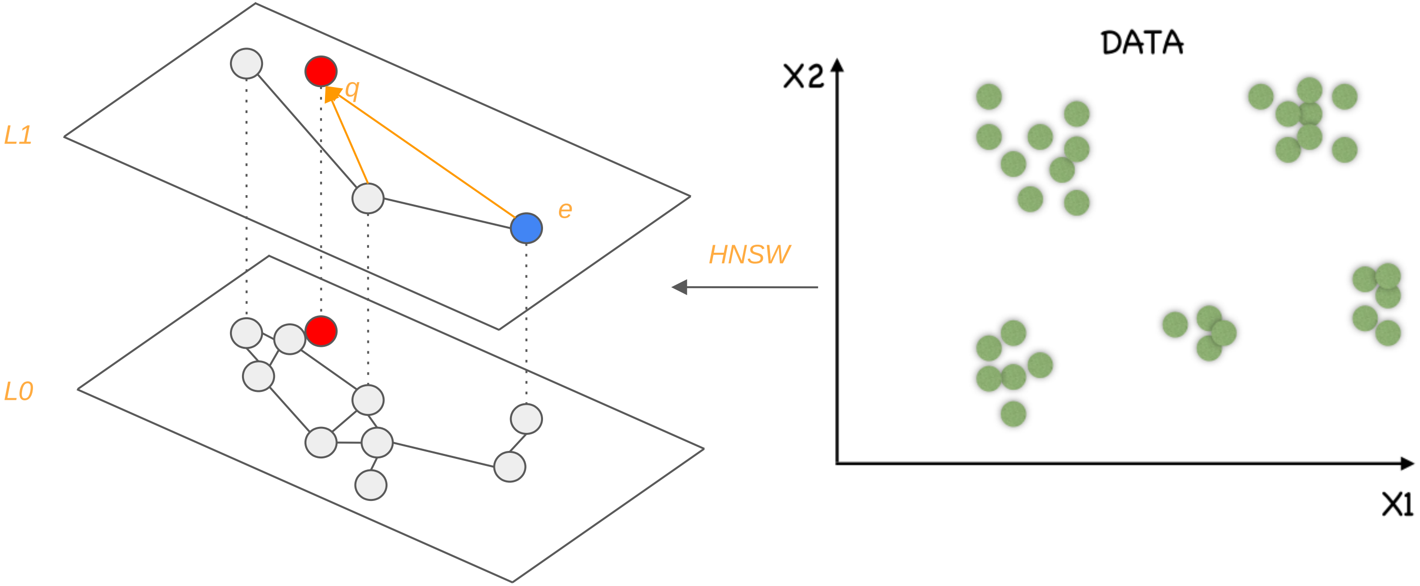

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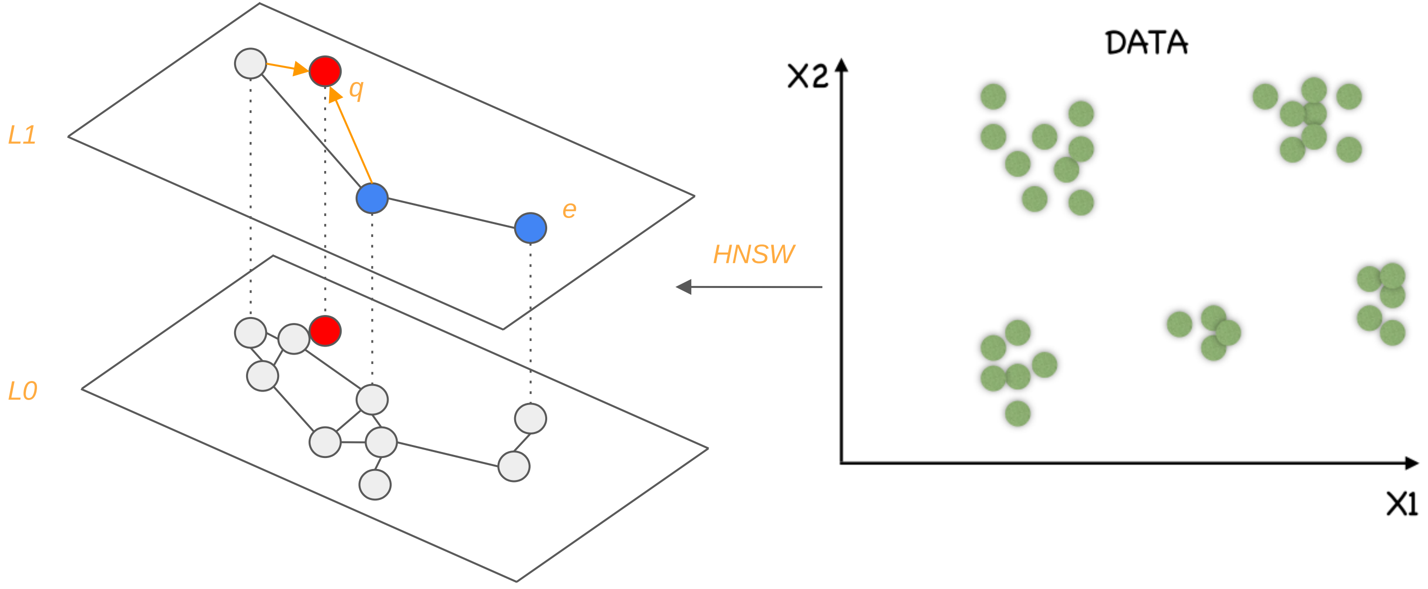

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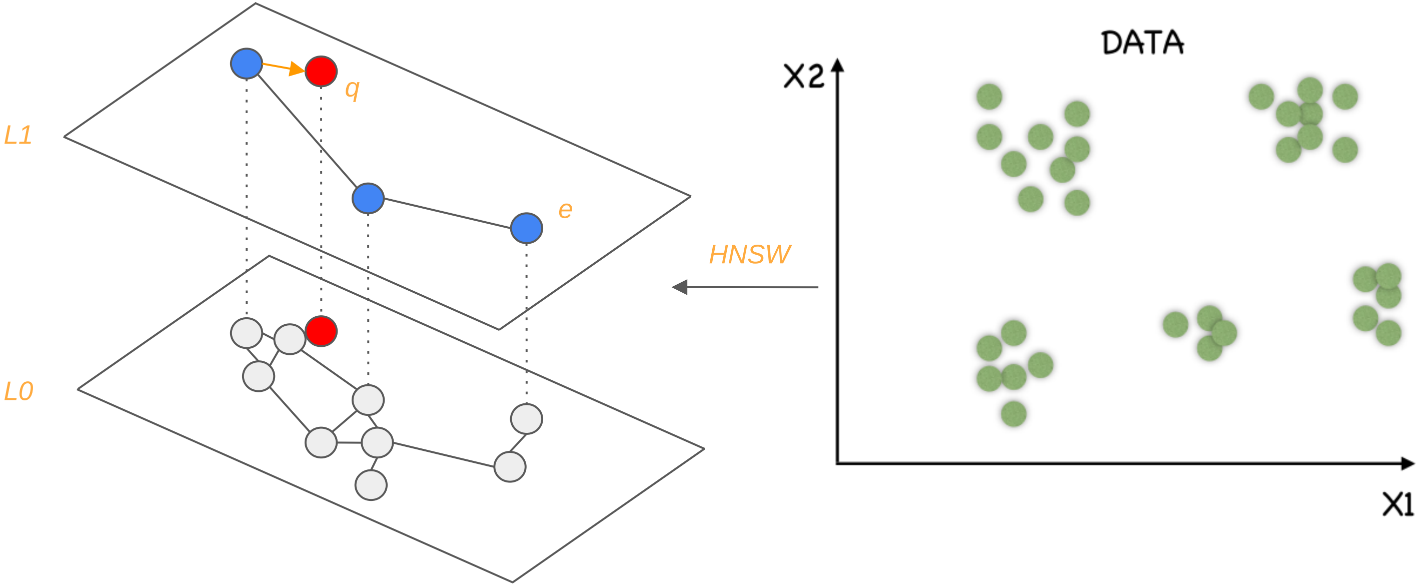

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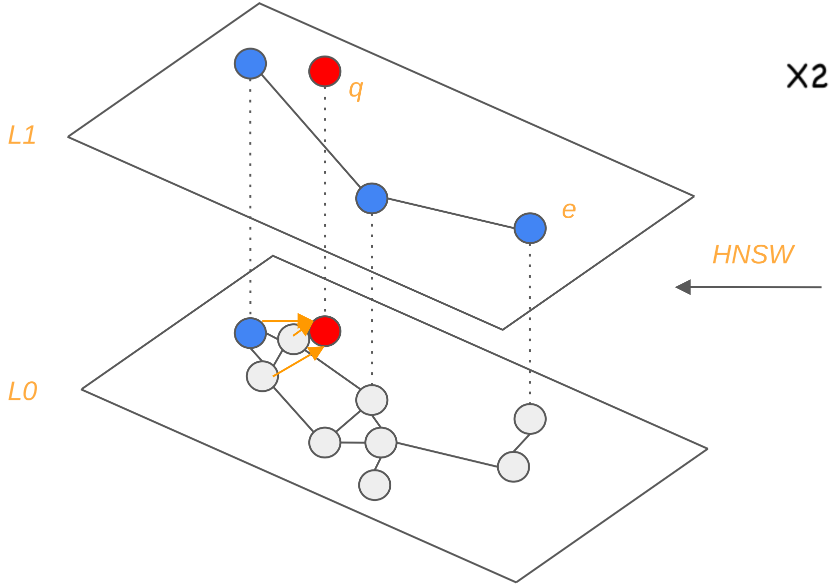

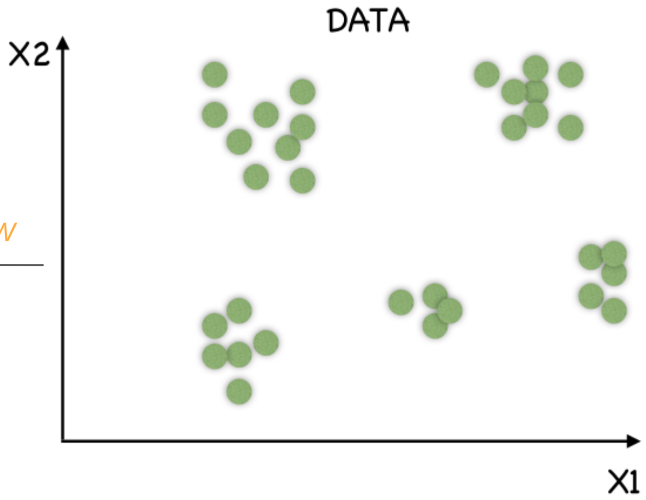

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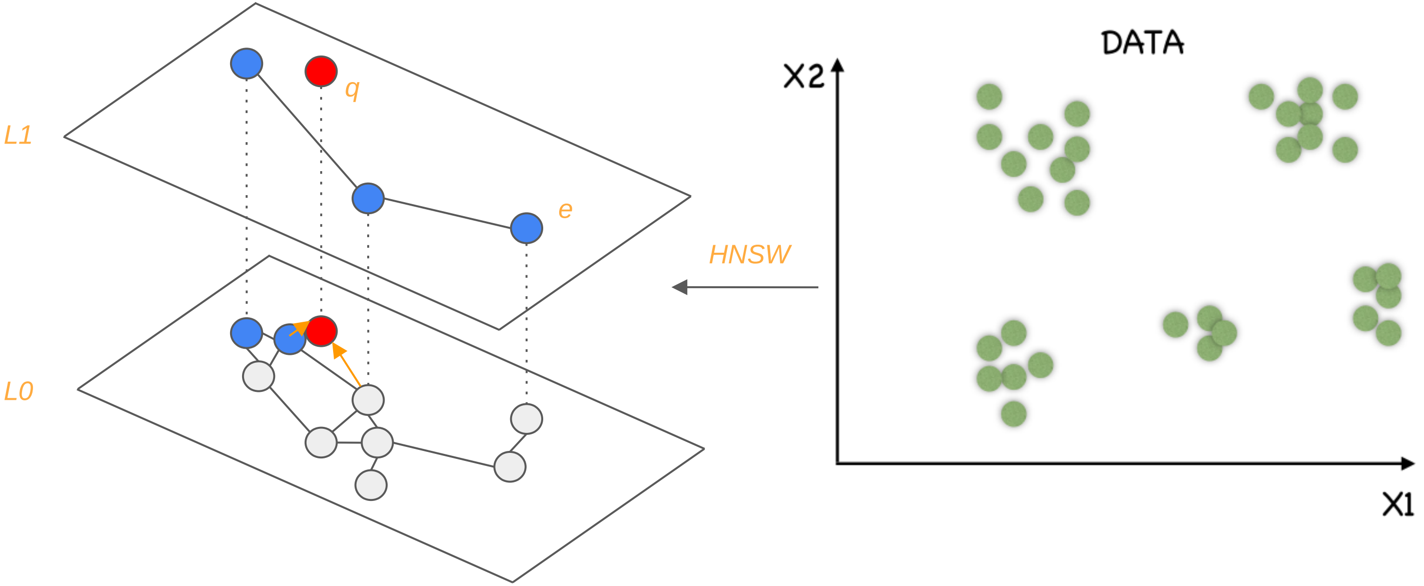

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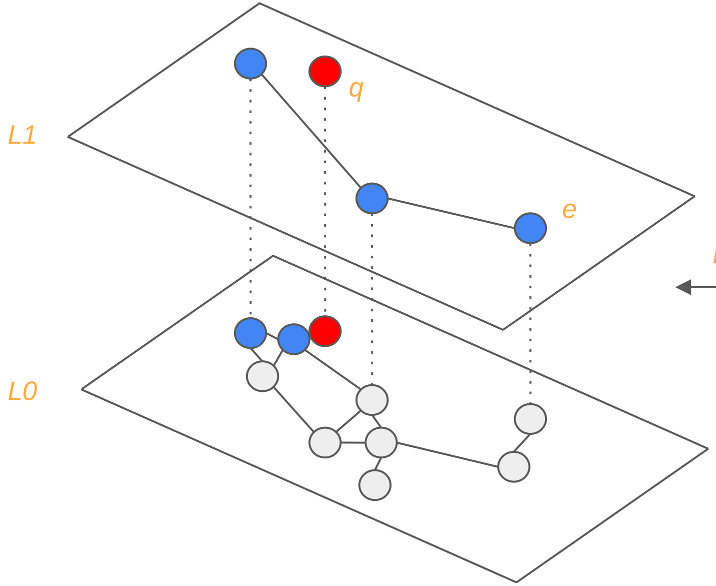

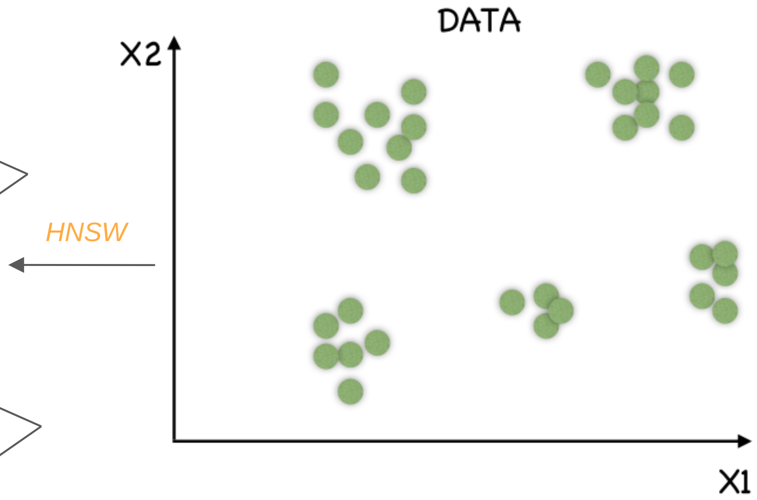

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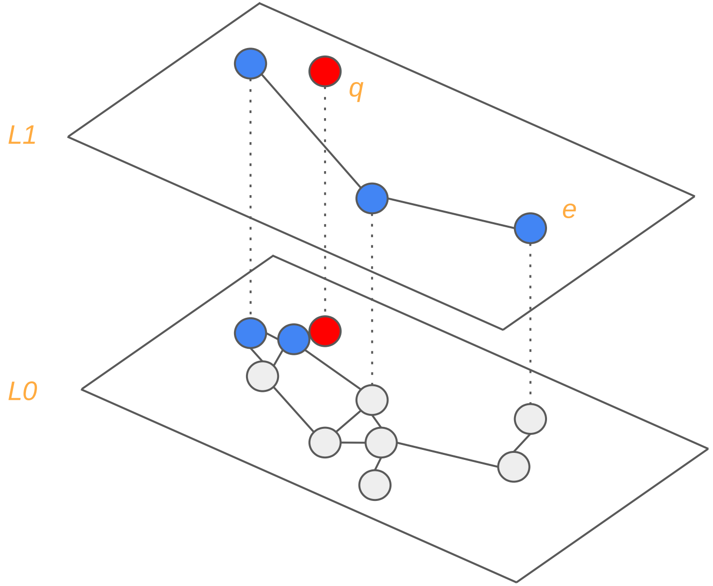

BUT:

- Graph construction can be very compute and memory intensive
- More difficult to parallelize

Search via greedy graph traversal
(keeping closest k visited nodes along the way)

[Malkov and Yashunin, 2016]

Vector Search

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[Postgres implementation](#)

Most well-known and popular: *pgvector*
[https://github.com/pgvector/pgvector]

Introduces new PG type (vector), distance operators acting on vectors, and can build indices for vector columns.

Exact, and *HNSW* or *IVFFLAT* based approximate vector search. Many different metrics, but here we are mainly interested in euclidean distance (*L2*).

Query example:

```
select * from table where embedding <-> '[...]' < 10 order by embedding <-> '[...]' limit 10000
```

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Column of vector type

Metric operator (L2)
acting on vector types

Vector type
for example: ‘[3,0.1,-1.2,5]’

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Query example:

Index on vector column

select * from table where embedding <-> ‘[...]’ < 10 order by embedding <-> ‘[...]’ limit 10000

Reduce number of required distance calculations via “index” / approx vector search.
(Worst case: For all rows)

Vector Search

pgvector

PostgreSQL plan generation (simplified)

FROM

↓

WHERE

↓

ORDER BY

↓

LIMIT

Vector Search

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pgvector

PostgreSQL plan generation (simplified)

FROM ← Sequential or index scan (depending on cost estimate)

↓

WHERE

↓

ORDER BY

↓

LIMIT

Vector Search

pgvector

PostgreSQL plan generation (simplified)

FROM ← Pgvector implements INDEXAM (Index Access Method Interface)

↓

WHERE

↓

ORDER BY

↓

LIMIT

Vector Search

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pgvector

PostgreSQL plan generation (simplified)

FROM

↓

WHERE

↓

ORDER BY

↓

LIMIT

Pgvector implements INDEXAM
(Index Access Method Interface)

Core index functions:

ambuild
aminsert
ambeginscan
amrescan
amendscan
amgettuple
...

Vector Search

[pgvector]

PostgreSQL plan generation (simplified)

FROM

↓

WHERE

↓

ORDER BY

↓

LIMIT

One or both will be pushed down to INDEXAM implementation

More on this later ...

Pgvector implements INDEXAM (Index Access Method Interface)

↓

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PostgreSQL execution
ROW based

Has to return *ItemPointerData* on each call (*xs_heaptid*)

Vector Search

pgvector

PostgreSQL plan generation (simplified)

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Pgvector implements INDEXAM
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Core index functions:

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...

Pointer to an item within a disk page of a known file (block + offset)

PostgreSQL execution
ROW based

Has to return *ItemPointerData* on each call (*xs_heaptid*)

Vector Search

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PostgreSQL plan generation (simplified)

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More on this later ...

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Core index functions:

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...

First call:
Pgvector performs approx vector search.

Subsequent calls:
Found *ItemPointers* are returned.

PostgreSQL execution
ROW based

Vector Search

pgvector

What about performance ?

GIST-960 dataset [http://corpus-texmex.irisa.fr/] [Jégou, Douze and Schmid, 2011]

Details:

- 1M vectors
- 960d
- 1k test vectors
- Pre-computed 100 nearest neighbors

(Vectors given by global GIST descriptors of image dataset. GIST summarizes the gradient information for different parts of an image.)

Vector Search

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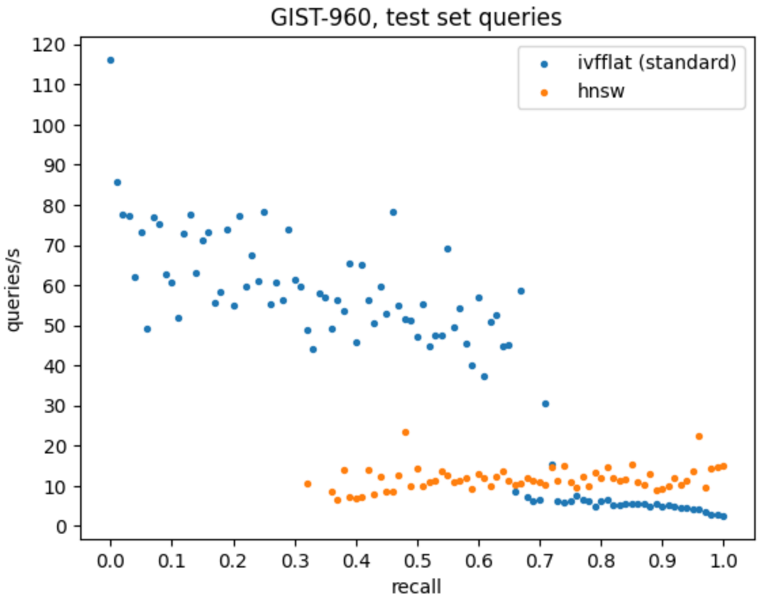
[pgvector]

What about performance ?

GIST-960 dataset

Note:

- Ubuntu on i9-13900H + RTX 4070
- Standard Postgres v15
  (no special compile flags besides -g)
- Pg_vector master on Mar 24, 2025
  (commit 05182479a2a62e04300386b4da18be02fcb819b5)
  (compiled with -O3 -march=native -g)
- Ivfflat 200 clusters; hnsw.ef_search=100
- Queried locally via python+psycopg2
  (on persistent connection)
- Recall computation for ivfflat via taking smallest # probes for fixed recall + median at fixed recall



Query: *select id from gist order by embedding <-> "+q+" limit 100*

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pgvector

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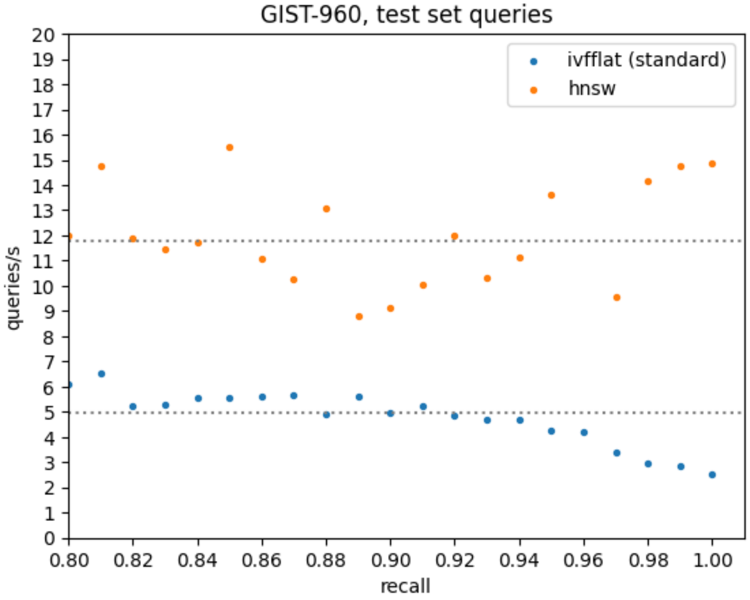

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Vector Search

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[pgvector (ivfflat)]()

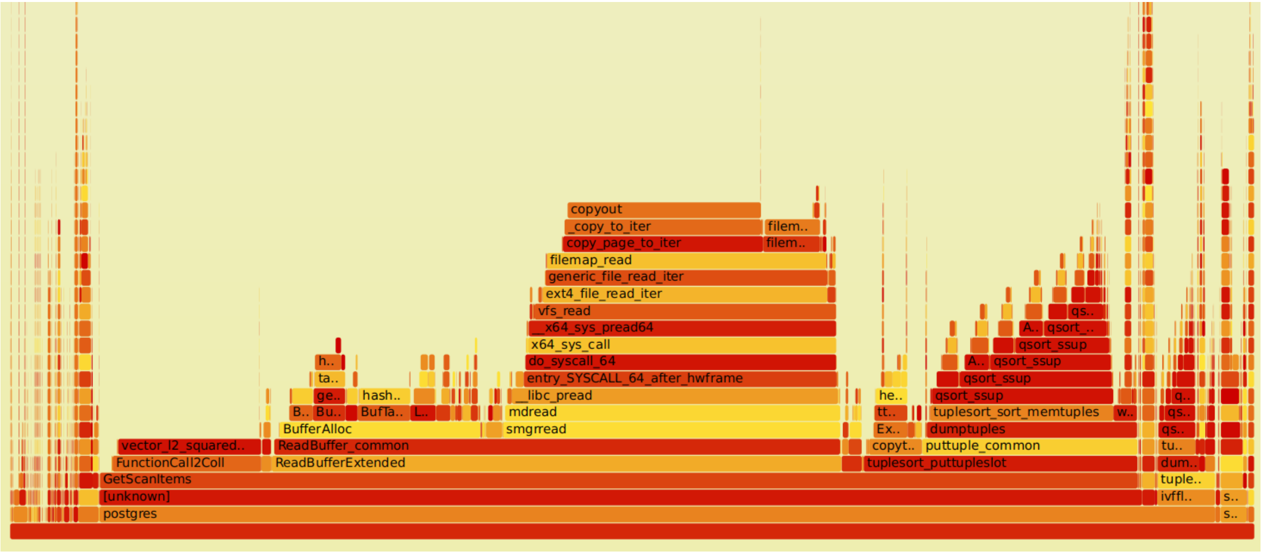
What about performance ?

GIST-960 dataset

Ivfflat perf analysis [https://github.com/brendangregg/FlameGraph]

Time thieves:

- ReadBuffers
- Tuplesort
- L2 distance calc



Vector Search

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[pgvector (ivfflat)]

What about performance ?

Time thieves:

- ReadBuffers
- Tuplesort
- L2 distance calc

License of pgvector, 2025

```c
buf = ReadBufferExtended(scan->indexRelation, MAIN_FORKNUM, searchPage, RBM_NORMAL, so->bas);
LockBuffer(buf, BUFFER_LOCK_SHARE);
page = BufferGetPage(buf);
maxoffno = PageGetMaxOffsetNumber(page);

for (OffsetNumber offno = FirstOffsetNumber; offno <= maxoffno; offno = OffsetNumberNext(offno))
{
    IndexTuple  itup;
    Datum       datum;
    bool        isnull;
    ItemId      itemid = PageGetItemId(page, offno);

    itup = (IndexTuple) PageGetItem(page, itemid);
    datum = index_getattr(itup, 1, tupdesc, &isnull);

    /*
     * Add virtual tuple
     *
     * Use procinfo from the index instead of scan key for
     * performance
     */
    ExecClearTuple(slot);
    slot->tts_values[0] = so->distfunc(so->procinfo, so->collation, datum, value);
    slot->tts_isnull[0] = false;
    slot->tts_values[1] = PointerGetDatum(&itup->t_tid);
    slot->tts_isnull[1] = false;
    ExecStoreVirtualTuple(slot);

    tuplesort_puttupleslot(so->sortstate, slot);
}
```

All points in cluster(s) are read on each call !

pgvector github, ivfscan.c, 2025

... HACKING PGVECTOR ...

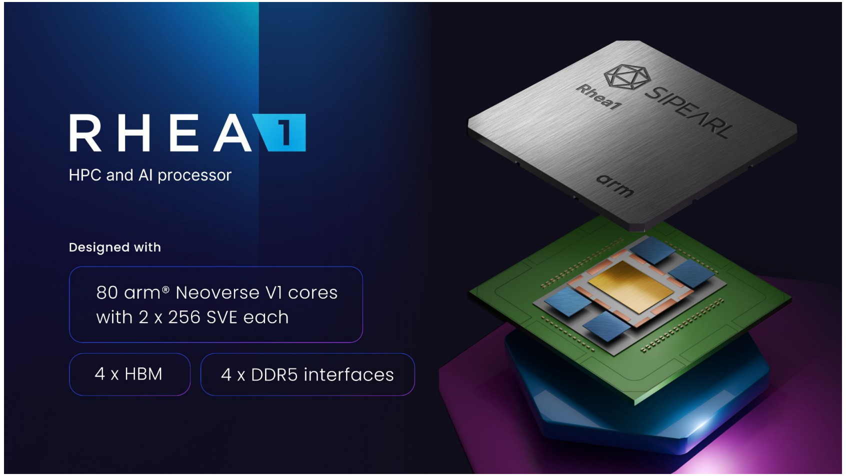
Vector Search

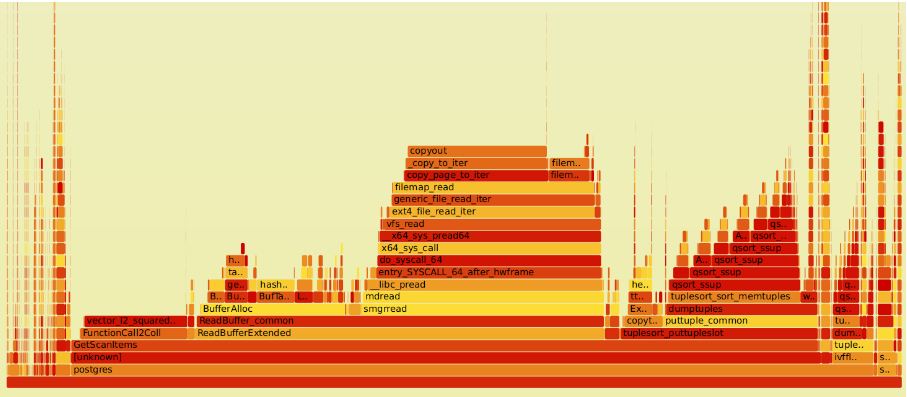
[pgvector hack (ivfflat)]

Can we do better ? [https://github.com/Sednai/pgvector/tree/AERO]

If we have sufficient memory, keep index data persistent (in Non-Postgres mem).

- No Buffers but continuous 2D arrays
- Avoiding TupleSort
- Possibility for better optimization for hardware





sednai

pgvector hack (ivfflat)

Implementation

Own Postgres *background process* with task queue in shared memory.

```
BackgroundWorker worker;
BackgroundWorkerHandle *handle;
BgwHandleStatus status;
pid_t       pid;

memset(&worker, 0, sizeof(worker));
worker.bgw_flags = BGWORKER_SHMEM_ACCESS | BGWORKER_BACKEND_DATABASE_CONNECTION;
worker.bgw_start_time = BgWorkerStart_RecoveryFinished;
worker.bgw_restart_time = BGW_NEVER_RESTART; // Time in s to restart if crash. Use BGW_NEVER_RESTART for no restart;

char* WORKER_LIB = GetConfigOption("ivfflat.lib",true,true);

sprintf(worker.bgw_library_name, WORKER_LIB);
sprintf(worker.bgw_function_name, "pgv_gpuworker_main");

snprintf(worker.bgw_name, BGW_MAXLEN, "%s",buf);

worker.bgw_notify_pid = MyProcPid;

if (!RegisterDynamicBackgroundWorker(&worker, &handle))
    elog(ERROR,"Could not register background worker");

status = WaitForBackgroundWorkerStartup(handle, &pid);
```

Vector Search

sednai

[pgvector hack (ivfflat)]

Implementation

Own Postgres *background process* with task queue in shared memory.

Re-routing the index tuple scan as task to background worker during scan:

```
/*
 * Fetch the next tuple in the given scan
 */
bool
ivfflatgettuple(IndexScanDesc scan, ScanDirection dir)
```

own process

```
/*
    Exec task
*/
dlist_node* dnode = dlist_pop_head_node(&worker_head->exec_list);
worker_exec_entry* entry = dlist_container(worker_exec_entry, node, dnode);

SpinLockRelease(&worker_head->lock);

load_index(entry->nodeid, entry->tupdesc, entry->usetriangle);

// Compute
if(!entry->usegpu) {
    entry->returns = exec_query_cpu(entry, worker_head);
}
else
```

Vector Search

sednai

[pgvector hack (ivfflat)]

Implementation

For an indexed table, we store the index vectors and corresponding location info (*ItemPointerData*) as raw native arrays in Non-Postgres memory.

(The data will be persistent over the lifetime of the background process. We have not implemented active memory management yet. Background process will crash if you run out of memory !)

```
/*
 * Fetch the next tuple in the given scan
 */
bool
ivfflatgettuple(IndexScanDesc scan, ScanDirection dir)
```

own process

```
/*
    Exec task
*/
dlist_node* dnode = dlist_pop_head_node(&worker_head->exec_list);
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// Compute
if(!entry->usegpu) {
    entry->returns = exec_query_cpu(entry, worker_head);
}
else
```

C++

Vector Search

pgvector hack (ivfflat)

Implementation

For a query point (vector), we compute its *distance* against all index vectors and distance *sort*. Location infos are returned to the user process.
(More precisely, the corresponding page number and ItemPointerData are returned.)

```
/*
 * Fetch the next tuple in the given scan
 */
bool
ivfflatgettuple(IndexScanDesc scan, ScanDirection dir)
```

own process

```
/*
    Exec task
*/
dlist_node* dnode = dlist_pop_head_node(&worker_head->exec_list);
worker_exec_entry* entry = dlist_container(worker_exec_entry, node, dnode);

SpinLockRelease(&worker_head->lock);

load_index(entry->nodeid, entry->tupdesc, entry->usetriangle);

// Compute
if(!entry->usegpu) {
    entry->returns = exec_query_cpu(entry, worker_head);
}
else
```

C++

Vector Search

sednai

[pgvector hack (ivfflat)]

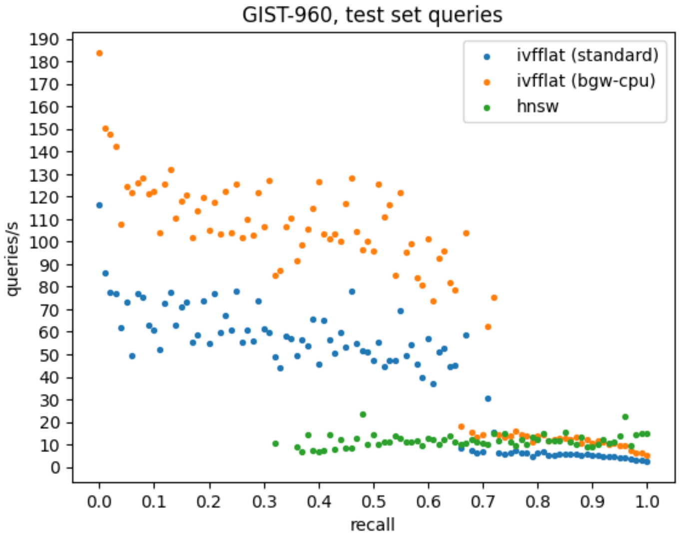
What about performance ?

GIST-960 dataset

Note for ivfflat (bgw cpu):

- No special tricks
- No parallelisation
- No manual vector instructions
- No HBM memory

Query: *select id from gist order by embedding <-> "+q+" limit 100*



Vector Search

sednai

[pgvector hack (ivfflat)]

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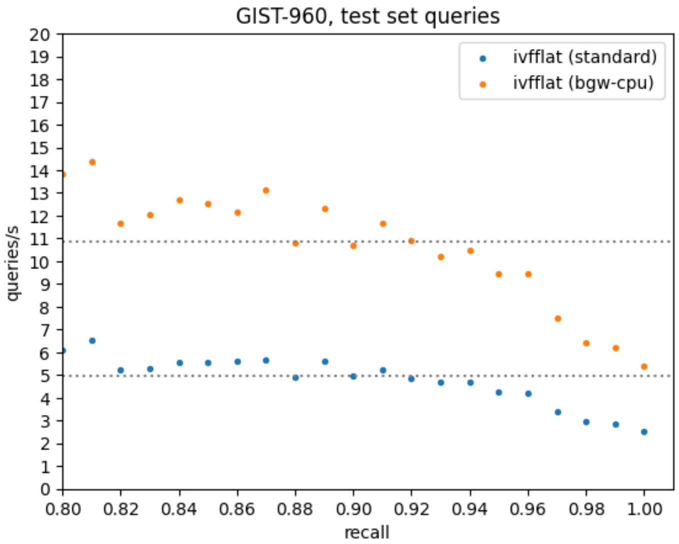

Vector Search

sednai

pgvector hack (ivfflat)

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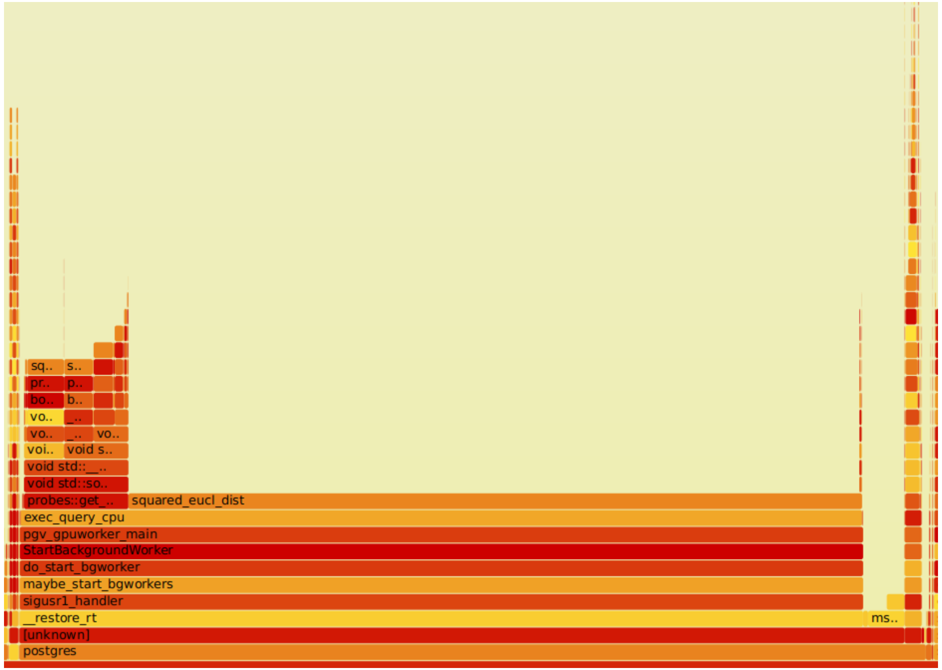

Vector Search

sednai

[pgvector hack (ivfflat)]

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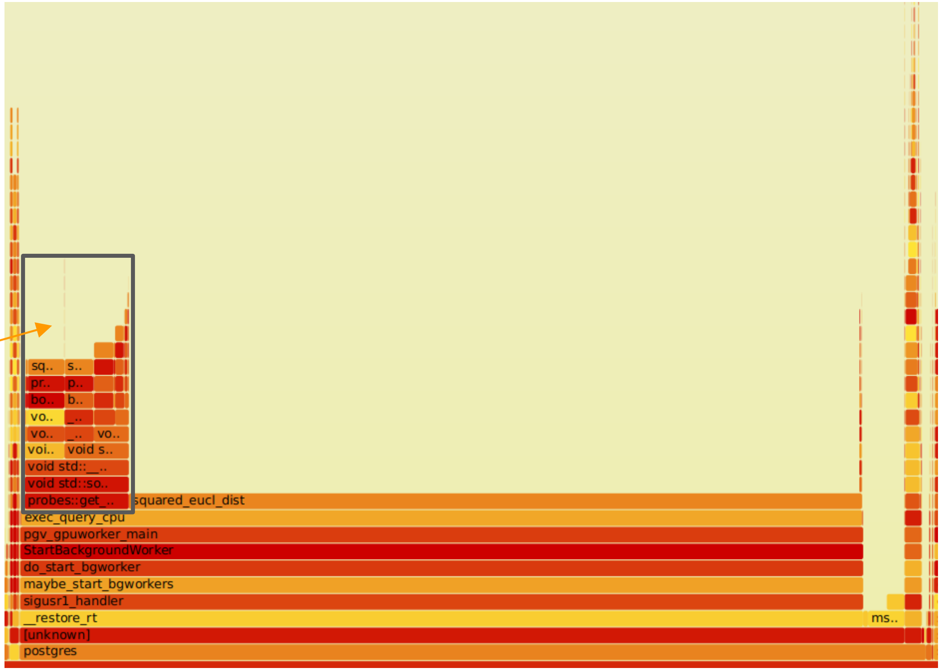

Homework exercise:

Maybe can be optimized ...

Vector Search

[pgvector hack (ivfflat)]

Can we do better ?

Since we have already a setup to keep index persistent in Non-Postgres memory, we can easily go one step further and offload the index and compute to a GPU !

→ Compute of *distances* and *sort* on device.
Return only sorted index ids from device
(Mapping to location info on CPU)

Vector Search

pgvector hack (ivfflat)

Can we do better ?

Since we have already a setup to keep index persistent in Non-Postgres memory, we can easily go one step further and offload the index and compute to a GPU !

→ Compute of *distances* and *sort* on device
Return only sorted index ids from device
(Mapping to location info on CPU)

Recall: We have 6x A100 GPUs in our distributed Postgres database

→ 480 GB in additional memory !

For FP32 vectors of dim 100 that is enough to keep > 1B index points persistent

sednai

... GPU ACCELERATED VECTOR SEARCH ...

sednai

pgvector hack (ivfflat)

Implementation

For an indexed table, we store now the index vectors on a GPU device.
(The data will be persistent over the lifetime of the background process. We have not implemented active memory management yet. Background process will crash if you run out of memory !)

```
/*
 * Fetch the next tuple in the given scan
 */
bool
ivfflatgettuple(IndexScanDesc scan, ScanDirection dir)
```

own process

```
/*
    Exec task
*/
dlist_node* dnode = dlist_pop_head_node(&worker_head->exec_list);
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SpinLockRelease(&worker_head->lock);

load_index(entry->nodeid, entry->tupdesc, entry->usetriangle);

// Compute
if(!entry->usegpu) {
    entry->returns = exec_query_cpu(entry, worker_head);
}
else
```

C++ / CUDA
(essentially one big cudaMemcpy)

Vector Search

sednai

pgvector hack (ivfflat)

Implementation

For a query point (vector), we compute its *distance* against all index vectors and distance *sort* on device. Only ordered index ids are returned from GPU to CPU process.

```
/*
 * Fetch the next tuple in the given scan
 */
bool
ivfflatgettuple(IndexScanDesc scan, ScanDirection dir)
```

own process

```
        load_index(entry->nodeid, entry->tupdesc, entry->usetriangle);

        // Compute
        if(!entry->usegpu) {
            entry->returns = exec_query_cpu(entry, worker_head);
        }
        else
#ifdef GPU
            entry->returns = exec_query_gpu(entry, worker_head);
#else
            entry->returns = exec_query_cpu(entry, worker_head);
#endif
```

C++ / CUDA
(custom kernels)

Vector Search

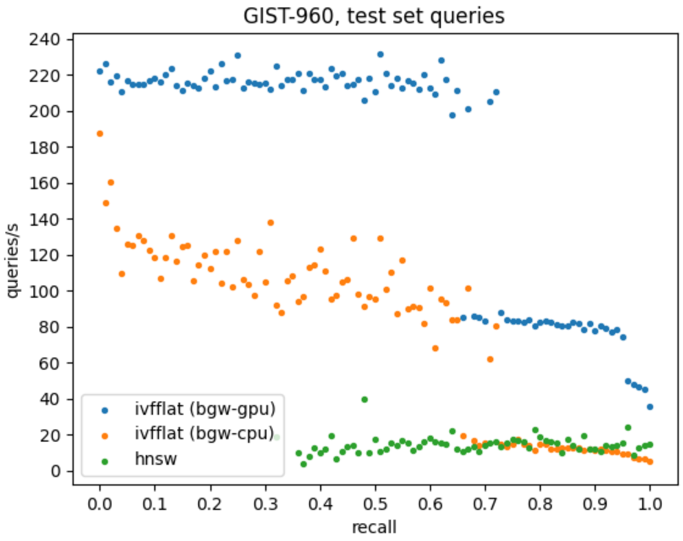
sednai

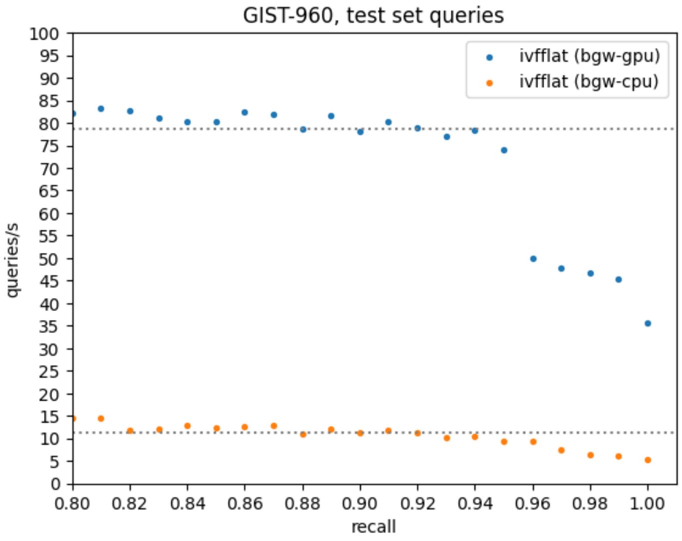
[pgvector hack (ivfflat)]

What about performance ?

GIST-960 dataset

Query: *select id from gist order by embedding <-> "+q+" limit 100*





oneAPI

Aero aims to complement the efforts of the *EU Processor Initiative (EPI)* project by developing the open-source software ecosystem required to not only improve the efficiency of the EPI hardware but also accelerate and ease the processor’s integration into the cloud.

Heterogeneous hardware

PROBLEM: Divers set of accelerators from different vendors (NVIDIA, AMD, INTEL,...)

oneAPI

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Heterogeneous hardware

Open, cross-industry, standards-based, unified, multi-architecture, multi-vendor programming model, adopted by Intel.

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Heterogeneous hardware

Open, cross-industry, standards-based, unified, multi-architecture, multi-vendor programming model, adopted by Intel.

Intel oneAPI base toolkit plugins for NVIDIA and AMD

Vector Search

sednai

[pgvector hack (ivfflat)]

Implementation

For a query point (vector), we compute its *distance* against all index vectors and distance *sort* on device. Only ordered index ids are returned from GPU to CPU process.

```
/*
 * Fetch the next tuple in the given scan
 */
bool
ivfflatgettuple(IndexScanDesc scan, ScanDirection dir)
```

own process

```
        load_index(entry->nodeid, entry->tupdesc, entry->usetriangle);

        // Compute
        if(!entry->usegpu) {
            entry->returns = exec_query_cpu(entry, worker_head);
        }
        else
#ifdef GPU
            entry->returns = exec_query_gpu(entry, worker_head);
#else
            entry->returns = exec_query_cpu(entry, worker_head);
#endif
```

C++ / oneAPI
(custom kernels)

Vector Search

[pgvector hack (ivfflat)]

Implementation

For a query point (vector), we compute its *distance* against all index vectors and distance *sort* on device. Only ordered index ids are returned from GPU to CPU process.

```
void calc_squared_euclidean_distances(float* M, float* V, sort_item* C, int* p, int N, int L, int probe) {

    Q->parallel_for(range<1>(N),
    [=](id<1> k){
        int pos = *p;

        float tmp = 0;
        for(int i = 0; i < L; i++) {
            tmp += (M[L*k+i] - V[i])*(M[L*k+i] - V[i]);
        }

        C[pos+k].distance = tmp;
        C[pos+k].probe = probe;
        C[pos+k].pos = k;

    });

    Q->wait();
}
```

Vector Search

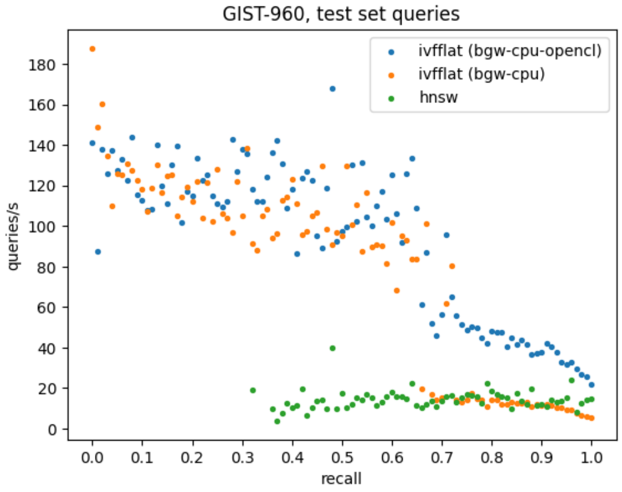
[**pgvector hack (ivfflat)**]

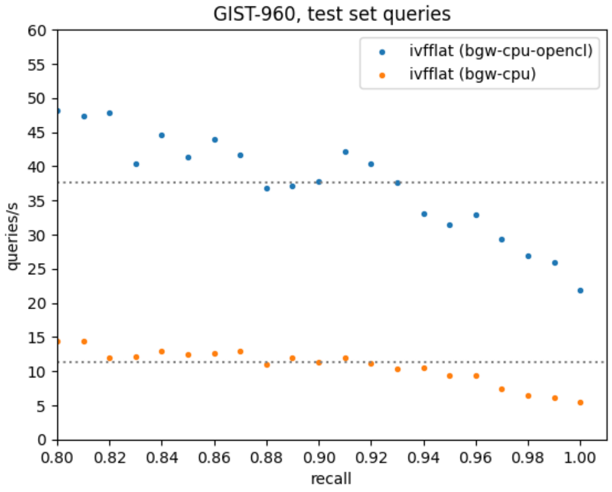
What about performance ?

GIST-960 dataset

Query: *select id from gist order by embedding <-> "+q+" limit 100*

With OpenCL CPU oneAPI backend





sednai

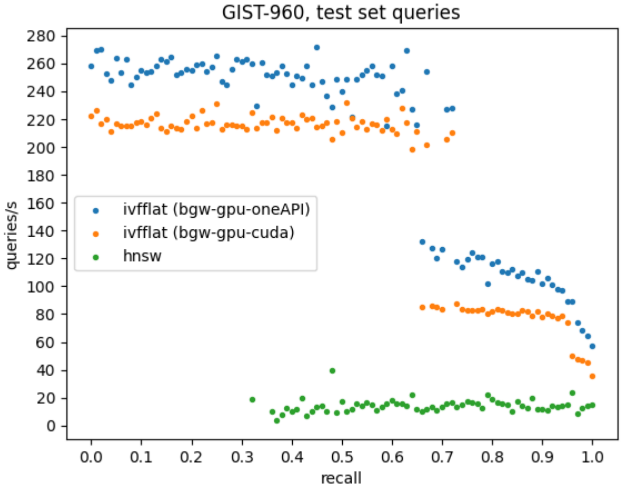
[pgvector hack (ivfflat)]

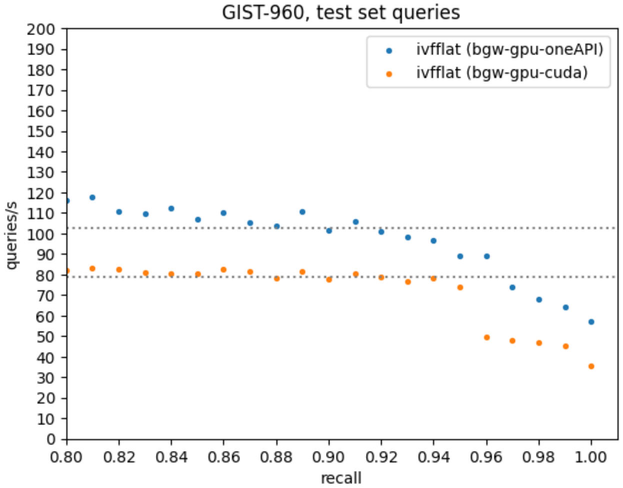
What about performance ?

GIST-960 dataset

Query: *select id from gist order by embedding <-> "+q+" limit 100*

With Nvidia GPU oneAPI backend





Vector Search

sednai

[pgvector hack (ivfflat)]

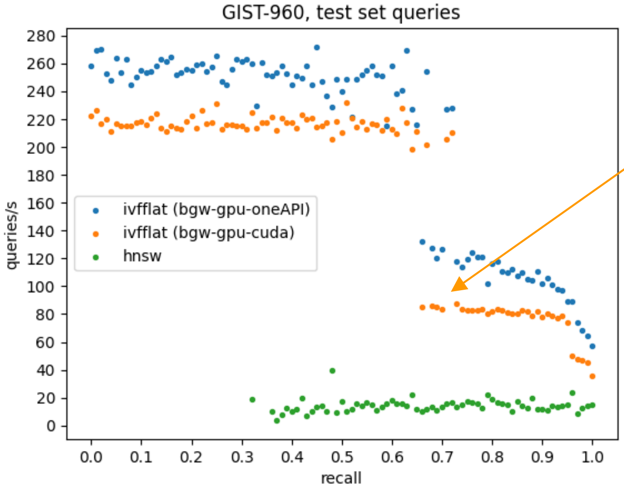
What about performance ?

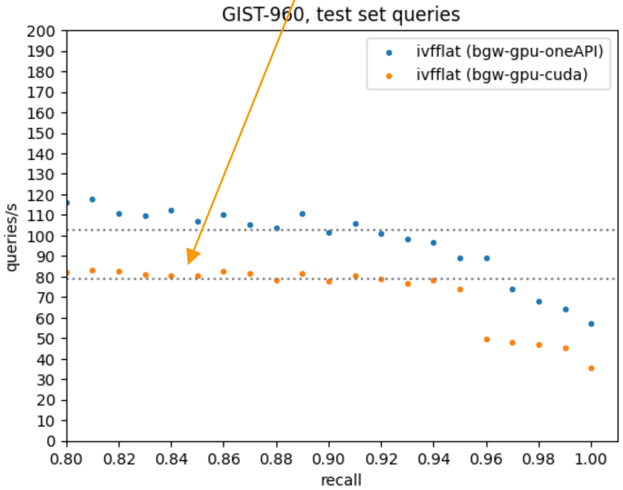
GIST-960 dataset

Query: *select id from gist order by embedding <-> "+q+" limit 100*

Seems my CUDA kernels could be improved ...

With Nvidia GPU oneAPI backend





Vector Search

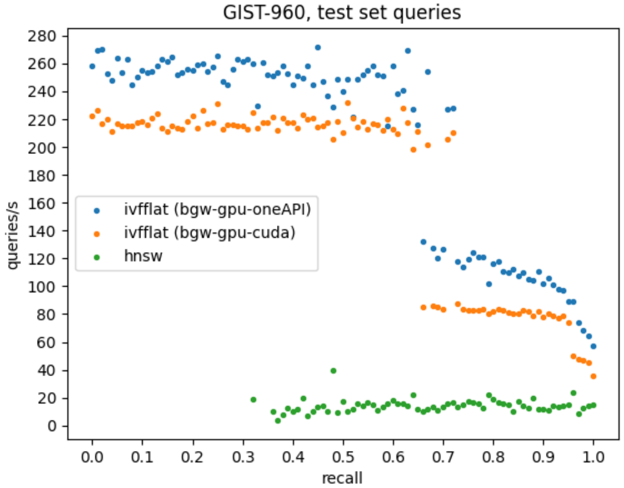
[pgvector hack (ivfflat)]

What about performance ?

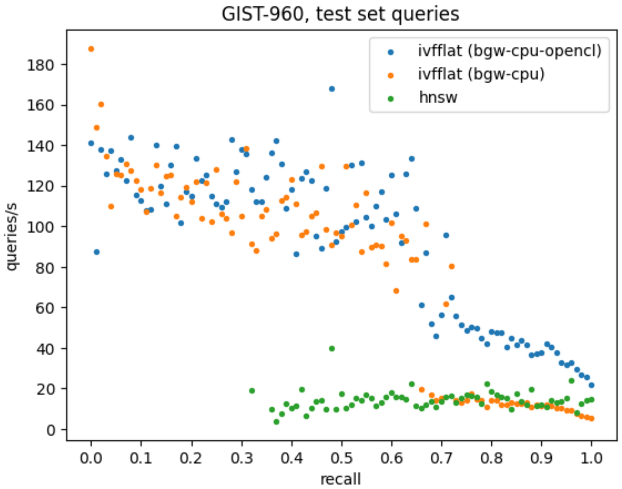
GIST-960 dataset

Query: *select id from gist order by embedding <-> "+q+" limit 100*

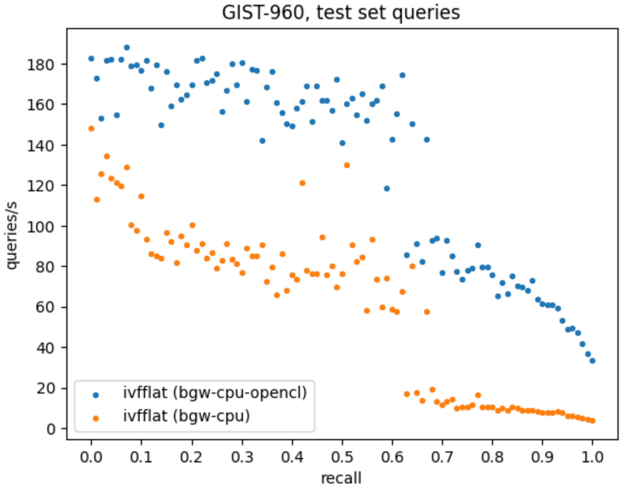
Laptop GPU



Laptop CPU



AMD EPYC CPU [64 threads]



... A SPECIAL CASE ...

Vector Search

pgvector

What we want:

Fast way to retrieve (most) points up to a max distance from a query point.

Vector Search

sednai

pgvector

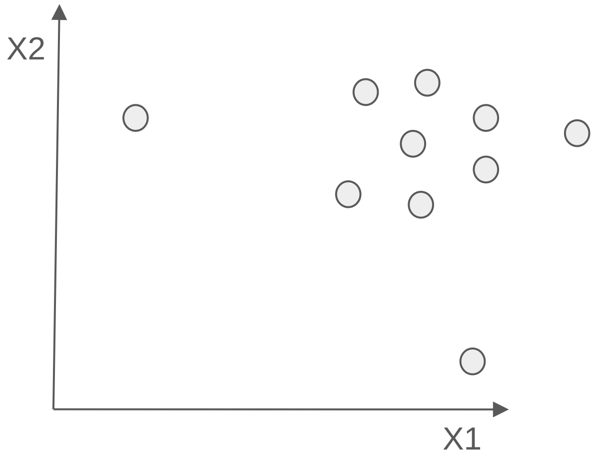
What we want:

Fast way to retrieve (most) points up to a max distance from a query point.

Why ?

Core ingredient to density based clustering algorithms.

Simplified:



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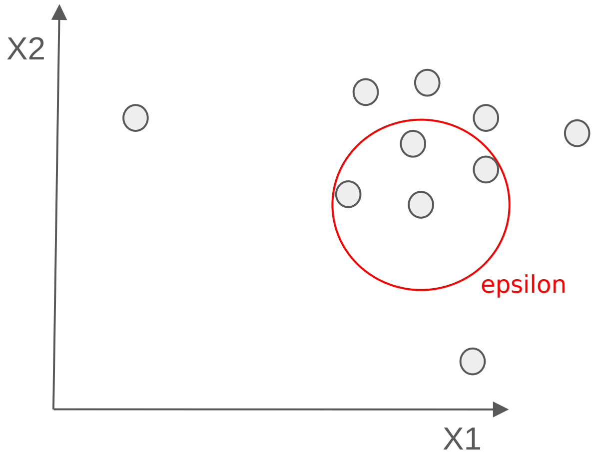

Vector Search

[pgvector]

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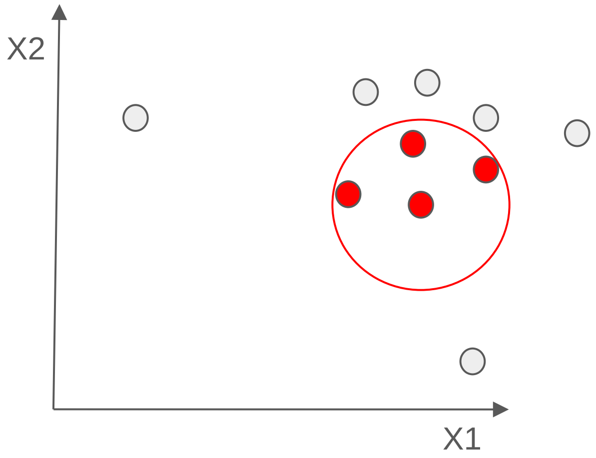

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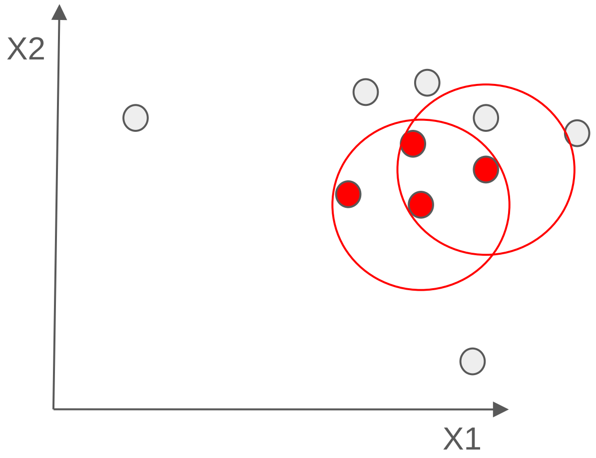

Vector Search

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[**pgvector**]

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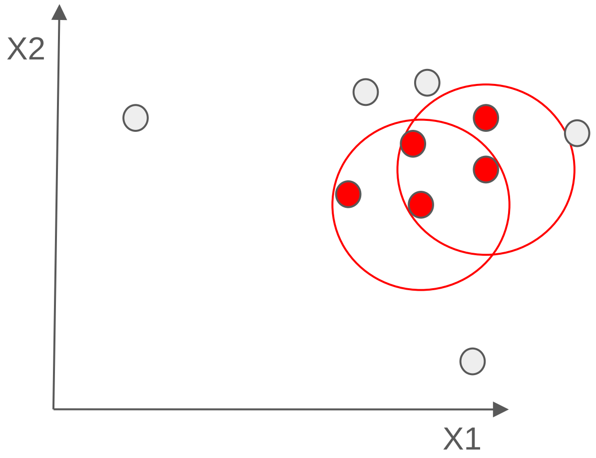

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[pgvector]

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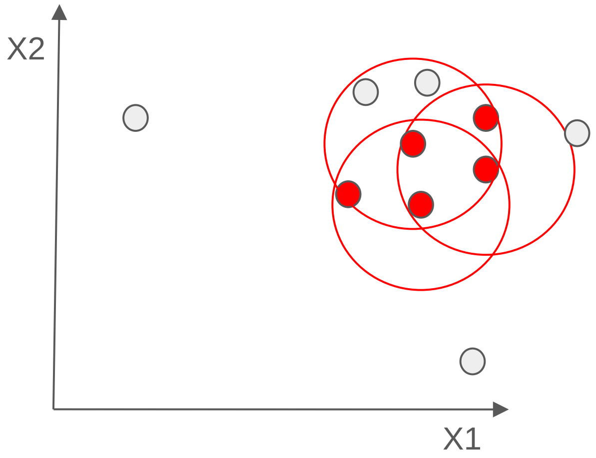

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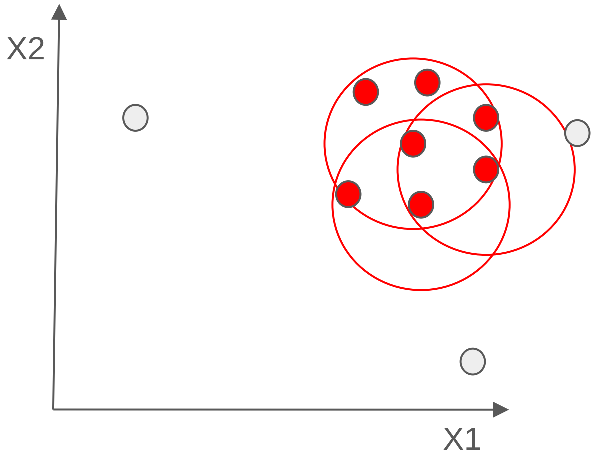

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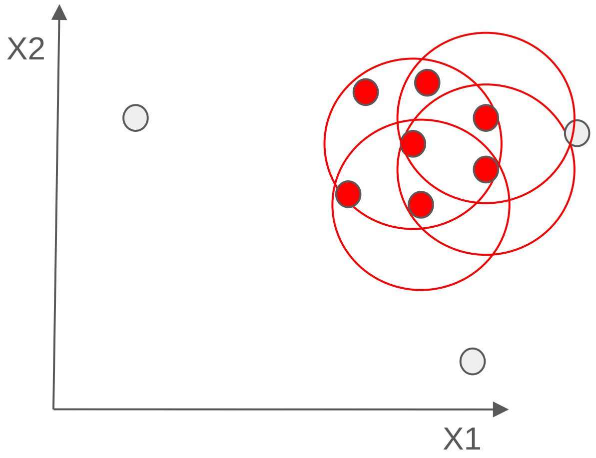

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[pgvector]

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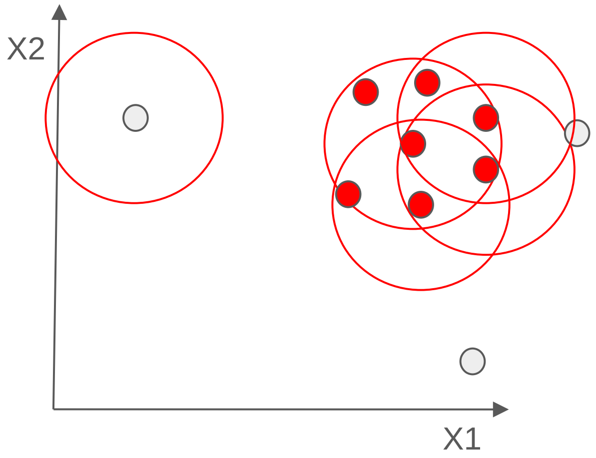

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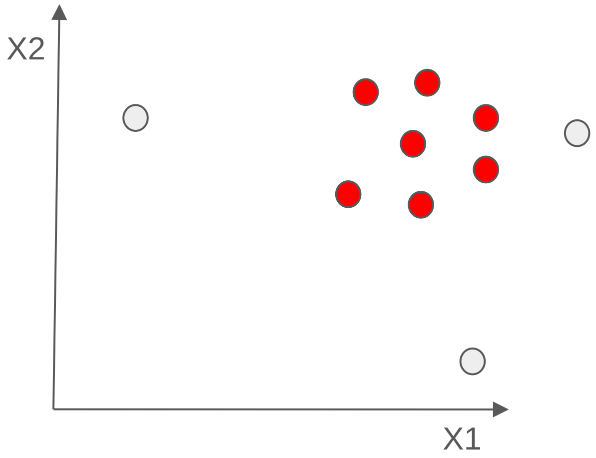

Vector Search

[pgvector]

What we want:

Fast way to retrieve (most) points up to a max distance from a query point.

Get rows within a certain distance

```
SELECT * FROM items WHERE embedding <-> '[3,1,2]' < 5;
```

Note: Combine with `ORDER BY` and `LIMIT` to use an index

(From pgvector github README.md, 2025)

Vector Search

sednai

pgvector

What we want:

Fast way to retrieve (most) points up to a max distance from a query point.

Get rows within a certain distance

Operator for L2 distance

```
SELECT * FROM items WHERE embedding <-> '[3,1,2]' < 5;
```

Note: Combine with `ORDER BY` and `LIMIT` to use an index

(From pgvector github README.md, 2025)

Need quite large limit !

Vector Search

sednai

pgvector

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```

Note: Combine with `ORDER BY` and `LIMIT` to use an index

(From pgvector github README.md, 2025)

Need quite large limit !

PROBLEM: Very very slow ...

Vector Search

sednai

[pgvector]

Why ?

Let us look with GDB what actually happens for a query of type

*select * from table where embedding <-> '[...]' < 10 order by embedding <-> '[...]' limit 10000*

by setting a breakpoint at ivfscan.c:ivfflatgettuple :

```
(gdb) break ivfscan.c:353
Breakpoint 1 at 0x7c106d843e7b: file src/ivfscan.c, line 358.
(gdb) c
Continuing.

Breakpoint 1, ivfflatgettuple (scan=0x60700e9406f8, dir=ForwardScanDirection) at src/ivfscan.c:360
360             if (so->first)
(gdb) p* scan
$1 = {heapRelation = 0x7c106d7925e8, indexRelation = 0x7c106d796818, xs_snapshot = 0x60700e8a8a68, numberOfKeys = 0, numberOfOrderBys = 1, keyData = 0x0,
  orderByData = 0x60700e940808, xs_want_itup = false, xs_temp_snap = false, kill_prior_tuple = false, ignore_killed_tuples = true, xactStartedInRecovery = false,
  opaque = 0x60700e940898, xs_itup = 0x0, xs_itupdesc = 0x0, xs_hitup = 0x0, xs_hitupdesc = 0x0, xs_heaptid = {ip_blkid = {bi_hi = 0, bi_lo = 8680}, ip_posid = 4},
  xs_heap_continue = false, xs_heapfetch = 0x60700e9409a8, xs_recheck = false, xs_orderbyvals = 0x0, xs_orderbynulls = 0x0, xs_recheckorderby = false,
  parallel_scan = 0x0}
(gdb) 
```

Vector Search

sednai

[pgvector]

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Let us look with GDB what actually happens for a query of type

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(gdb) p* scan
$1 = {heapRelation = 0x7c106d7925e8, indexRelation = 0x7c106d796818, xs_snapshot = 0x60700e8a8a68, numberOfKeys = 0, numberOfOrderBys = 1, keyData = 0x0,
  orderByData = 0x60700e940808, xs_want_itup = false, xs_temp_snap = false, kill_prior_tuple = false, ignore_killed_tuples = true, xactStartedInRecovery = false,
  opaque = 0x60700e940898, xs_itup = 0x0, xs_itupdesc = 0x0, xs_hitup = 0x0, xs_hitupdesc = 0x0, xs_heaptid = {ip_blkid = {bi_hi = 0, bi_lo = 8680}, ip_posid = 4},
  xs_heap_continue = false, xs_heapfetch = 0x60700e9409a8, xs_recheck = false, xs_orderbyvals = 0x0, xs_orderbynulls = 0x0, xs_recheckorderby = false,
  parallel_scan = 0x0}
(gdb)
```

IndexScanDesc

No scan keys are pushed down !

Vector Search

sednai

pgvector

ExecInitBuildScanKeys: quals are Null

Why no scan keys ?

iss_NumScanKeys = 0 already in IndexScanState

We have to dig deeper …

```
(gdb) bt
#0  ivfflatgettuple (scan=0x60700e9406f8, dir=ForwardScanDirection) at src/ivfscan.c:360
#1  0x000060700c44b319 in index_getnext_tid (scan=0x60700e9406f8, direction=ForwardScanDirection) at indexam.c:575
#2  0x000060700c44b529 in index_getnext_slot (scan=0x60700e9406f8, direction=ForwardScanDirection, slot=0x60700e9586d0) at indexam.c:667
#3  0x000060700c6b234d in IndexNextWithReorder (node=0x60700e958430) at nodeIndexscan.c:264
#4  0x000060700c68ad18 in ExecScanFetch (node=0x60700e958430, accessMtd=0x60700c6b2158 <IndexNextWithReorder>, recheckMtd=0x60700c6b2675 <IndexRecheck>)
    at execScan.c:132
#5  0x000060700c68adbd in ExecScan (node=0x60700e958430, accessMtd=0x60700c6b2158 <IndexNextWithReorder>, recheckMtd=0x60700c6b2675 <IndexRecheck>) at execScan.c:198
#6  0x000060700c6b2b73 in ExecIndexScan (pstate=0x60700e958430) at nodeIndexscan.c:533
#7  0x000060700c686cce in ExecProcNodeFirst (node=0x60700e958430) at execProcnode.c:464
#8  0x000060700c6b5207 in ExecProcNode (node=0x60700e958430) at ../../../src/include/executor/executor.h:262
#9  0x000060700c6b53f7 in ExecLimit (pstate=0x60700e958140) at nodeLimit.c:96
#10 0x000060700c686cce in ExecProcNodeFirst (node=0x60700e958140) at execProcnode.c:464
#11 0x000060700c67b20a in ExecProcNode (node=0x60700e958140) at ../../../src/include/executor/executor.h:262
#12 0x000060700c67dac5 in ExecutePlan (queryDesc=0x60700e965c68, operation=CMD_SELECT, sendTuples=true, numberTuples=0, direction=ForwardScanDirection,
    dest=0x60700e9531e0) at execMain.c:1640
#13 0x000060700c67b71c in standard_ExecutorRun (queryDesc=0x60700e965c68, direction=ForwardScanDirection, count=0, execute_once=false) at execMain.c:362
#14 0x000060700c67b621 in ExecutorRun (queryDesc=0x60700e965c68, direction=ForwardScanDirection, count=0, execute_once=false) at execMain.c:311
#15 0x000060700c8b9b66 in PortalRunSelect (portal=0x60700e8f4328, forward=true, count=0, dest=0x60700e9531e0) at pquery.c:922
#16 0x000060700c8b97d1 in PortalRun (portal=0x60700e8f4328, count=9223372036854775807, isTopLevel=true, run_once=true, dest=0x60700e9531e0, altdest=0x60700e9531e0,
```

=> Already before execution level no scan keys !

Vector Search

sednai

pgvector

Why no scan keys ?

We have to dig deeper …

Let us look into indxpath.c:

```
/*-------------------------------------------------------------------------
 *
 * indxpath.c
 *    Routines to determine which indexes are usable for scanning a
 *    given relation, and create Paths accordingly.
 *
 * Portions Copyright (c) 1996-2022, PostgreSQL Global Development Group
 * Portions Copyright (c) 1994, Regents of the University of California
 *
 *
 * IDENTIFICATION
 *    src/backend/optimizer/path/indxpath.c
 *
```

```
/*
 * match_clause_to_indexcol()
 *    Determine whether a restriction clause matches a column of an index,
 *    and if so, build an IndexClause node describing the details.
 *
 *    To match an index normally, an operator clause:
 *
 *    (1)  must be in the form (indexkey op const) or (const op indexkey);
 *         and
 *    (2)  must contain an operator which is in the index's operator family
 *         for this column; and
 *    (3)  must match the collation of the index, if collation is relevant.
 *
```

Vector Search

pgvector

Why no scan keys ?

We have to dig deeper …

Let us look into indxpath.c:

Query:

*select * from table where embedding <-> '[…]' < 10 …*

```
/*
 * match_clause_to_indexcol()
 *    Determine whether a restriction clause matches a column of an index,
 *    and if so, build an IndexClause node describing the details.
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 *    To match an index normally, an operator clause:
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 *    (1)  must be in the form (indexkey op const) or (const op indexkey);
 *         and
 *    (2)  must contain an operator which is in the index's operator family
 *         for this column; and
 *    (3)  must match the collation of the index, if collation is relevant.
 *
```

Indexkey can not be matched !

op(indexkey, '[…']) op const

Vector Search

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pgvector

Why no scan keys ?

We have to dig deeper …

Let us look into indxpath.c:

Query:

*select * from table where embedding <-> ‘[…]’ < 10 …*

→ *Indexkey can not be matched !*

op(indexkey, ’[…’]) op const

=> Looks like Postgres enhancement required !

BUT: May take ages to get upstream …

Vector Search

sednai

pgvector hack

Quicker to production:

Let us introduce a new operator, thereby hacking the *WHERE* into the *ORDER BY*:

New operator for `WHERE` clause in index scan:

```
vector <!> vector_adv
```

with

```
vector_adv = (vector,int,float)
```

`int` specifies the filter operator and `float` the condition value

```
2: >=
1: >
0: ==
-1: <
-2: <=
-100: no filter
```

(At the time being, only for euclidean metric)

Vector Search

pgvector hack

Quicker to production:

Let us introduce a new operator, thereby hacking the *WHERE* into the *ORDER BY*:

Query:

*select * from table order by embedding <!> (‘[...]’, -1, 10.0) limit 10000*

Vector Search

sednai

pgvector hack

Quicker to production:

Let us introduce a new operator, thereby hacking the *WHERE* into the *ORDER BY*:

Query:

*select * from table order by embedding <!> ('[...]', -1, 10.0) limit 10000*

Will be evaluated inside of pgvector !

=> Can be executed on GPU !

Vector Search

[pgvector]

What about performance ?

- 2M row Gaia dataset, 79 float8 features
- 40 ivfflat clusters, ivfflat.probes = 20
- Retrieve points up to a max distance from a query point (sparse return)
- After warmup

Original pgvector

```
 Limit  (cost=0.00..9416.48 rows=10000 width=16) (actual time=113.688..563.274 rows=2 loops=1)
   ->  Index Scan using lorenzo_attrs_idx on lorenzo  (cost=0.00..569379.89 rows=604663 width=16) (actual time=113.685..563.269 rows=2 loops=1)
         Order By: (attrs <-> '[-0.36719987,0.8524608,-0.5427666,-1.6615063,1.1010165,0.06038815,-0.8972259,-1.1181297,0.23769811,1.6662519,-1.
473,-0.042955805,0.17839357,0.08050123,0.27791676,-0.425645,0.11280374,0.84778684,0.08167486,1.8496727,0.8007245,0.5793525,-0.5038844,0.2299031
,0.12975255,-1.9553635,0.9473572,-2.2433414,-0.30360684,0.33857238,-0.21312521,2.3237233,-0.060708717,0.339421,-2.0196183,-0.35616732,1.8636712,
749731,-1.5635711,-1.2368783,-0.96010184,-0.6722383,0.8274576,-0.7714504,-0.16363333,-0.96023947,-0.16326201,-1.0754527,-0.6974341,-2.3611114,-
03672114,1.2685906,-0.22232309,-0.17129573,-0.30436236,-1.1221358,0.6857615,-0.60302067,0.22385728,-1.0727525,-1.6519747,-0.9824103,-1.5251932,
1835048,-2.293227,1.9016955,-2.8030064,-0.045054823,-0.14567287]'::vector)
         Filter: ((attrs <-> '[-0.36719987,0.8524608,-0.5427666,-1.6615063,1.1010165,0.06038815,-0.8972259,-1.1181297,0.23769811,1.6662519,-1.5
73,-0.042955805,0.17839357,0.08050123,0.27791676,-0.425645,0.11280374,0.84778684,0.08167486,1.8496727,0.8007245,0.5793525,-0.5038844,0.22990316,
0.12975255,-1.9553635,0.9473572,-2.2433414,-0.30360684,0.33857238,-0.21312521,2.3237233,-0.060708717,0.339421,-2.0196183,-0.35616732,1.8636712,
49731,-1.5635711,-1.2368783,-0.96010184,-0.6722383,0.8274576,-0.7714504,-0.16363333,-0.96023947,-0.16326201,-1.0754527,-0.6974341,-2.3611114,-1.
3672114,1.2685906,-0.22232309,-0.17129573,-0.30436236,-1.1221358,0.6857615,-0.60302067,0.22385728,-1.0727525,-1.6519747,-0.9824103,-1.5251932,-
835048,-2.293227,1.9016955,-2.8030064,-0.045054823,-0.14567287]'::vector) < '6'::double precision)
         Rows Removed by Filter: 578577
 Planning Time: 0.204 ms
 Execution Time: 563.326 ms
(7 rows)

pgv2=# 
```

Vector Search

sednai

[pgvector hack]

What about performance ?

- 2M row Gaia dataset, 79 float8 features
- 40 ivfflat clusters, ivfflat.probes = 20
- Retrieve points up to a max distance from a query point (sparse return)
- After warmup

BGW with filter on CPU

```
------------------------------------------------------------------------------------------
 Limit  (cost=0.00..3105.50 rows=10000 width=16) (actual time=18.928..18.932 rows=1 loops=1)
   ->  Index Scan using lorenzo_attrs_idx on lorenzo  (cost=0.00..563333.26 rows=1813988 width=16) (actual time=18.925..18.927 rows=1 loops=1)
         Order By: (attrs <!> '("[-0.36719987,0.8524608,-0.5427666,-1.6615063,1.1010165,0.06038815,-0.8972259,-1.1181297,0.23769811,1.6662519,-1
18473,-0.042955805,0.17839357,0.08050123,0.27791676,-0.425645,0.11280374,0.84778684,0.08167486,1.8496727,0.8007245,0.5793525,-0.5038844,0.22990
75,0.12975255,-1.9553635,0.9473572,-2.2433414,-0.30360684,0.33857238,-0.21312521,2.3237233,-0.060708717,0.339421,-2.0196183,-0.35616732,1.86367
.0749731,-1.5635711,-1.2368783,-0.96010184,-0.6722383,0.8274576,-0.7714504,-0.16363333,-0.96023947,-0.16326201,-1.0754527,-0.6974341,-2.3611114,
0.03672114,1.2685906,-0.22232309,-0.17129573,-0.30436236,-1.1221358,0.6857615,-0.60302067,0.22385728,-1.0727525,-1.6519747,-0.9824103,-1.525193
1.1835048,-2.293227,1.9016955,-2.8030064,-0.045054823,-0.14567287]",-1,4)'::vector_adv)
 Planning Time: 0.188 ms
 Execution Time: 18.980 ms
(5 rows)

pgv2=#
```

Vector Search

sednai

pgvector hack

What about performance ?

- 2M row Gaia dataset, 79 float8 features
- 40 ivfflat clusters, ivfflat.probes = 20
- Retrieve points up to a max distance from a query point (sparse return)
- After warmup

BGW with filter on GPU

```
---------------------------------------------------------------------------------------
 Limit  (cost=0.00..3105.50 rows=10000 width=16) (actual time=2.482..2.488 rows=1 loops=1)
   ->  Index Scan using lorenzo_attrs_idx on lorenzo  (cost=0.00..563333.26 rows=1813988 width=16) (actual time=2.478..2.482 rows=1 loops=1)
         Order By: (attrs <!> '("[-0.36719987,0.8524608,-0.5427666,-1.6615063,1.1010165,0.06038815,-0.8972259,-1.1181297,0.23769811,1.6662519,-1
18473,-0.042955805,0.17839357,0.08050123,0.27791676,-0.425645,0.11280374,0.84778684,0.08167486,1.8496727,0.8007245,0.5793525,-0.5038844,0.229903
75,0.12975255,-1.9553635,0.9473572,-2.2433414,-0.30360684,0.33857238,-0.21312521,2.3237233,-0.060708717,0.339421,-2.0196183,-0.35616732,1.863671
.0749731,-1.5635711,-1.2368783,-0.96010184,-0.6722383,0.8274576,-0.7714504,-0.16363333,-0.96023947,-0.16326201,-1.0754527,-0.6974341,-2.3611114,
0.03672114,1.2685906,-0.22232309,-0.17129573,-0.30436236,-1.1221358,0.6857615,-0.60302067,0.22385728,-1.0727525,-1.6519747,-0.9824103,-1.525193
1.1835048,-2.293227,1.9016955,-2.8030064,-0.045054823,-0.14567287]",-1,4)'::vector_adv)
 Planning Time: 0.199 ms
 Execution Time: 2.548 ms
(5 rows)

pgv2=#
```

Vector Search

sednai

[pgvector hack]

What about performance ?

- 2M row Gaia dataset, 79 float8 features
- 40 ivfflat clusters, ivfflat.probes = 20
- Retrieve points up to a max distance from a query point (sparse return)
- After warmup

BGW with filter on GPU

```
-----------------------------------------------------------------------------------------
 Limit  (cost=0.00..3105.50 rows=10000 width=16) (actual time=2.482..2.488 rows=1 loops=1)
   ->  Index Scan using lorenzo_attrs_idx on lorenzo  (cost=0.00..563333.26 rows=1813988 width=16) (actual time=2.478..2.482 rows=1 loops=1)
         Order By: (attrs <!> '("[-0.36719987,0.8524608,-0.5427666,-1.6615063,1.1010165,0.06038815,-0.8972259,-1.1181297,0.23769811,1.6662519,-1
18473,-0.042955805,0.17839357,0.08050123,0.27791676,-0.425645,0.11280374,0.84778684,0.08167486,1.8496727,0.8007245,0.5793525,-0.5038844,0.229903
75,0.12975255,-1.9553635,0.9473572,-2.2433414,-0.30360684,0.33857238,-0.21312521,2.3237233,-0.060708717,0.339421,-2.0196183,-0.35616732,1.863671
.0749731,-1.5635711,-1.2368783,-0.96010184,-0.6722383,0.8274576,-0.7714504,-0.16363333,-0.96023947,-0.16326201,-1.0754527,-0.6974341,-2.3611114,
0.03672114,1.2685906,-0.22232309,-0.17129573,-0.30436236,-1.1221358,0.6857615,-0.60302067,0.22385728,-1.0727525,-1.6519747,-0.9824103,-1.525193
1.1835048,-2.293227,1.9016955,-2.8030064,-0.045054823,-0.14567287]",-1,4)'::vector_adv)
 Planning Time: 0.199 ms
 Execution Time: 2.548 ms
(5 rows)

pgv2=#
```

=> 200x speedup !

Vector Search

pgvector hack

General remarks:

- No active memory management
  (memory freed only upon killing the worker)
- Enough shared memory needs to be reserved for number of expected returns
- As more sparse the return, as better will be the speedup

Vector Search

sednai

pgvector hack

General remarks:

- No active memory management
  (memory freed only upon killing the worker)
- Enough shared memory needs to be reserved for number of expected returns
- As more sparse the return, as better will be the speedup

Can we do more ?

- Improvements of code (GPU kernels) are possible.
- Faster initial loading via Nvidia GPUDirect (NVMe <-> GPU DMA)
- Product quantization
- For significant performance improvement, more *vectorization* …
  (for instance, to query for several points at once)

... OUTLOOK ...

Intro

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AERO

Aero aims to complement the efforts of the *EU Processor Initiative (EPI)* project by developing the open-source software ecosystem required to not only improve the efficiency of the EPI hardware but also accelerate and ease the processor’s integration into the cloud.

Intertwined Gaia+SED pilots:

- *Process efficiently constantly increasing volumes of data.*

→ - *Enable GPU computations directly within the database*

Example: Hack to GPU accelerate a Postgres vector index

(WARNING: That was actually easy ...)

ICCS UBITECH SIPEARL PIERER INNOVATION Red Hat FORTH UNIVERSITÀ DI PISA Virtual Open Systems UNIVERSITÉ DE GENÈVE sednai MANCHESTER 1824 The University of Manchester codeplay

Outlook

SED pilot:

- *Enable GPU computations directly within the database*

→ Multi-faceted

- Adaptation of *PG-Strom* to distributed Postgres (XL/XC lineage)
  [https://heterodb.github.io/pg-strom/]
  (for GPU acceleration of general scans, aggregates and joins …)

→ First milestone reached in modernizing XL/XC
(pushed XC to PGv15 with sufficient functionality)

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... THANK YOU ...

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and Innovation

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Confederaziun svizra

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