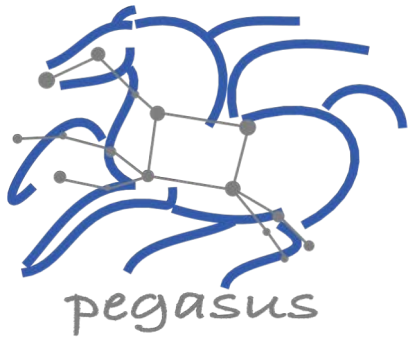
Pegasus 5.0 Workflows



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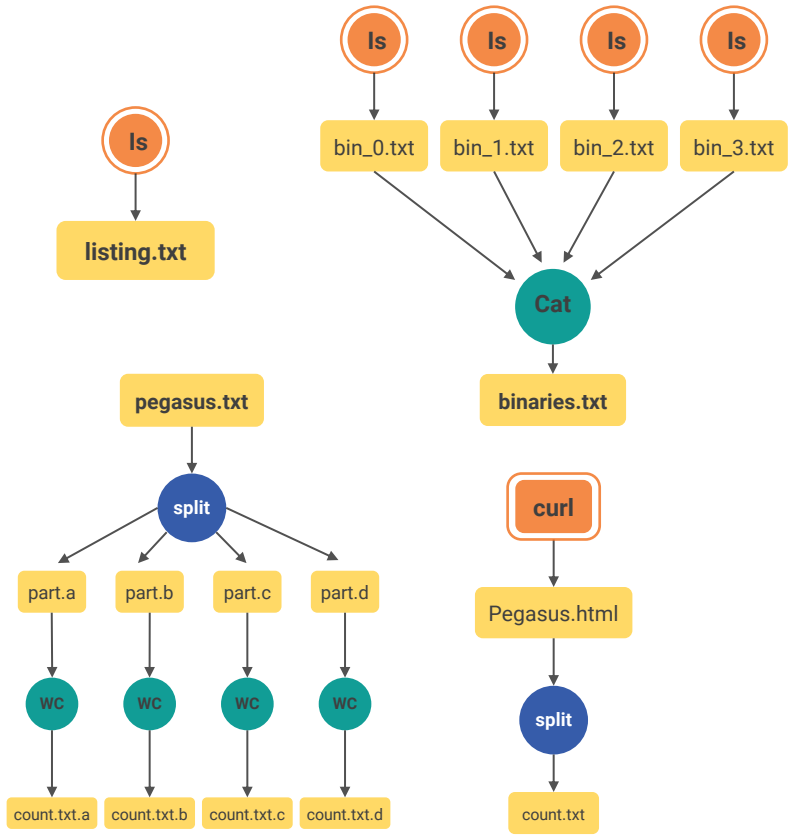
What are Scientific Workflows

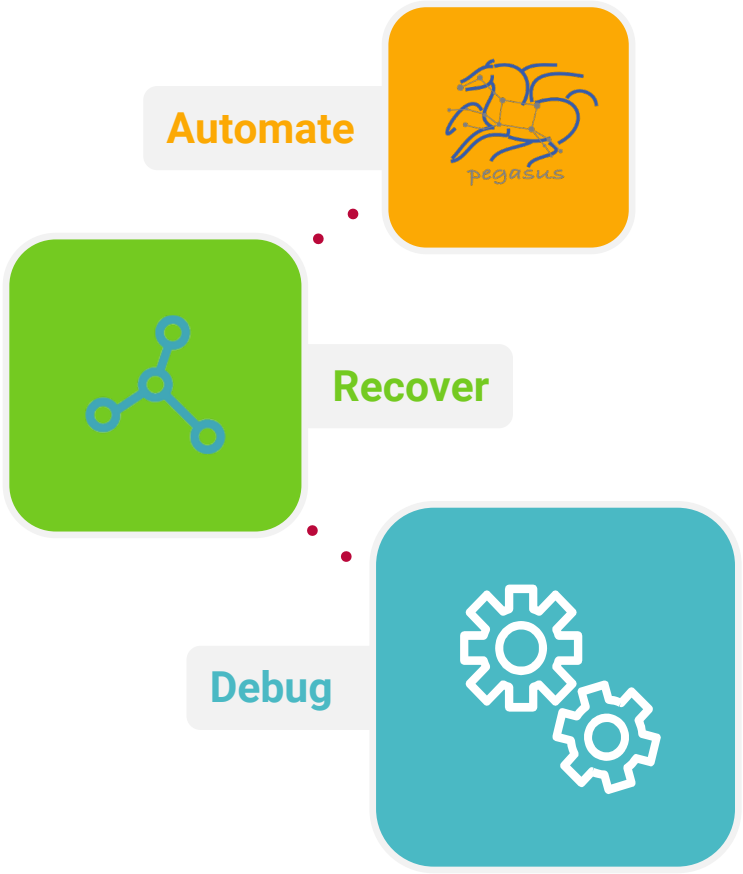
- **Conducts a series of computational tasks.**
  - Resources distributed across Internet.
- **Chaining (outputs become inputs) replaces manual hand-offs.**
  - Accelerated creation of products.
- **Ease of use - gives non-developers access to sophisticated codes.**
  - Resources distributed across Internet.
- **Provides framework to host or assemble community set of applications.**
  - Honors original codes. Allows for heterogeneous coding styles.
- **Framework to define common formats or standards when useful.**
  - Promotes exchange of data, products, codes. Community metadata.
- **Multi-disciplinary workflows can promote even broader collaborations.**
  - E.g., ground motions fed into simulation of building shaking.
- **Certain rules or guidelines make it easier to add a code into a workflow.**

Workflow Building Blocks



Slide Content Courtesy of David Okaya, SCEC, USC

Why Pegasus?



- **Automates Complex**, Multi-stage Processing Pipelines
- Enables Parallel, **Distributed Computations**
- **Automatically Executes** Data Transfers
- Reusable, Aids **Reproducibility**
- Records How Data was Produced **(Provenance)**
- Handles **Failures** with to Provide Reliability
- Keeps Track of Data and **Files**
- Ensures **Data Integrity** during workflow execution

HTCondor High Throughput Computing

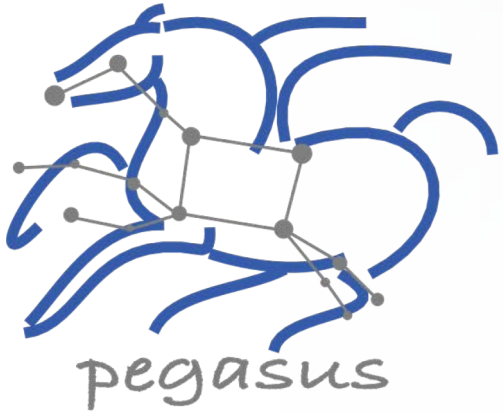
NSF funded project since 2001,
with close collaboration with HTCondor team

Workflow Challenges Across Domains

- Describe complex workflows in a simple way
- Access distributed, heterogeneous data and resources (heterogeneous interfaces)
- Deal with resources/software that change over time
- Ease of use. Ability to debug and monitor large workflows

Our Focus

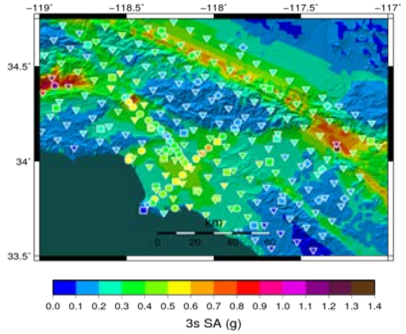
- Separation between workflow description and workflow execution
- Workflow planning and scheduling (scalability, performance)
- Task execution (monitoring, fault tolerance, debugging, web dashboard)
- Provide additional assurances that a scientific workflow is not accidentally or maliciously tampered with during its execution.



Some of The Success Stories...

Pegasus

Southern California Earthquake Center's CyberShake



Mix of MPI and single-core jobs, mix of CPU, GPU codes.
Large data sets (10s of TBs), ~300 workflows with 420,000 tasks each
Supported since 2005: changing CI, x-platform execution

First Physics-Based "Shake map" of Southern California

Laser Interferometer Gravitational-Wave Observatory (LIGO)

High-throughput computing workload, access to HPC resources, ~ 21K Pegasus workflows, ~ 107M tasks

Supported since 2001, distributed data, opportunistic computing resources

First direct detection of a gravitational wave (colliding black holes)

XENONnT - Dark Matter Search

Custom data management
Rucio for data management
MongoDB instance to track science runs and data products.

Monte Carlo simulations and the main processing pipeline.

Southern California Earthquake Center's CyberShake

CPU jobs
(Mesh generation, seismogram synthesis)
1,094,000 node-hours

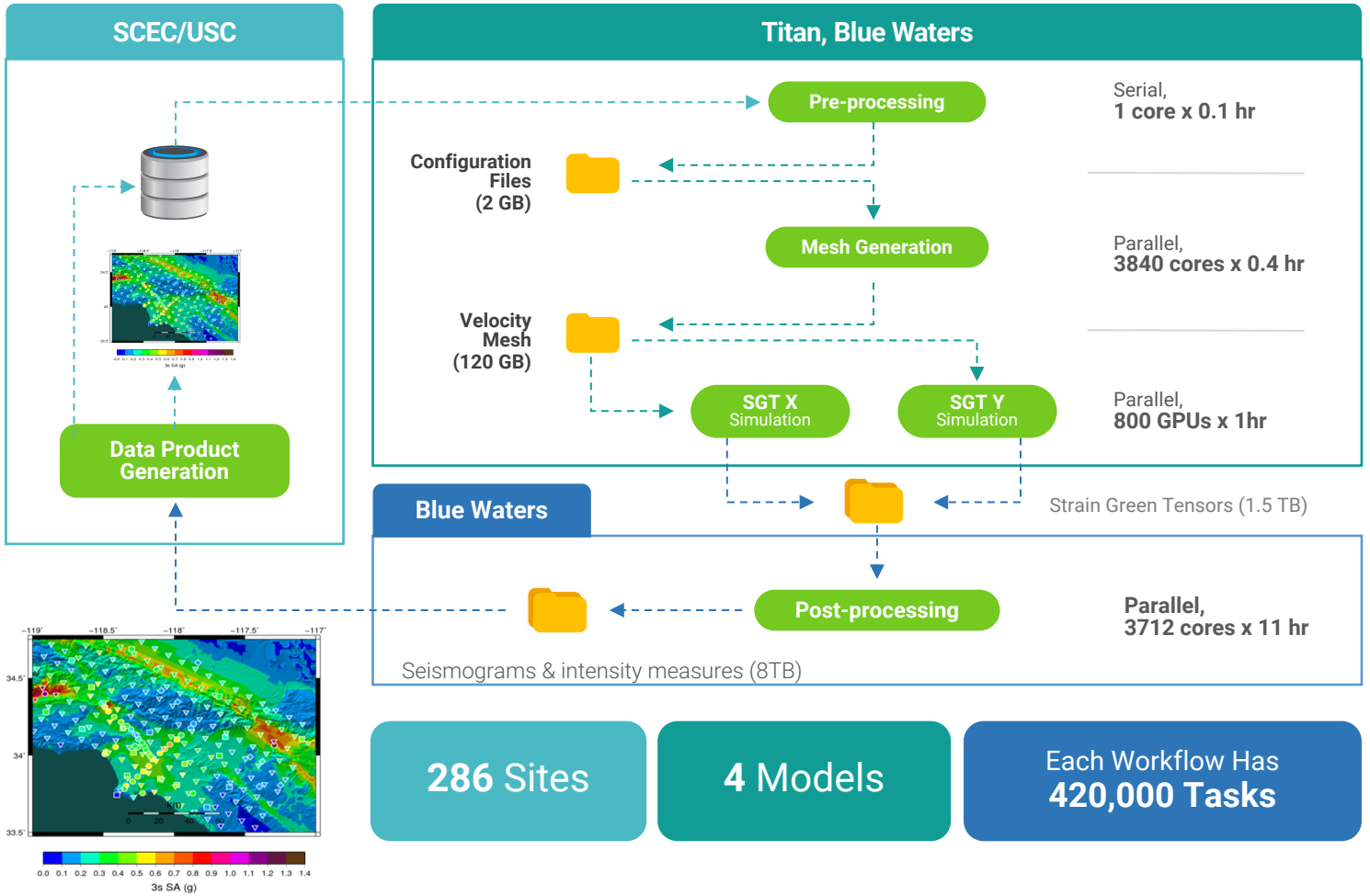
GPU jobs:
439,000 node-hours
AWP-ODC finite-difference code
5 billion points per volume, 23,000 timesteps
200 GPUs for 1 hour

Titan:
421,000 CPU node-hours, 110,000 GPU node-hours

Blue Waters:
673,000 CPU node-hours, 329,000 GPU node-hours

Builders ask seismologists:
What will the peak ground motion be at my new building in the next 50 years?

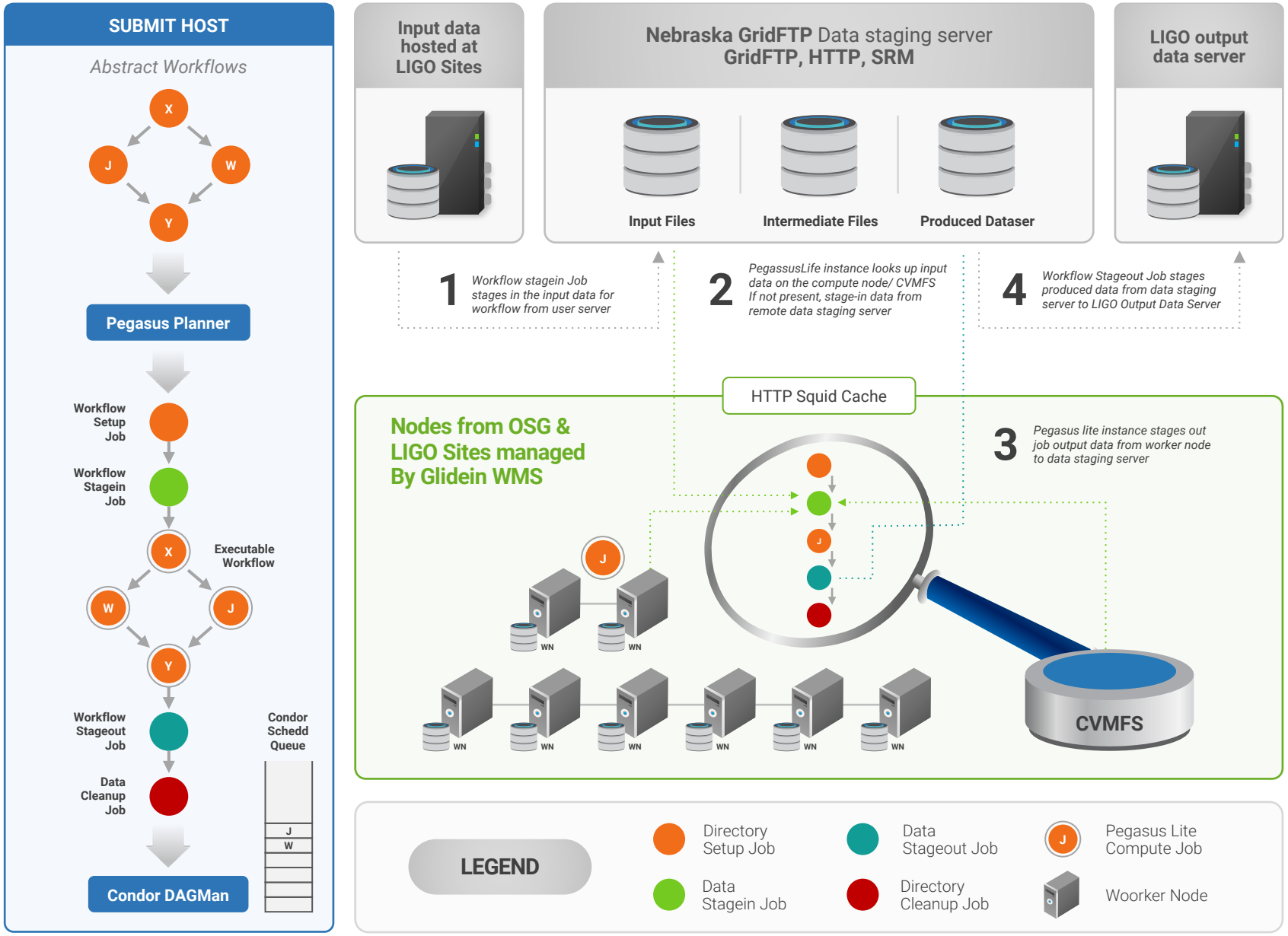
Seismologists answer this question
using Probabilistic Seismic Hazard Analysis (PSHA)



286 Sites

4 Models

Each Workflow Has **420,000 Tasks**



Data Flow for **LIGO** **Pegasus Workflows** in OSG

Advanced LIGO

Laser Interferometer
Gravitational Wave Observatory

60,000 Compute Tasks

Input Data: 5000 files (10GB total)

Output Data: 60,000 files (60GB total)

Processed Data: 725 GB

Executed on **LIGO Data Grid, EGI, Open Science Grid and XSEDE**

Event Horizon Telescope

Bringing Black Holes into Focus

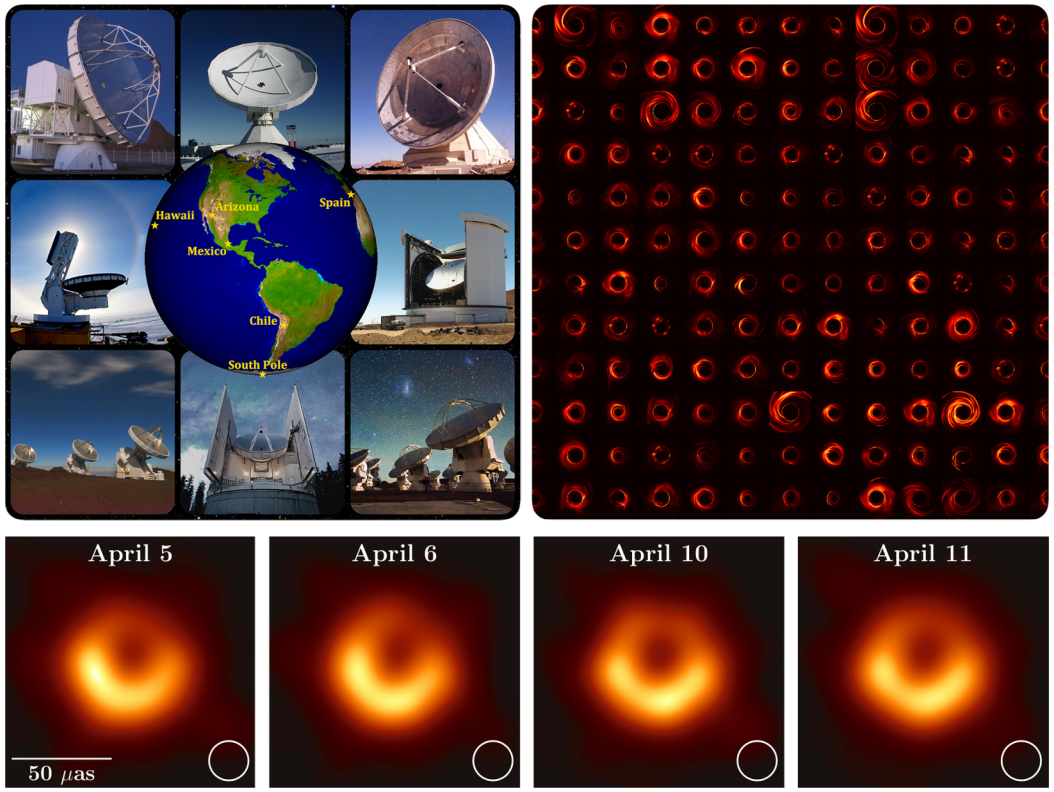
480,000 jobs - 2,600,000 core hours

#15 in all OSG projects in last 6 months

#2 in all OSG astronomy projects in the last 6 months

8 telescopes: 5 PB of data

60 simulations: 35 TB data

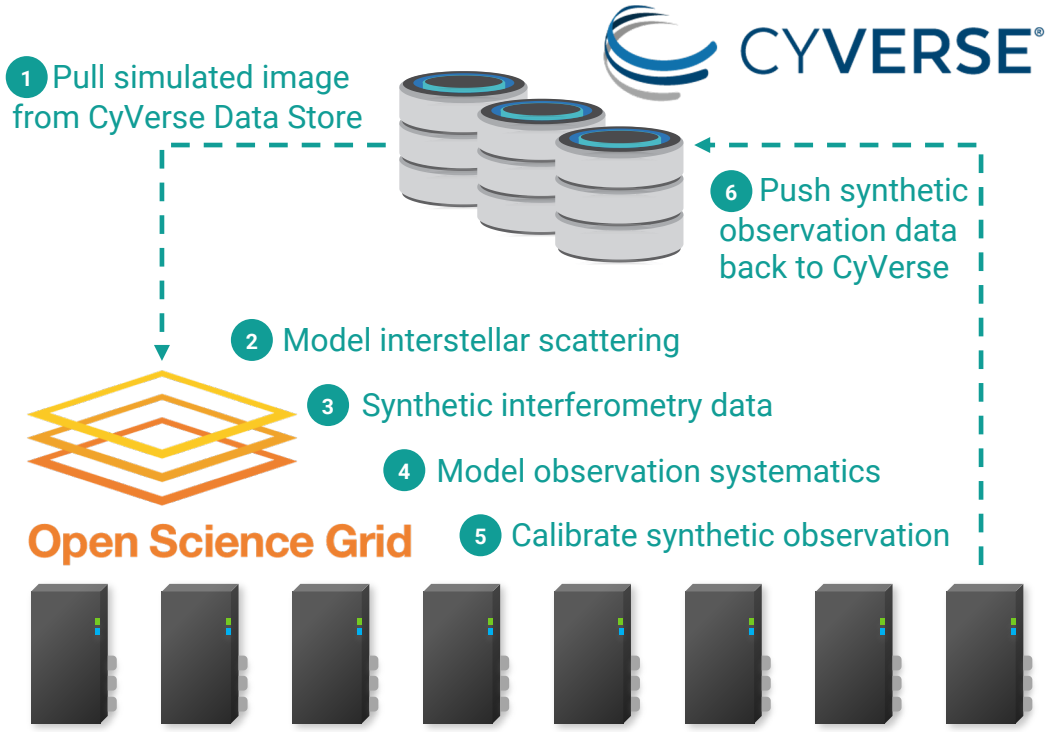


First images of black hole at the center of the M87 galaxy

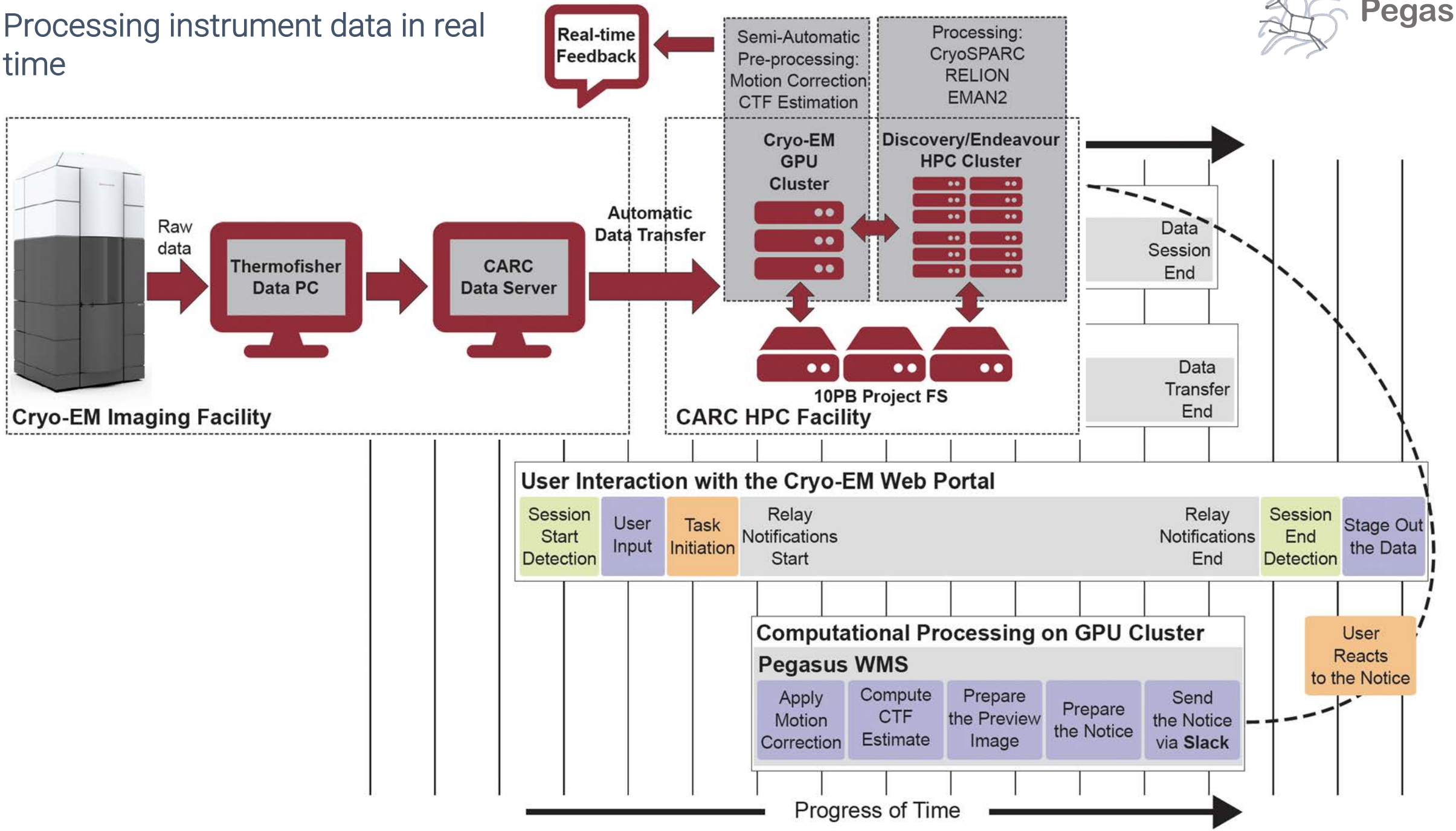
Improve constraints on Einstein's theory of general relativity by 500x

Pegasus-SYMBA Pipeline

Physically accurate synthetic observation data from simulations are keys to develop calibration and imaging algorithms, as well as comparing the observation with theory and interpreting the results.



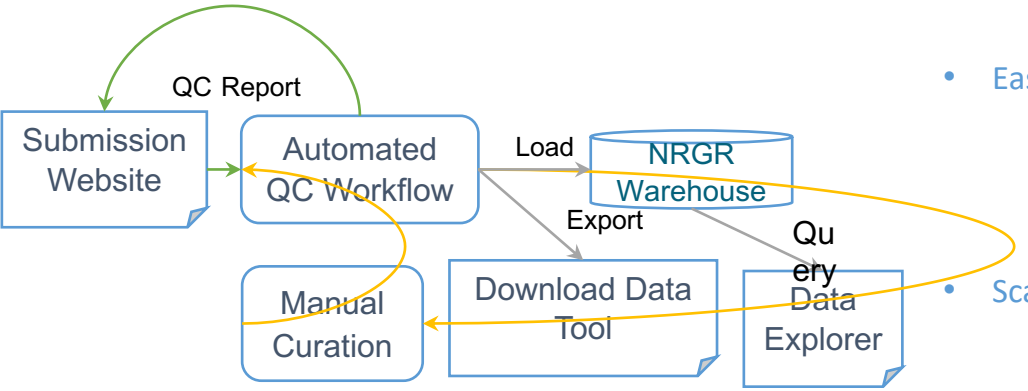
Processing instrument data in real time

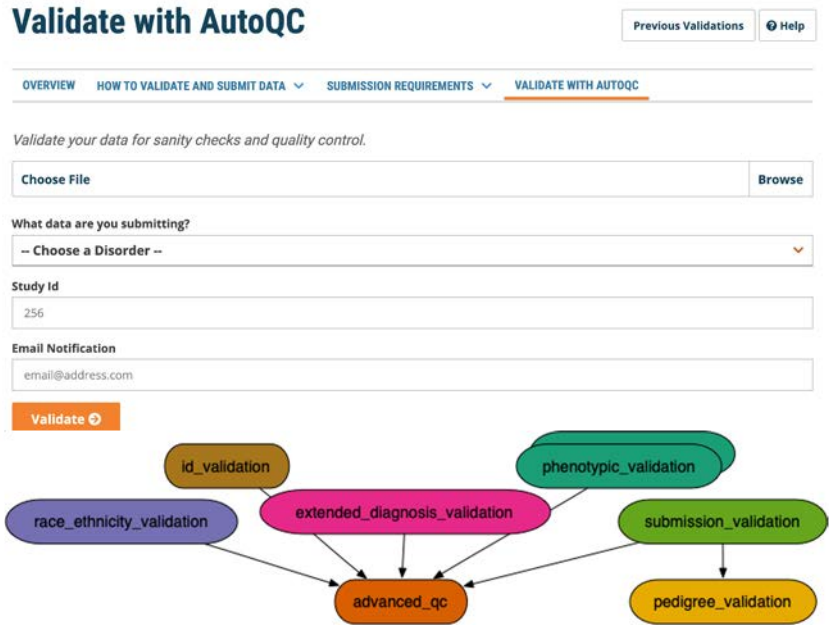


NIMH REPOSITORY & GENOMICS RESOURCE Automated Quality Control of Phenotypic Datasets

Pegasus

The NIMH Center for Collaborative Genomic Studies on Mental Disorders, now known as the NIMH Repository and Genomics Resource (NRGR), maintains biomaterials, demographic, and phenotypic data from over 200,000 well-characterized individuals with a range of psychiatric illnesses, their family members, and unaffected controls.



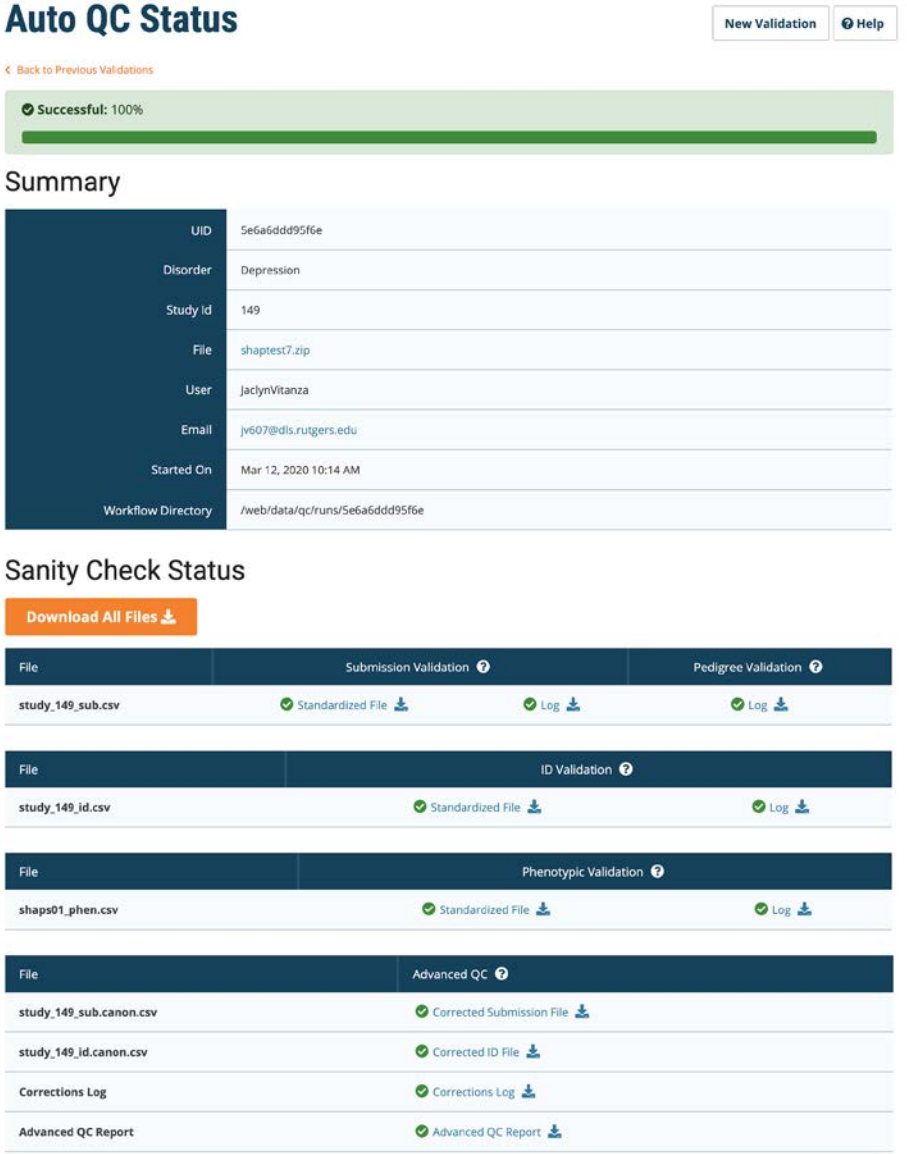


- Easy to Use Web-Based Interface
  - Simple Submission
  - Real-time Monitoring and Error Reports
  - After automated QC, submit corrected files for expert curation
- Scalable
  - Workflow based architecture using Pegasus WMS
- Extensible Design
  - Easily add new QC steps, and checks
- Enables Complex checks
  - Pedigree Checks
  - QC Checks validating data with external sources
  - QC Checks can correlate data across multiple files and across multiple fields within files

○ Ensures high-quality uniform data deposited at NRGR

○ Better resource utilization: solve most QC problems automatically, use expert curation for hard cases

https://pegasus.isi.edu



Basic Concepts…

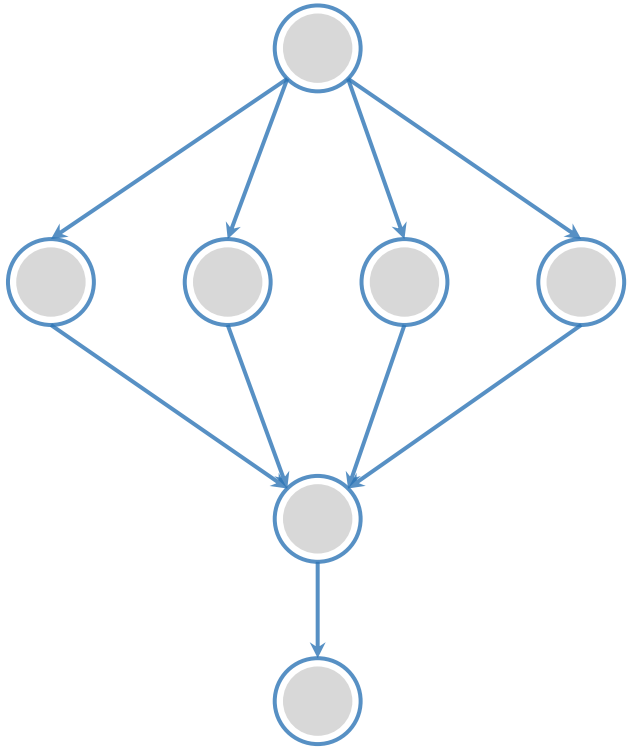
Key Pegasus Concepts

- **Pegasus WMS == Pegasus planner (mapper) + DAGMan workflow engine + HTCondor scheduler/broker**
  - Pegasus maps workflows to infrastructure
  - DAGMan manages dependencies and reliability
  - HTCondor is used as a broker to interface with different schedulers

- **Workflows are DAGs**
  - Nodes: jobs, edges: dependencies
  - No while loops, no conditional branches
  - Jobs are standalone executables

- **Planning occurs ahead of execution**

- **Planning converts an abstract workflow into a concrete, executable workflow**
  - Planner is like a compiler



Input Workflow Specification YAML formatted

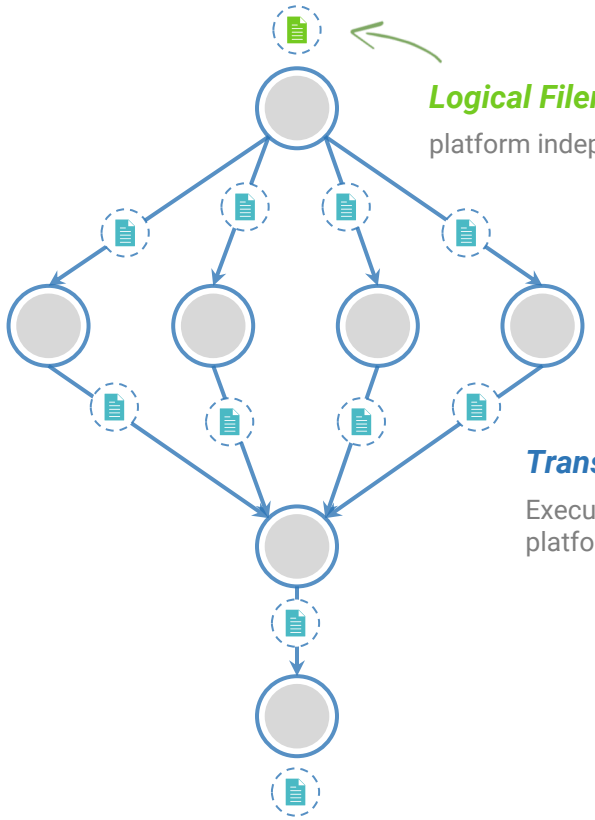
directed-acyclic graphs

Output Workflow

Portable Description

Users do not worry about low level execution details

ABSTRACT WORKFLOW

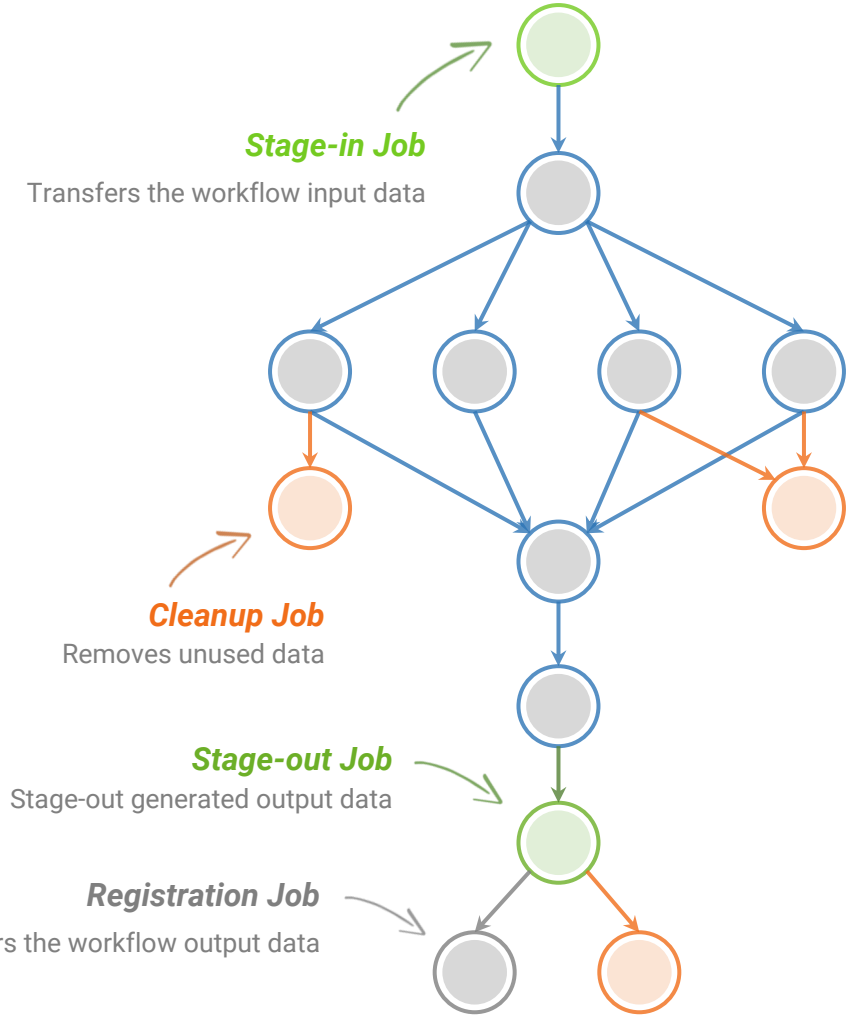


Logical Filename (LFN)

platform independent (abstraction)

Transformation

Executables (or programs)
platform independent



Stage-in Job

Transfers the workflow input data

Cleanup Job

Removes unused data

Stage-out Job

Stage-out generated output data

Registration Job

Registers the workflow output data

EXECUTABLE WORKFLOW

So, what information does Pegasus need?

Site Catalog

Describes the sites where
The workflow jobs are to be executed

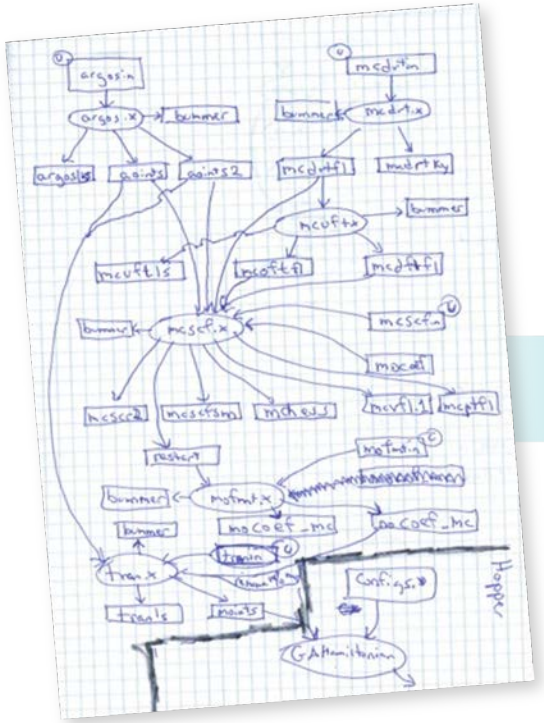
Transformation Catalog

Describes all of the executables
(called “transformations”)
used by the workflow

Replica Catalog

Describes all of the input data stored
on external servers

Pegasus also provides tools to generate the Abstract Workflow



```python
#!/usr/bin/env python3

import os
import logging
from pathlib import Path
from argparse import ArgumentParser

logging.basicConfig(level=logging.DEBUG)

# --- Import Pegasus API ----------------
from Pegasus.api import *

# --- Create Abstract Workflow ----------
wf = Workflow("pipeline")

webpage = File("pegasus.html")

# --- Create Parent Job -----------
curl_job = (
    Job("curl")
    .add_args("-o", webpage, "http://pegasus.isi.edu")
    .add_outputs(webpage, stage_out=False, register_replica=False)
)

count = File("count.txt")

# --- Create Dependent Job -----------
wc_job = (
    Job("wc")
    .add_args("-l", webpage)
    .add_inputs(webpage)
    .set_stdout(count, stage_out=True, register_replica=True)
)
# --- Add jobs to the Abstract Workflow --------
wf.add_jobs(curl_job, wc_job)

# --- Add control flow dependency ----------
wf.add_dependency(wc_job, parents=[curl_job])

# --- Write out the Abstract Workflow ----------
wf.write()
```

python™ Java R jupyter

```yaml
x-pegasus:
  apiLang: python
  createdBy: vahi
  createdOn: 11-19-20T14:57:58Z
pegasus: '5.0'
name: pipeline
jobs:
- type: job
  name: curl
  id: ID0000001
  arguments:
  - -o
  - pegasus.html
  - http://pegasus.isi.edu
  uses:
  - lfn: pegasus.html
    type: output
    stageOut: false
    registerReplica: false
- type: job
  name: wc
  id: ID0000002
  stdout: count.txt
  arguments:
  - -l
  - pegasus.html
  uses:
  - lfn: count.txt
    type: output
    stageOut: true
    registerReplica: true
  - lfn: pegasus.html
    type: input
jobDependencies:
- id: ID0000001
  children:
  - ID0000002
```

YAML Formatted

Abstract Workflow

Pegasus 5.0

- **New and fresh Python3 API to compose, submit and monitor workflows, and configure catalogs**
- **New Catalog Formats**
- **Python 3 Support**
  - All Pegasus tools are Python 3 compliant
  - Python PIP packages for workflow composition and monitoring
- **Zero configuration required to submit to local HTCondor pool.**
- **Data Management Improvements**
  - New output replica catalog that registers outputs including file metadata such as size and checksums
  - Improved support for hierarchical workflows
- **Reworked Documentation and Tutorial**
  - https://pegasus.isi.edu/documentation/

```
#!/usr/bin/env python3
import logging
import sys

from Pegasus.api import *

# logs to be sent to stdout
logging.basicConfig(level=logging.DEBUG, stream=sys.stdout)

# --- Transformations ----------------------------------------
echo = Transformation(
        "echo",
        pfn="/bin/echo",
        site="condorpool"
    )

tc = TransformationCatalog()\
        .add_transformations(echo)

# --- Workflow -----------------------------------------------
Workflow("hello-world", infer_dependencies=True)\
    .add_jobs(
        Job(echo)
            .add_args("Hello World")
            .set_stdout("hello.out")
    ).add_transformation_catalog(tc)\
    .plan(submit=True)\
    .wait()
```

Pegasus Deployment

Workflow Submit Node

- Pegasus WMS
- HTCondor

One or more Compute Sites

- Compute Clusters
- Cloud
- OSG

Input Sites

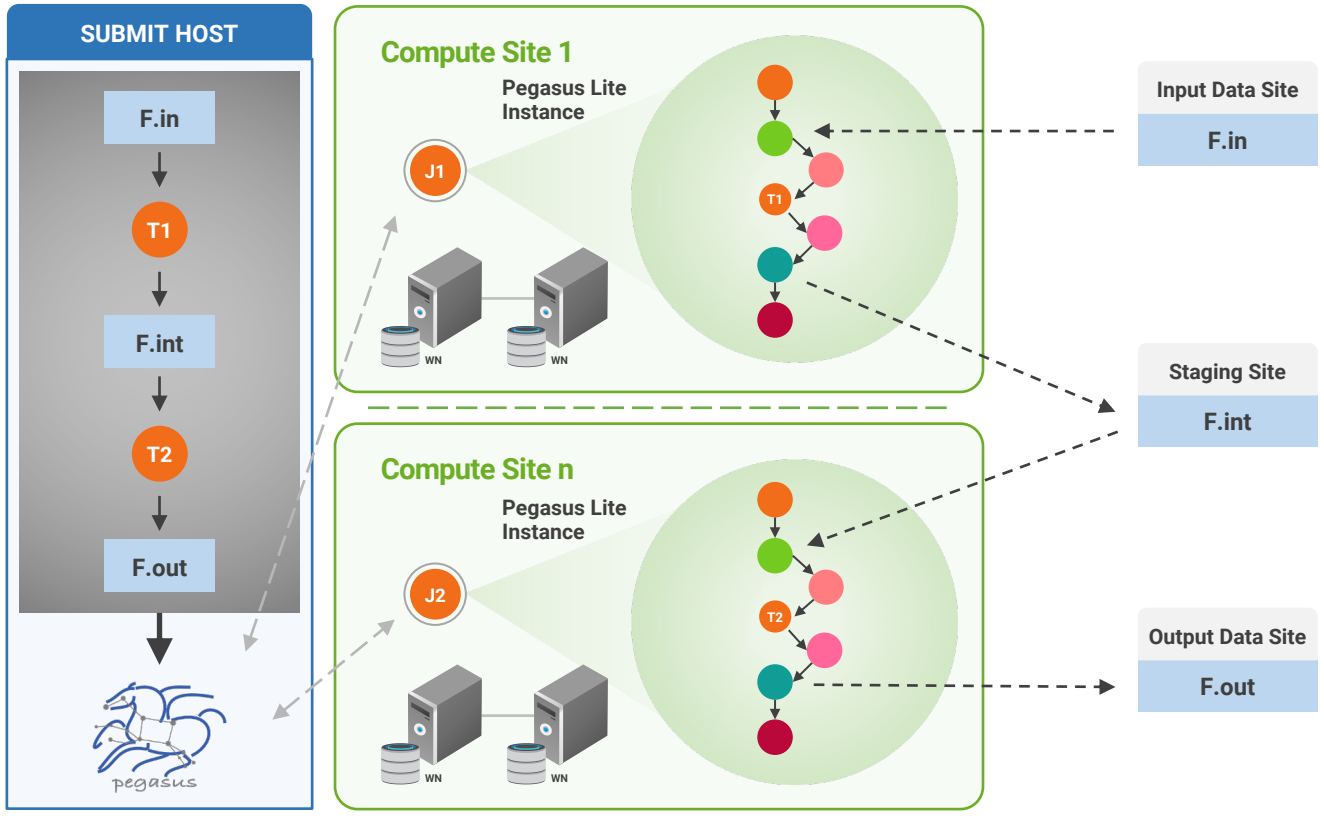
- Host Input Data

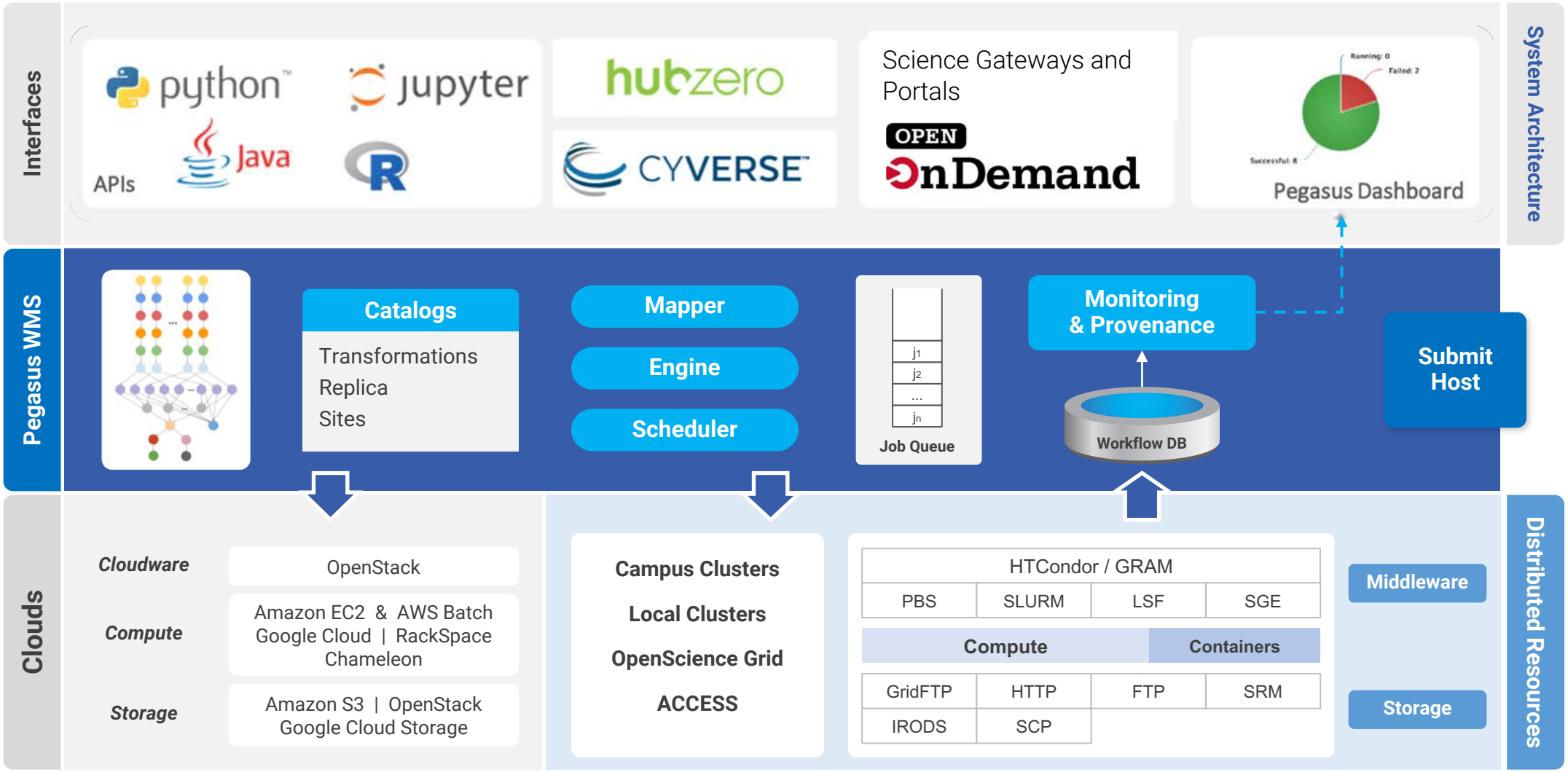
Data Staging Site

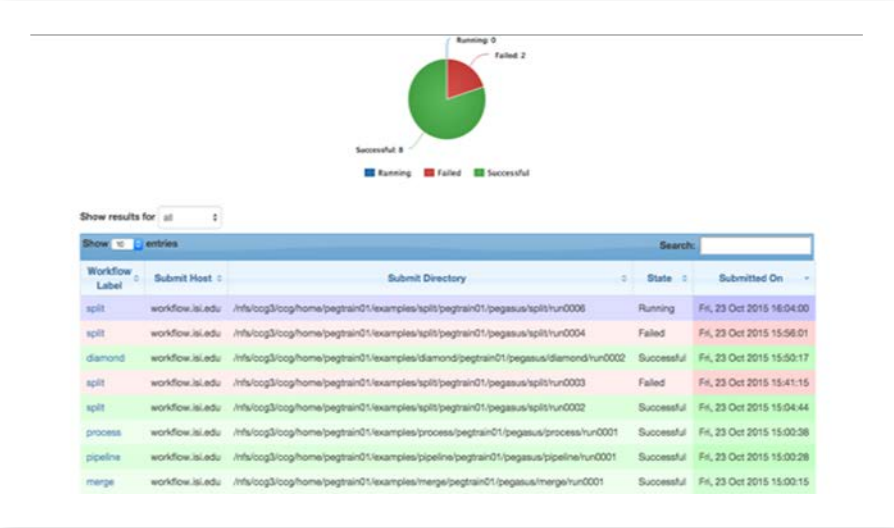
- Coordinate data movement for workflow

Output Site

- Where output data is placed




Interfaces
python
jupyter
APIs
Java
R
hubzero
CYVERSE
Science Gateways and Portals
OPEN OnDemand
Pegasus Dashboard
System Architecture
Pegasus WMS
Catalogs
Transformations
Replica
Sites
Mapper
Engine
Scheduler
j1
j2
...
jn
Job Queue
Monitoring & Provenance
Workflow DB
Submit Host
Clouds
Cloudware
OpenStack
Compute
Amazon EC2 & AWS Batch
Google Cloud | RackSpace
Chameleon
Storage
Amazon S3 | OpenStack
Google Cloud Storage
Campus Clusters
Local Clusters
OpenScience Grid
ACCESS
HTCondor / GRAM
PBS
SLURM
LSF
SGE
Compute
Containers
GridFTP
HTTP
FTP
SRM
IRODS
SCP
Middleware
Storage
Distributed Resources

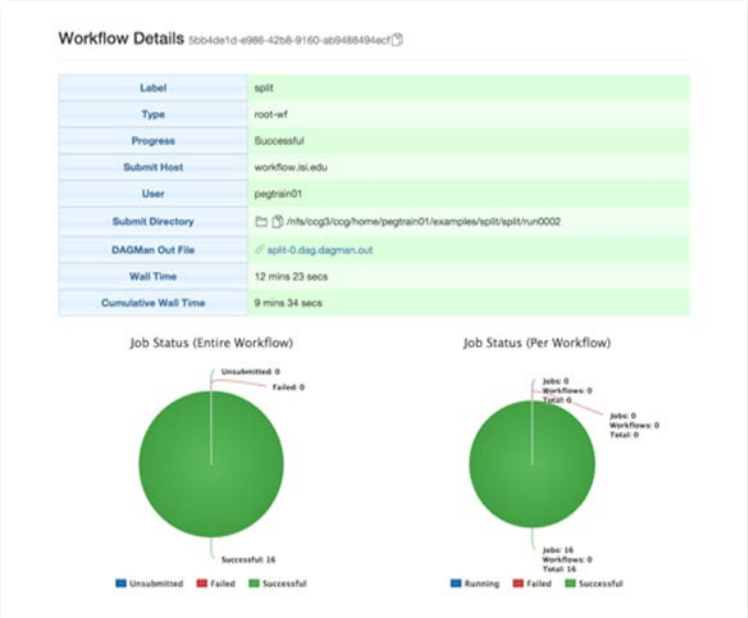


PEGASUS DASHBOARD

web interface for monitoring and debugging workflows

Real-time **monitoring** of workflow executions. It shows the **status** of the workflows and jobs, job **characteristics, statistics** and **performance** metrics.

Provenance data is stored into a relational database.



- **Real-time Monitoring**
- **Reporting**
- **Debugging**
- **Troubleshooting**
- **RESTful API**

command-line…

```
$ pegasus-status pegasus/examples/split/run0001
STAT IN_STATE JOB
Run 00:39 split-0 (/home/pegasus/examples/split/run0001)
Idle 00:03  └─split_ID0000001
Summary: 2 Condor jobs total (I:1 R:1)

UNRDY READY PRE IN_Q POST DONE FAIL %DONE STATE   DAGNAME
 14     0    0    1    0   2    0    11.8 Running *split-0.dag
```

```
$ pegasus-analyzer pegasus/examples/split/run0001
pegasus-analyzer: initializing...

**************************Summary***************************

Total jobs : 7 (100.00%)
# jobs succeeded : 7 (100.00%)
# jobs failed : 0 (0.00%)
# jobs unsubmitted : 0 (0.00%)
```

```
$ pegasus-statistics -s all pegasus/examples/split/run0001
------------------------------------------------------------------------------
Type           Succeeded Failed Incomplete Total Retries Total+Retries
Tasks              5       0        0        5     0         5
Jobs              17       0        0       17     0        17
Sub-Workflows      0       0        0        0     0         0
------------------------------------------------------------------------------

Workflow wall time : 2 mins, 6 secs
Workflow cumulative job wall time : 38 secs
Cumulative job wall time as seen from submit side : 42 secs
Workflow cumulative job badput wall time :
Cumulative job badput wall time as seen from submit side :
```

Provenance Data can be Summarized Pegasus-Statistics or Used for Debugging Pegasus-Analyzer

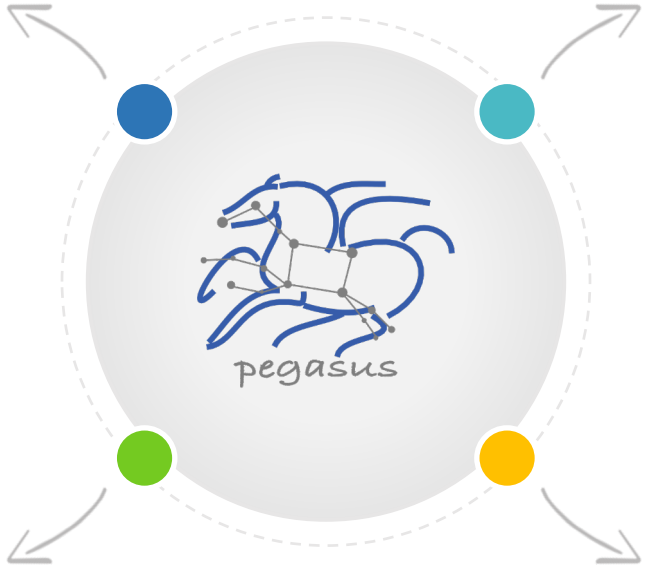
And if a job fails?

Postscript

detects non-zero exit code output parsing for success or failure message exceeded timeout do not produced expected output files

Job Retry

helps with transient failures set number of retries per job and run



Checkpoint Files

job generates checkpoint files staging of checkpoint files is automatic on restarts

Rescue DAGs

workflow can be restarted from checkpoint file recover from failures with minimal loss

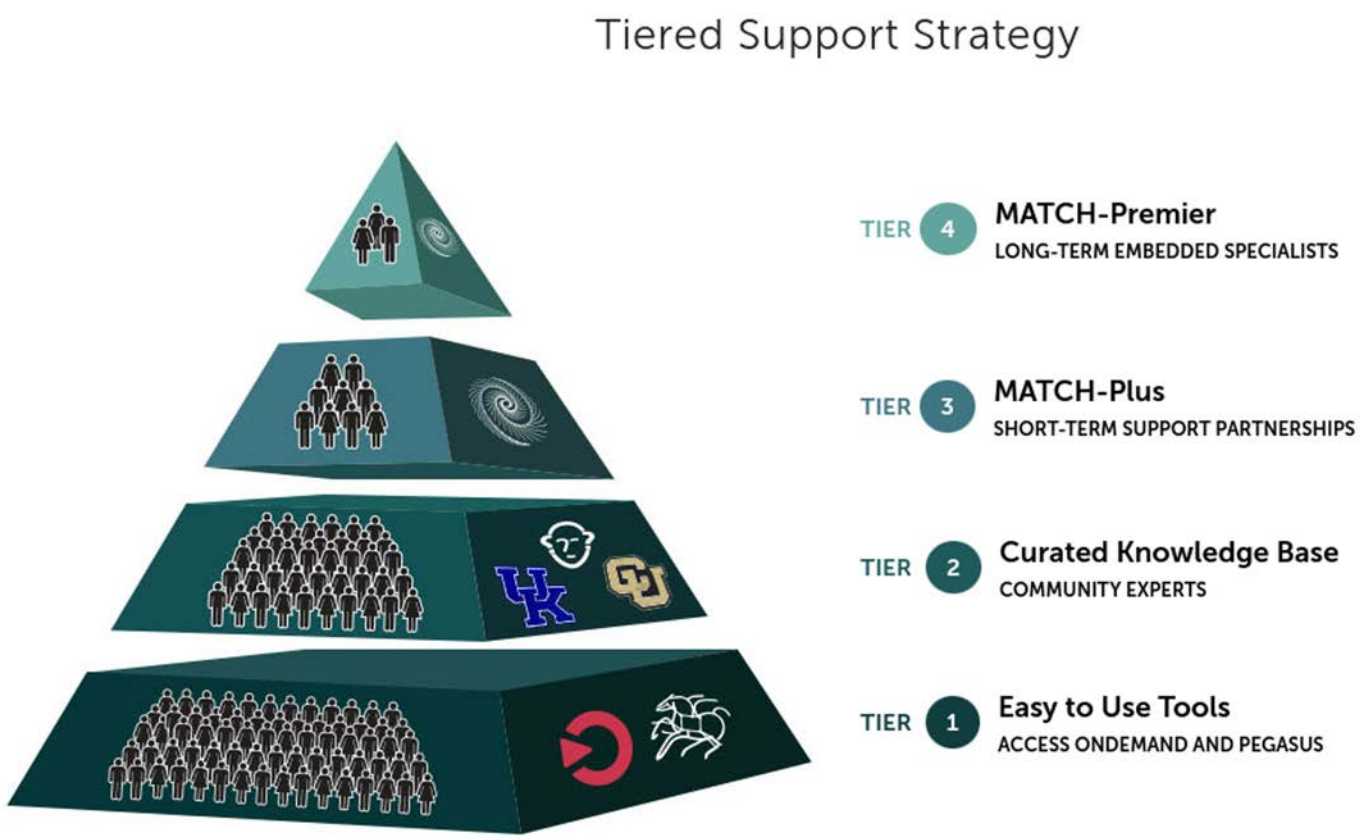
ACCESS…

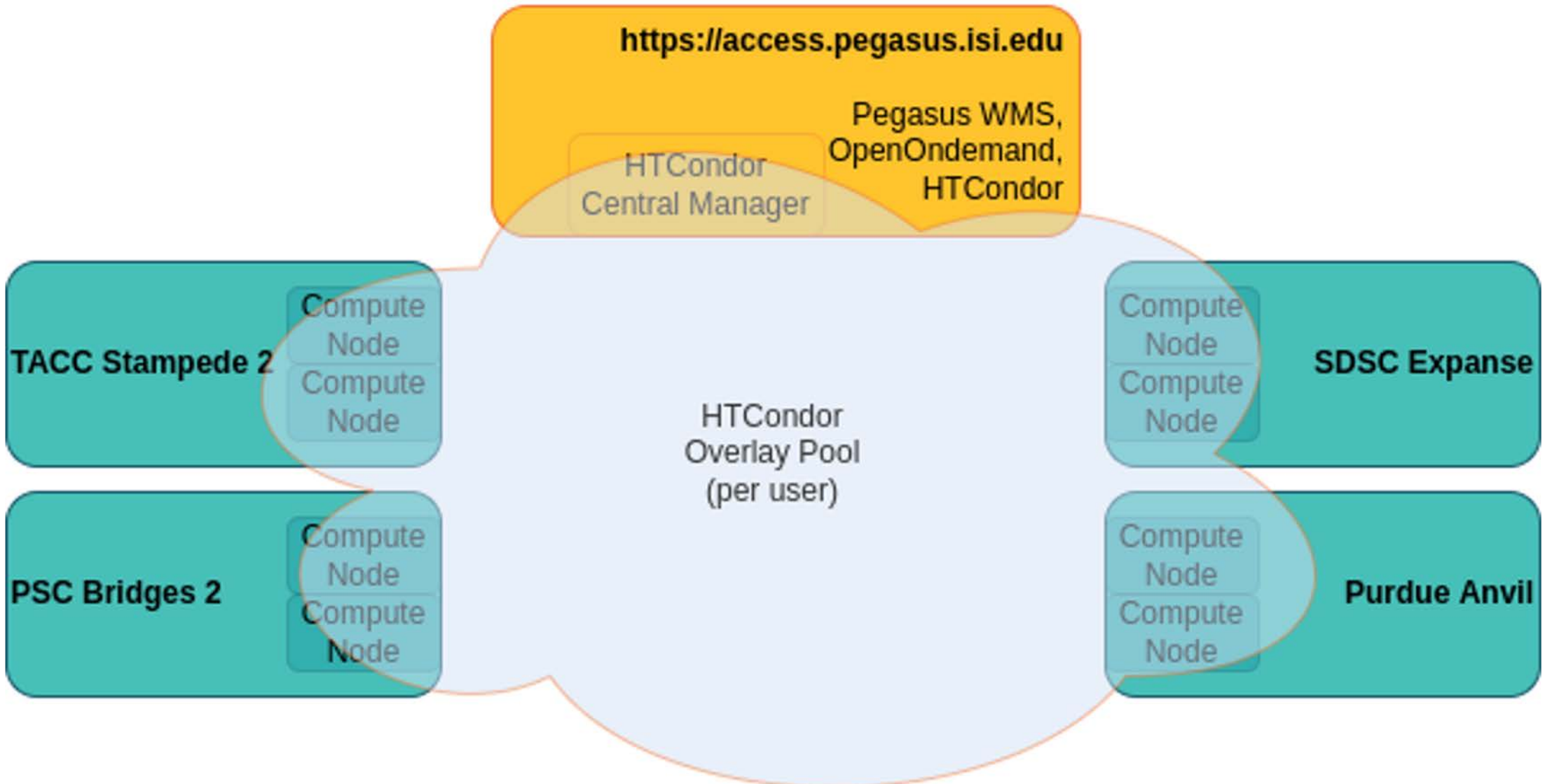
Pegasus is part of the ACCESS support strategy

Pegasus will be used as a tier 1 tool

Central Open OnDemand instance with Pegasus, HTCondor and Jupyter

It will be easy to run HTC workflows across ACCESS sites




https://access.pegasus.isi.edu
Pegasus WMS,
OpenOndemand,
HTCondor
HTCondor
Central Manager
TACC Stampede 2
Compute
Node
Compute
Node
PSC Bridges 2
Compute
Node
Compute
Node
HTCondor
Overlay Pool
(per user)
SDSC Expanse
Compute
Node
Compute
Node
Purdue Anvil
Compute
Node
Compute
Node

HTCondor Annex / Pilot Jobs

- **A pilot can run multiple user jobs** - it stays active until no more user jobs are available or until end of life has been reached, whichever comes first.
- **A pilot is partitionable** - job slots will dynamically be created based on the resource requirements in the user jobs. This means you can fit multiple user jobs on a compute node at the same time.
- **A pilot will only run jobs for the user who started it.**

Understanding Pegasus Features…

Pegasus-transfer

Pegasus' internal data transfer tool with support for a number of different protocols

- **Directory creation, file removal**
  - If protocol can support it, also used for cleanup
- **Two stage transfers**
  - e.g., GridFTP to S3 = GridFTP to local file, local file to S3
- **Parallel transfers**
- **Automatic retries**
- **Credential management**
  - Uses the appropriate credential for each site and each protocol (even 3rd party transfers)

```
HTTP
SCP
GridFTP
Globus
Online
iRods
Amazon S3
Google
Storage
SRM
FDT
Stashcp
Rucio
cp
ln -s
```

Data Staging Configurations

HTCondor I/O (HTCondor pools, OSG, …)

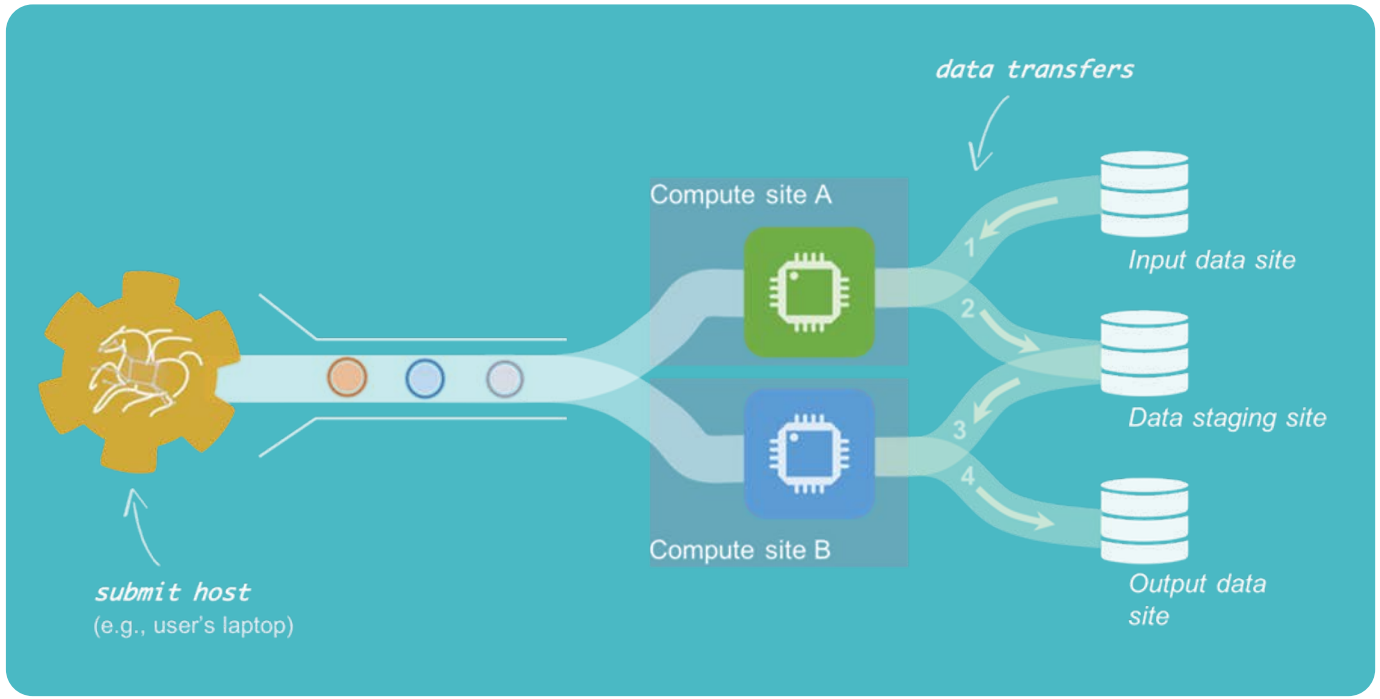
- Worker nodes do not share a file system
- Data is pulled from / pushed to the submit host via HTCondor file transfers
- Staging site is the submit host

Non-shared File System (clouds, OSG, …)

- Worker nodes do not share a file system
- Data is pulled / pushed from a staging site, possibly not co-located with the computation

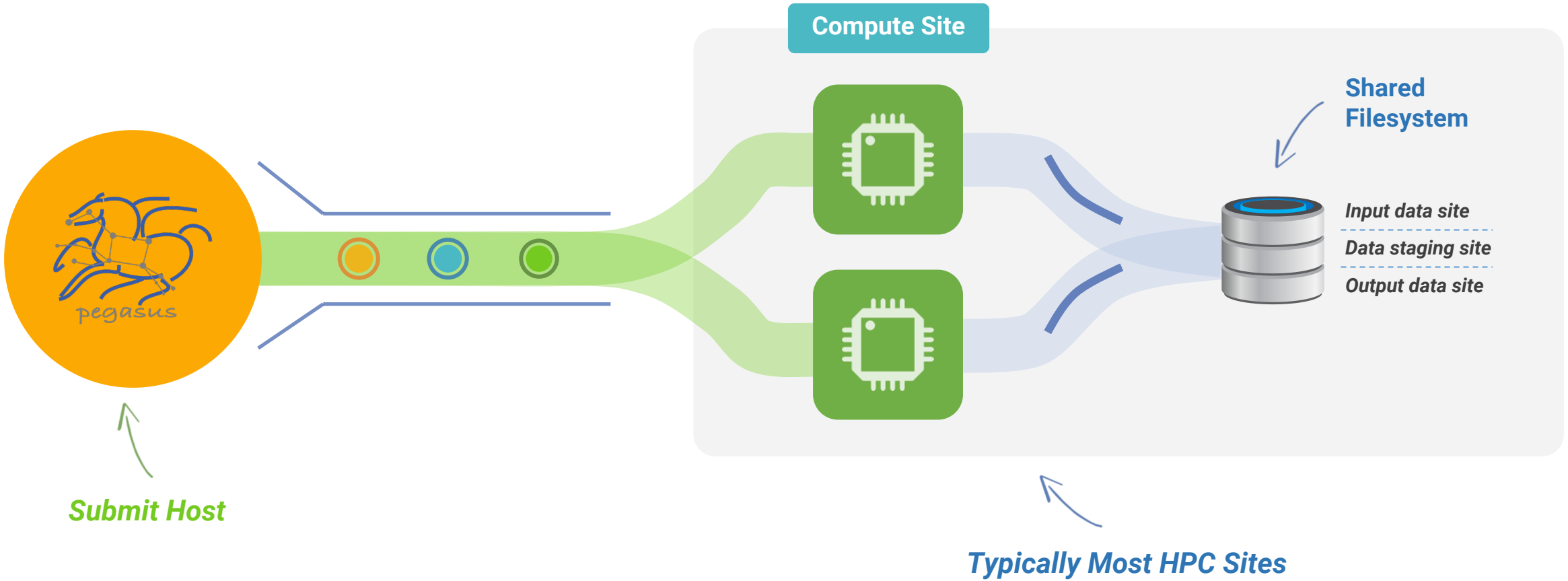
Shared File System (HPC sites, XSEDE, Campus clusters, …)

- I/O is directly against the shared file system



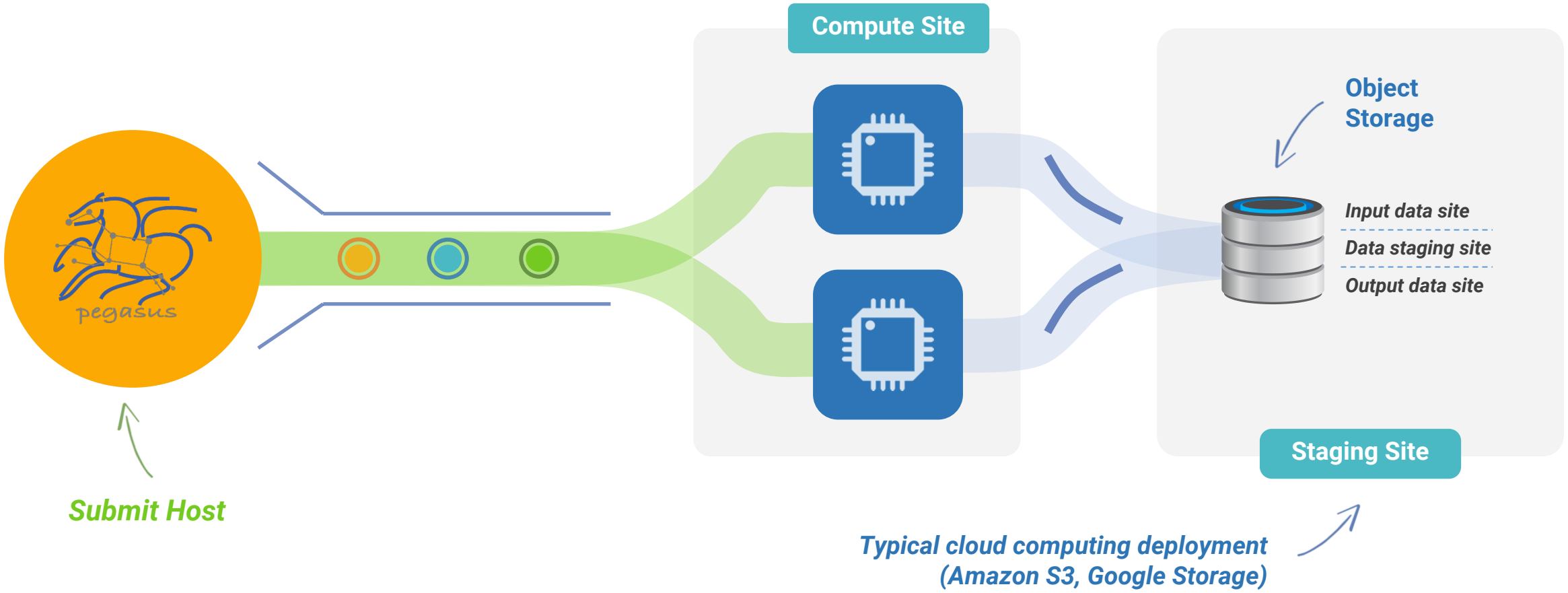
High Performance Computing

There are several possible configurations…



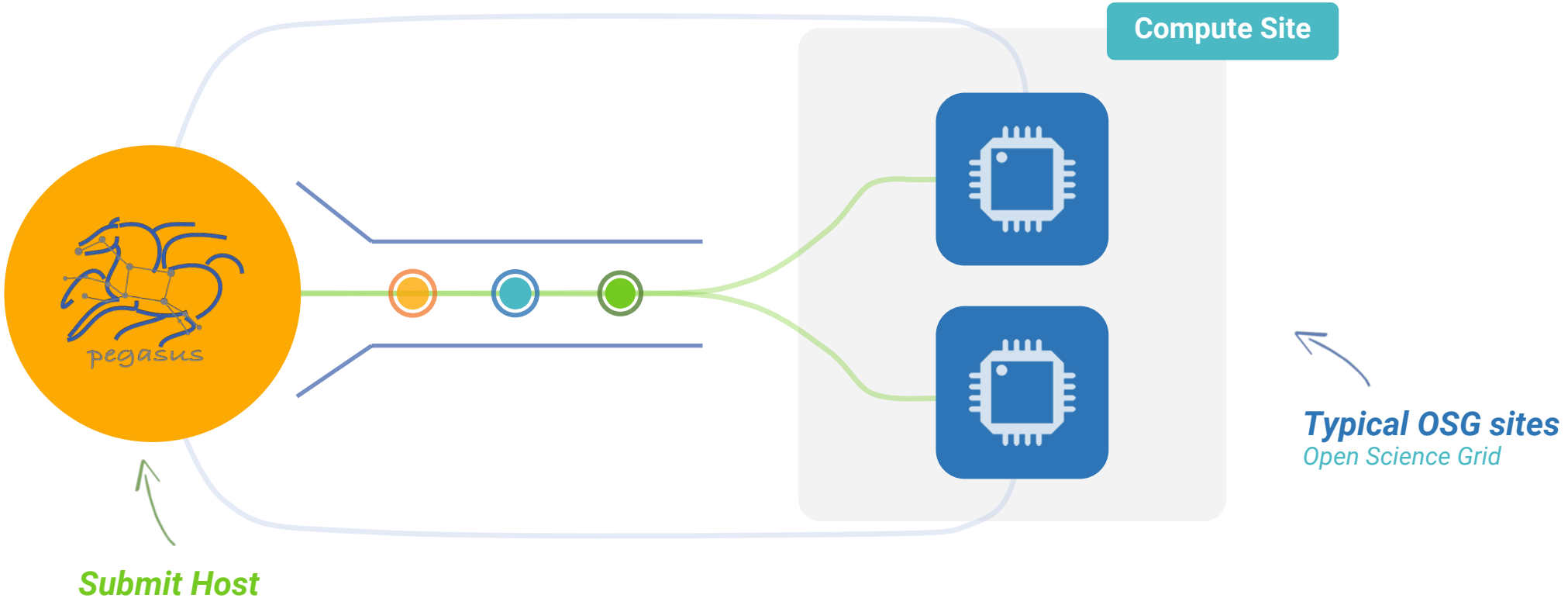
Cloud Computing

High-scalable object storages

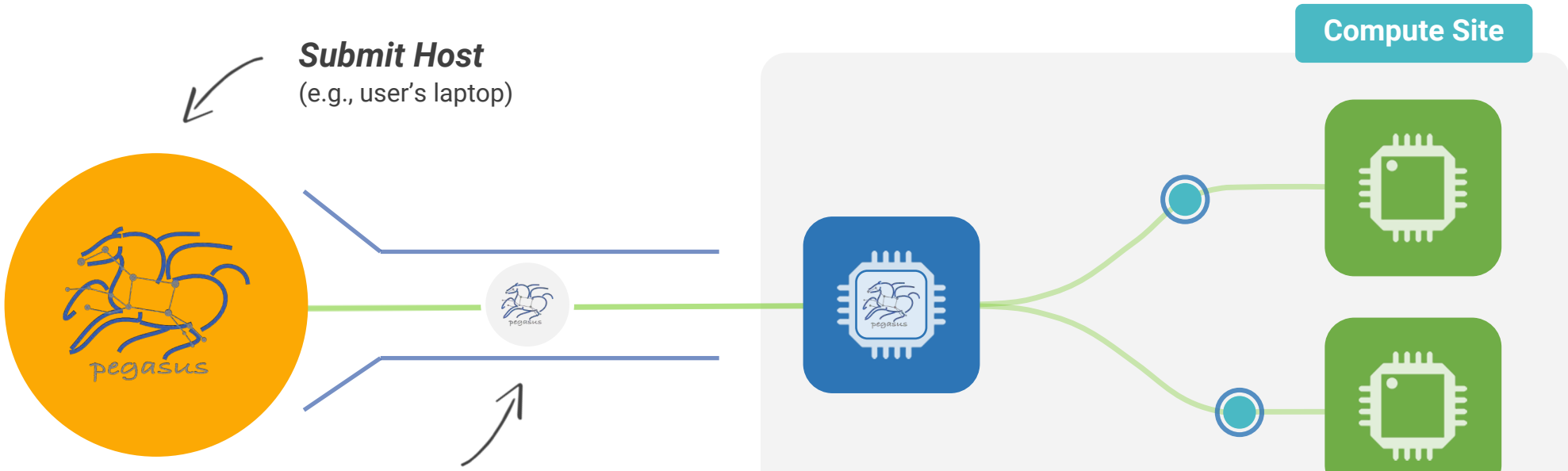


Grid Computing

Local data management



Running fine-grained workflows on HPC systems…



Workflow wrapped as an MPI job

Allows sub-graphs of a Pegasus workflow to be submitted as monolithic jobs to remote resources

Pegasus Container Support

Pegasus

docker SHIFTER

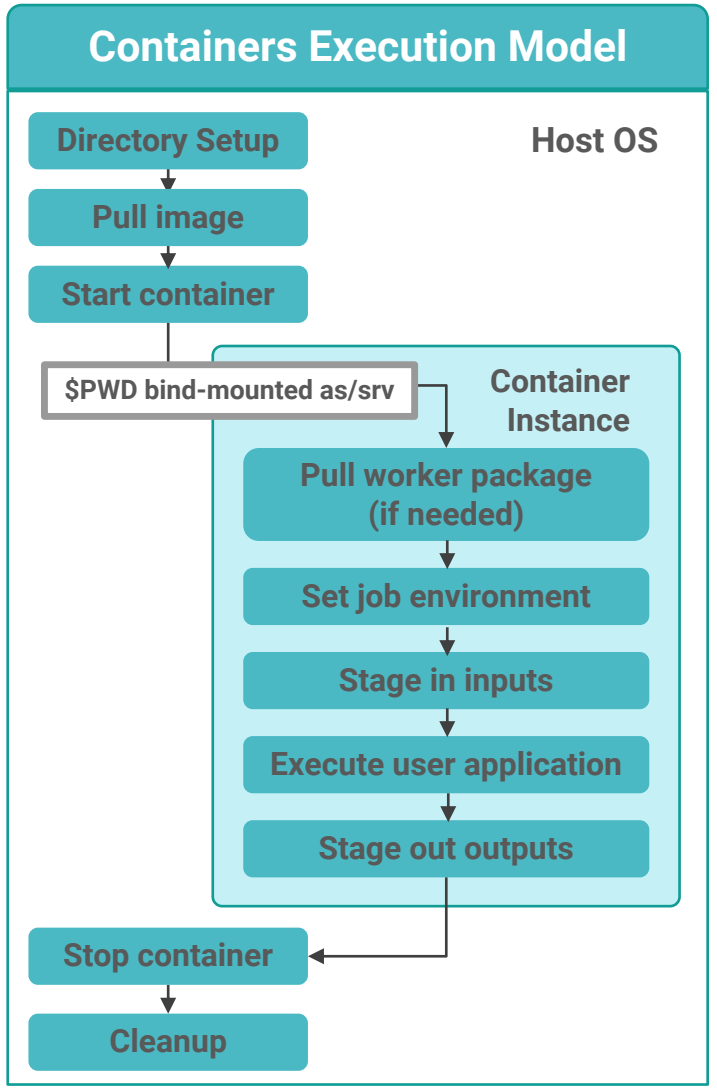
Users can refer to **containers** in the **Transformation Catalog** with their executable preinstalled

Users can **refer** to a **container** they want to **use – Pegasus stages** their executables and containers to the node

- Useful if you want to use a site recommended/standard container image.
- Users are using generic image with executable staging.

Future Plans

- Users can specify an image buildfile for their jobs.
- *Pegasus will build the Docker image as separate jobs in the executable workflow, export them as a tar file and ship them around*



Data Management for Containers


Containers are data too!

Pegasus treats containers as input data dependency

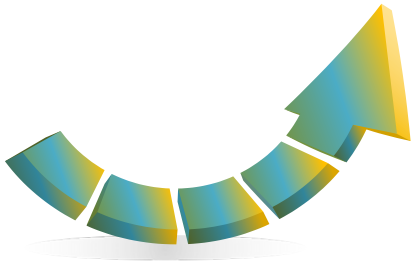
- Staged to compute node if not present
- Docker or Singularity Hub URL's
- Docker Image exported as a TAR file and available at a server, just like any other input dataset

Scaling up for larger workflows

- The image is pulled down as a tar file as part of data stage-in jobs in the workflow
- The exported tar file is then shipped with the workflow and made available to the jobs
- Pricing considerations. You are now charged if you exceed a certain rate of pulls from Hubs

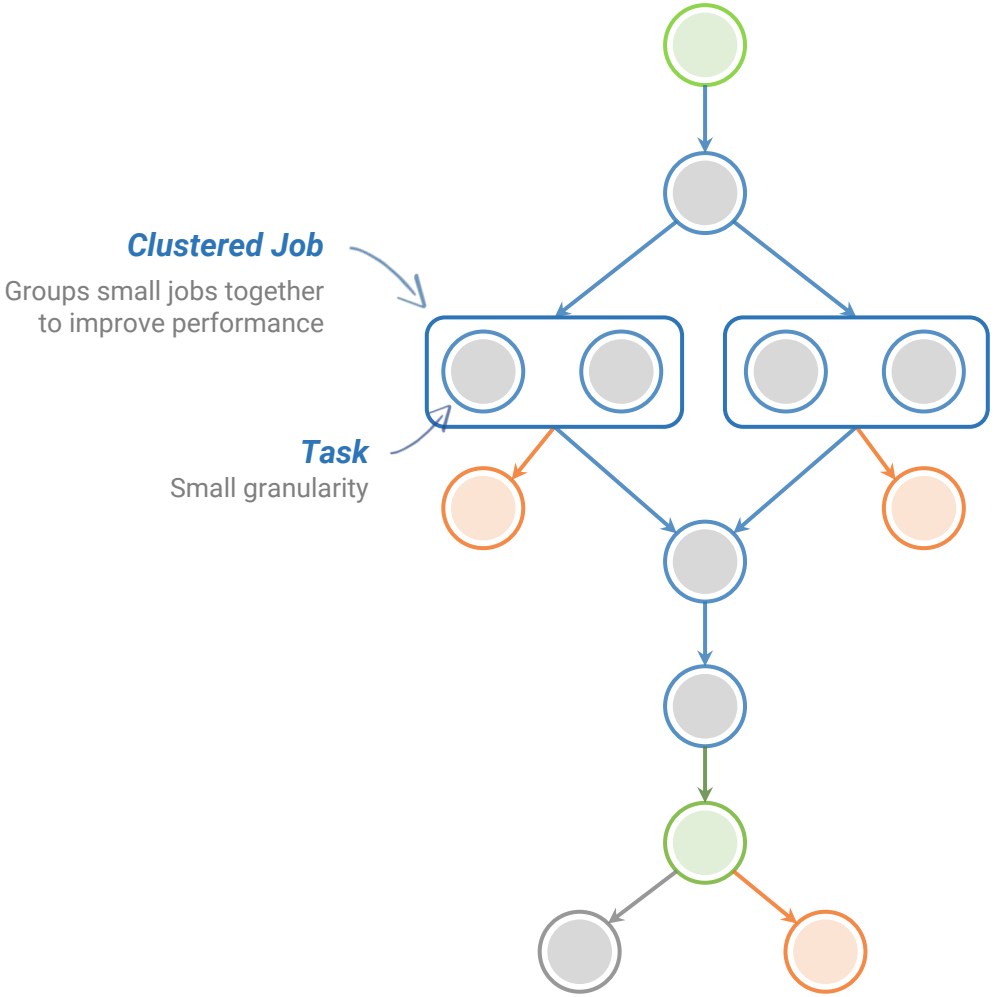
Other Optimizations

- Symlink against existing images on shared file system such as **CVMFS**
- The exported tar file is then shipped with the workflow and made available to the jobs

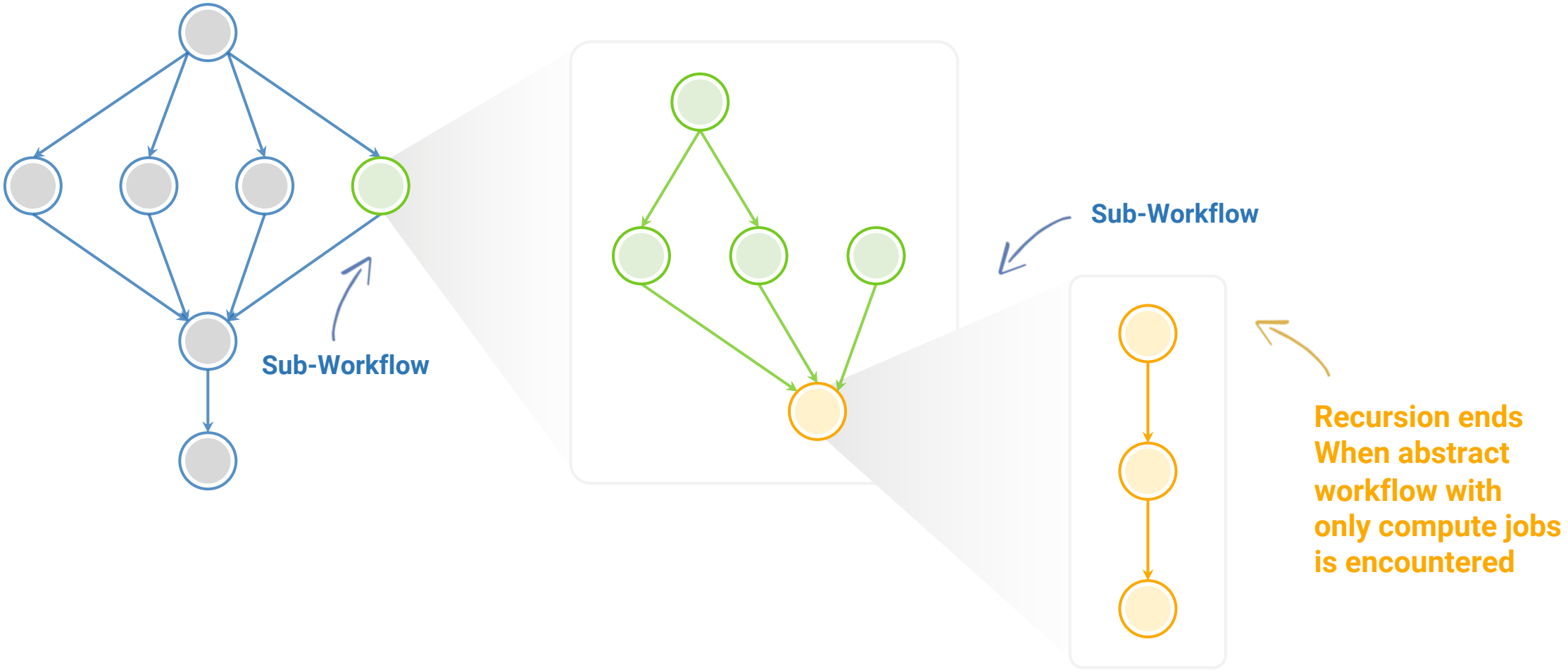


Performance.

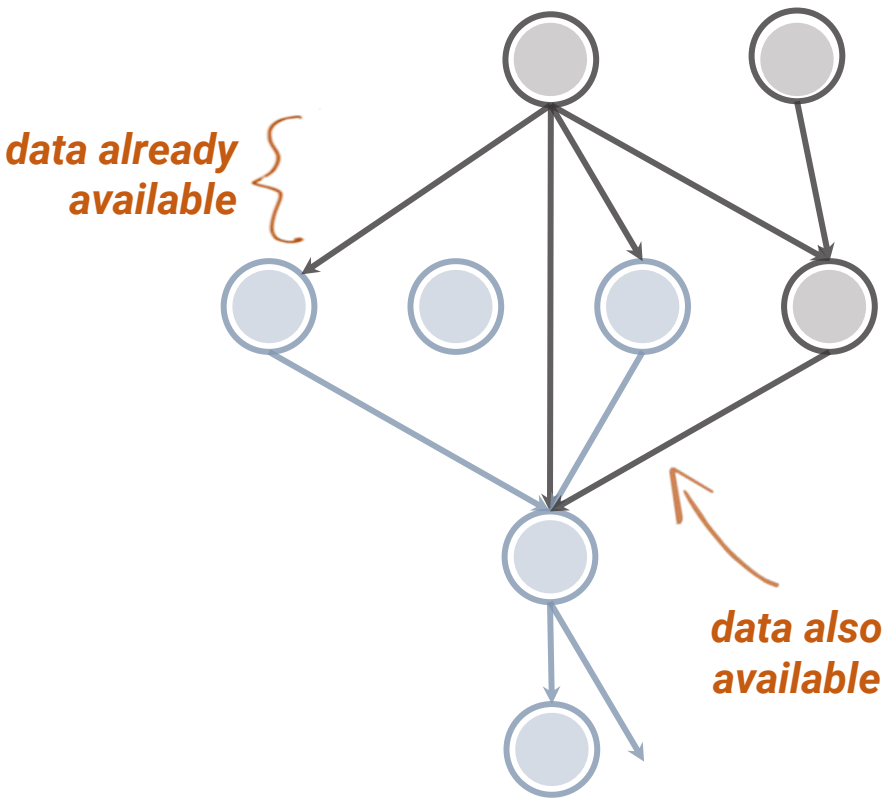
Why not improve it?



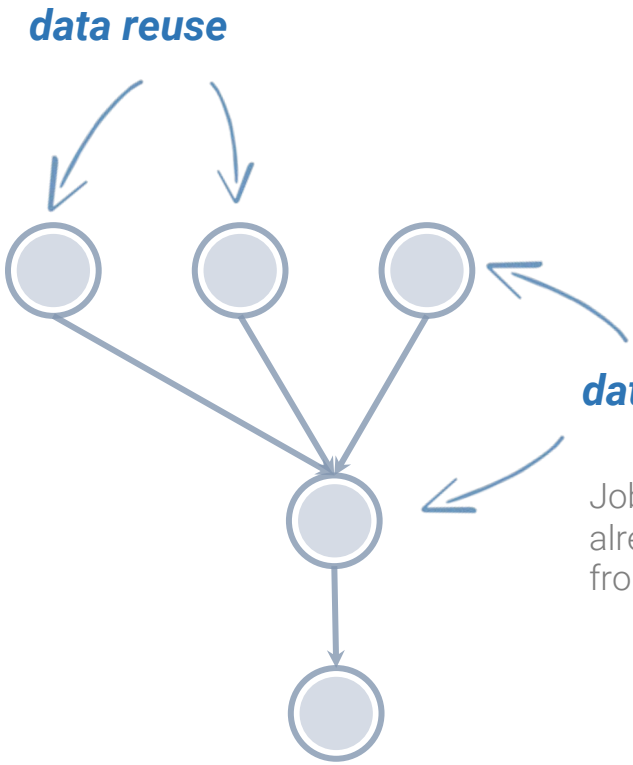
Pegasus also handles large-scale workflows



Data Reuse prune jobs if output data already exists



workflow reduction



Jobs which output data is already available are pruned from the DAG

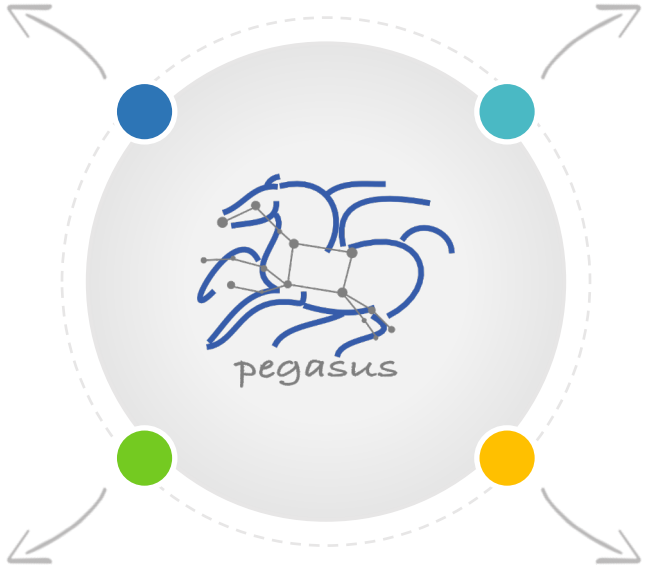
And if a job fails?

Postscript

detects non-zero exit code output parsing for success or failure message exceeded timeout do not produced expected output files

Job Retry

helps with transient failures set number of retries per job and run



Checkpoint Files

job generates checkpoint files staging of checkpoint files is automatic on restarts

Rescue DAGs

workflow can be restarted from checkpoint file recover from failures with minimal loss

Metadata

Can associate arbitrary key-value pairs with workflows, jobs, and files

Data Registration

Output files get tagged with metadata on registration in the workflow database

Static and Runtime Metadata

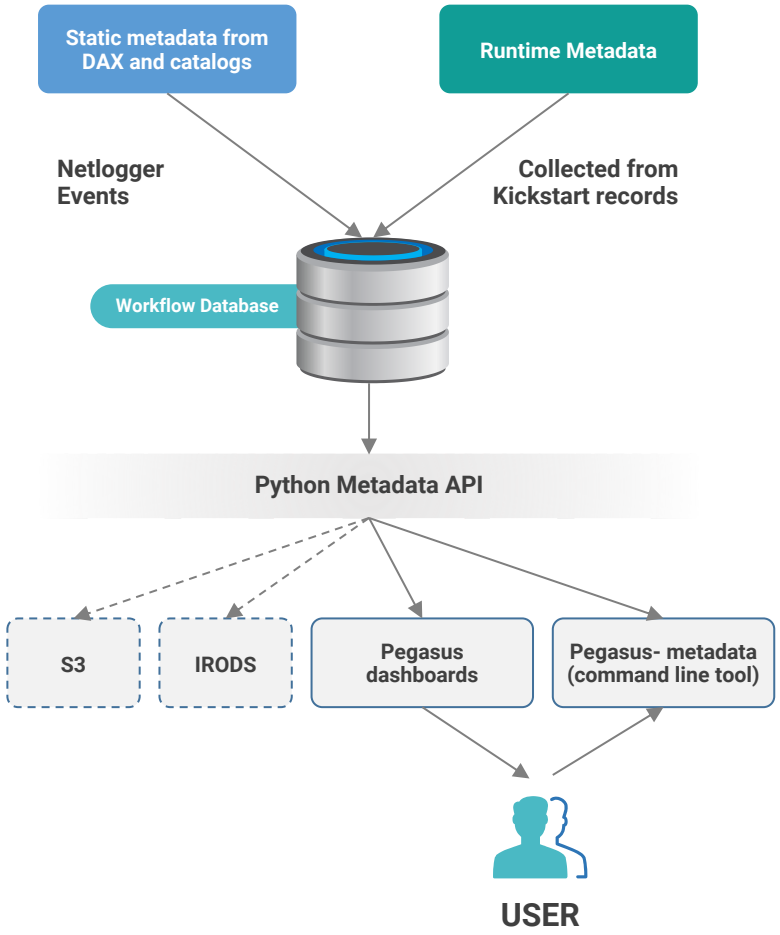
Static: application parameters
Runtime: performance metrics

Workflow, Job, File

```
x-pegasus:
apiLang: python
createdBy: vahi
createdOn: 12-08-20T10:08:48Z
pegasus: "5.0"
name: diamond
metadata:
    experiment:"par_all27_prot_lipid"
jobs:
- type: "job"
  name: "namd"
  id: "ID0000001"
  arguments: ["equilibrate.conf"]
  uses:
    - lfn: "Q42.psf"
      metadata:
        type: "psf"
        charge: "42"
    type: "input"
    - lfn: "eq.restart.coord"
      type: "output"
      metadata:
        type: "coordinates"
      stageOut: true
      registerReplica: true
  metadata:
    timesteps:500000
    temperature:200
    pressure:1.01353
```

Select Data Based on Metadata

Register Data With Metadata



Challenges to Scientific Data Integrity

Modern IT systems are not perfect
- errors creep in.

At modern **"Big Data"** sizes we are starting to see checksums breaking down.

Plus there is the threat of intentional changes:
malicious attackers, insider threats, etc.

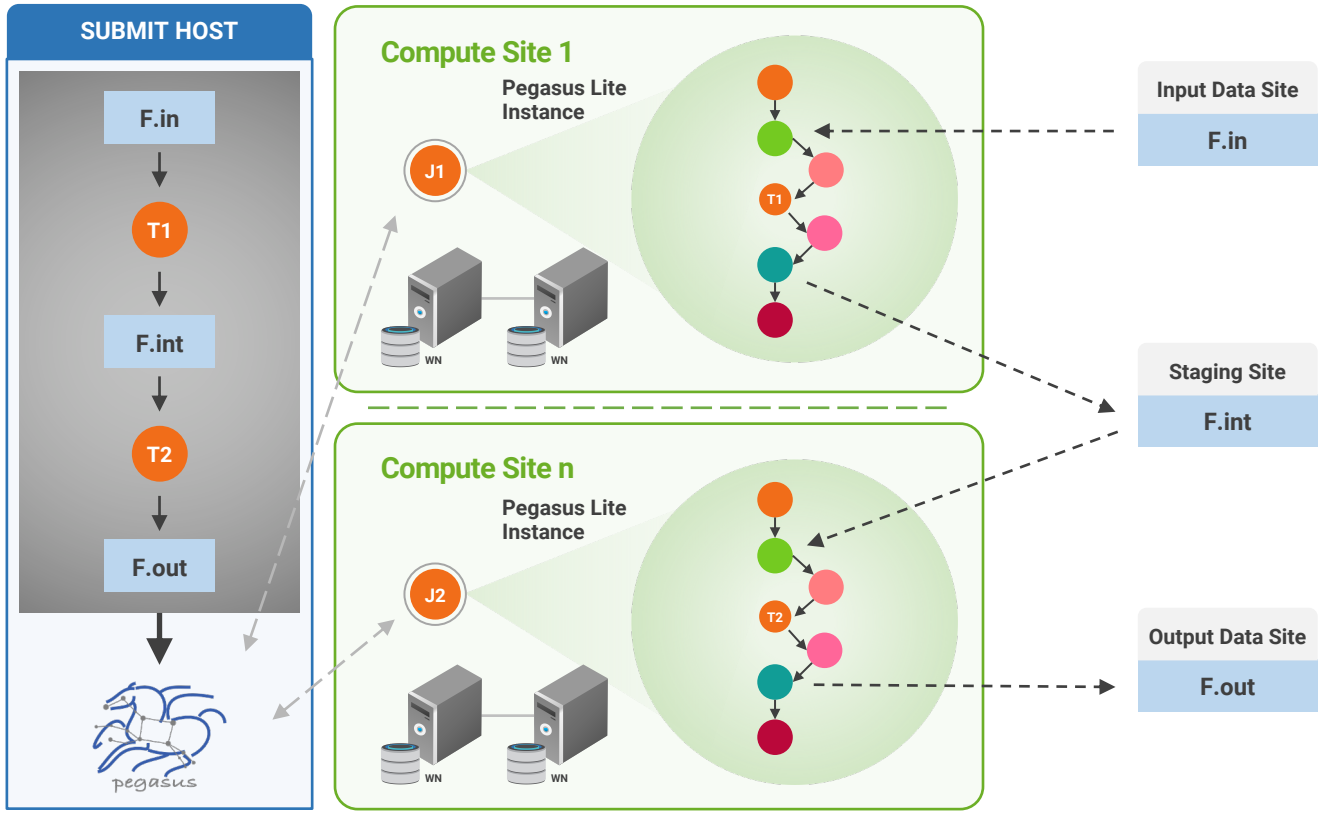
User Perception: "Am I not already protected? I have heard about TCP checksums, encrypted transfers, checksum validation, RAID and erasure coding – is that not enough?"

Automatic Integrity Checking in Pegasus

Pegasus performs integrity checksums on input files right before a job starts on the remote node.

- For raw inputs, **checksums specified in the input replica catalog** along with file locations
- All **intermediate** and **output** files checksums are generated and tracked within the system.
- Support for **sha256** checksums

Job failure is triggered if checksums fail



Pegasus

est. 2001

Automate, recover, and debug scientific computations.

Get Started

Pegasus Website
https://pegasus.isi.edu

Users Mailing List
pegasus-users@isi.edu

Support
pegasus-support@isi.edu

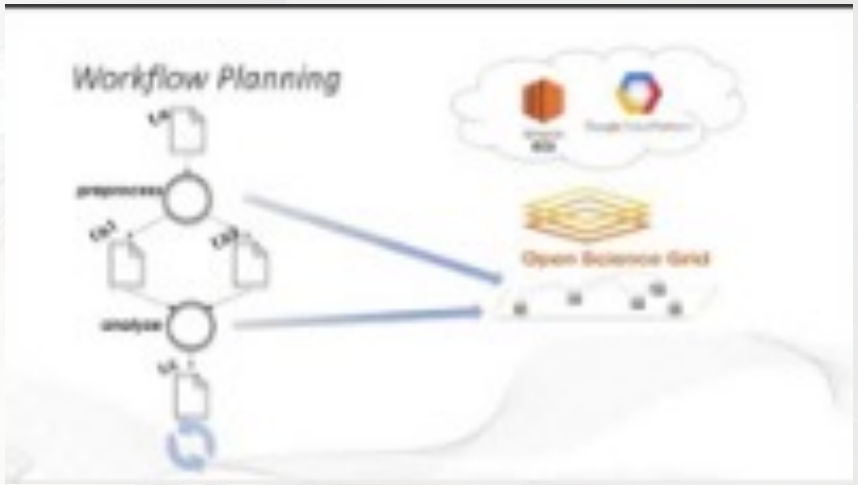
Slack
Ask for an invite by trying to join pegasus-users.slack.com in the Slack app

Pegasus Online Office Hours
https://pegasus.isi.edu/blog/online-pegasus-office-hours/

Bi-monthly basis on second Friday of the month, where we address user questions and also apprise the community of new developments

YouTube Channel

https://www.youtube.com/channel/UCwJQln1CqBvTJqiNr9X9F1Q/featured



Pegasus in 5 Minutes