THE EPICS SOFTWARE FRAMEWORK MOVES FROM CONTROLS TO PHYSICS

Greg White, for the EPICS Core Working Group

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EPICS Home Page: https://epics-controls.org
GitHub (source code) https://github.com/epics-base

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Talk Contents

1. Context
2. Additions to EPICS made by version 7
3. Selected Deployments
4. Performance and Reliability
5. Conclusions

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4 technology areas are revolutionizing our ability to operate accelerators and make experiments

1. Accelerator data and detector data sizes and rates
2. Experiment Frameworks, online tuning
3. Machine Learning and large scale optimization
4. High Level Applications rapid physics software development.

Controls Computing Strategic Drivers

Driver	Requirements
Accelerator Physics	Emittance Minimization, Luminosity Optimization. Online Modelling. Online Accelerator Physics Software (HLAs). Machine Wide Beam Synchronous Diagnostics. ML and Regression Analysis. Automated tuning. Prognostics, downtime minimization
Experiment / Detectors	Big Data – DAQ, Processing, Pipelining. Light Source Detector data size. Online Experiment Optimization.
Engineering	Control system + science data system integration. Faster, more effective development. EPICS control system version lab-wide standardization.
Economic and organizational	Cost control, funding optimization. Lab resource utilization. Interlab collaboration and resource sharing.

For these reasons, EPICS 7 was planned and developed.

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EPICS Version 7 in a Nutshell

1. New Fast Protocol, “pvAccess”
2. Structured data
3. Python and MATLAB APIs (and C++ and Java)
4. Data Services (Process variables with arguments)
5. Standardized Scientific Types
6. High Performance Streaming

- For engineers:
- Introspection interface, “pvData”
- Dynamic typing
- New smart database
- Codec based transport
- Python Services support

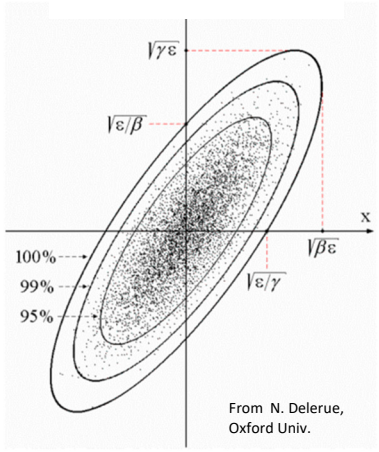
```
$ eget XCOR:LI24:900:TWISS
structure
    double energy 5.00512
    double psix 37.7625
    double alphax 13.6562
    double betax -2.78671
    double etax -0.00698294
    double etaxp 0.00107115
    double psiy 31.9488
    double alphay 116.762
    double betay 5.2592
    double etay 0
    double etayp 0
```

Figure: pvAccess method “eget”, which is for service data, getting PV of a structure of optics parameters. In this case a standard “Normative Type” type was not used, so the raw structure is displayed by eget

Faster. Structured data. Metadata. Easier.

Modelling Data through EPICS Control System

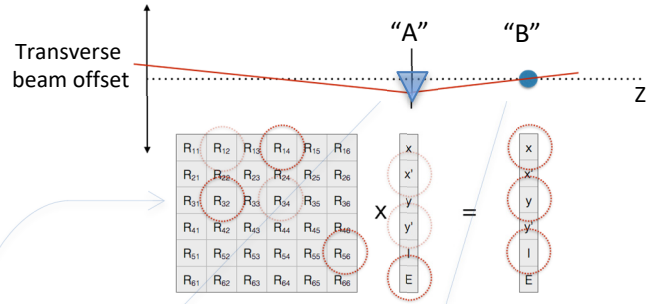
Twiss Parameters




```
$ pvget XCOR:LI24:900:TWISS
    energy 5.00512
    psix 37.7625
    alphax 13.6562
    betax -2.78671
    etax -0.00698294
    etaxp 0.00107115
    psiy 31.9488
    alphay 116.762
    betay 5.2592
    etay 0
    etayp 0
    z 2438.72
```

Structured data!

Transfer Matrices, example shows A to B




```
$ eget -s XCOR:IN20:491:RMAT -a b BPMS:IN20:525
     0.669591     0.694604            0            0 -3.08532e-19  2.41325e-19
    -0.570851     0.901275            0            0 -1.23627e-19  1.45491e-19
            0            0      1.33379     0.966896            0            0
            0            0     0.358415      1.00957            0            0
  -2.29302e-24  8.92892e-20            0            0            1  1.20724e-05
   1.00974e-28            0            0            0            0            1
```

Process Variable value, computed subject to user's arguments

Figures: EPICS 7 modelling service giving orbit response matrices and Twiss parameters for given devices - the basis of 90% of emittance minimization applications like feedback, steering, bumps, etc.

Greg White, Murali Shankar SLAC; Ivo List, ESS

Accelerator Infrastructure data through EPICS

Data Services now trivial to implement in EPICS. In Python, Java, C++, even MATLAB

Directory Services

```
# The names of PVs, by device name pattern:
$ eget -s ds -a name=XCOR:LI21:135:%
       name
       XCOR:LI21:135:ABORT
       XCOR:LI21:135:ACCESS
       XCOR:LI21:135:ALLFUNCGO
       XCOR:LI21:135:BACT
       XCOR:LI21:135:BACTFO
… (many rows snipped)
```

```
# Regular expression (restrict to sectors LI25-LI29)
$ eget -s ds -a regex='XCOR:LI2[5-9]:.*:BDES'
…
# Device names of the instruments in the laser heater region
$ eget -s ds -a etype INST -a tag LSRHTR -a show dname
…
# A recent search for invalid data in corrector PVs
$ eget -tTs ds -a name %COR:LTU%:%:%DES | \
eget -p ca -f - | grep nan
XCOR:LTU1:558:BDES nan
XCOR:LTU1:558:IDES nan
…
```

Oracle Database accessed through Control System:

```
$ eget -s LCLS:ELEMENTS
ELEMENT          ELEMENT_TYPE     EPICS_DEVICE_NAME            S_DISPLAY          OBSTRUCTION
CATHODE                   MAD         CATH:IN20:111               2014.7                    N
 SOL1BK                   MAD         SOLN:IN20:111               2014.7                    N
   CQ01                   MAD         QUAD:IN20:121               2014.9                    N
   SOL1                   MAD         SOLN:IN20:121               2014.9                    N
   XC00                   MAD         XCOR:IN20:121               2014.9                    N
 ... (many rows snipped)
```

Figure: Access to Oracle gives device infrastructure, magnet calibrations, drawing names, etc. Will be used in LCLS-II for such things as cryogenic plant system hierarchy etc.

Greg White, Murali Shankar SLAC

EPICS 7 Image Type (NTNDArray) Example

Command line request for a given image PV by name.

Data Type Identifier

Raw image data.

Widget learns how to display image form metadata

The image meta data; giving parameters to interpret data in the *value* field, and other information.

Figure: A screenshot of the output of the EPICS 7 "pvget" command, for an image.

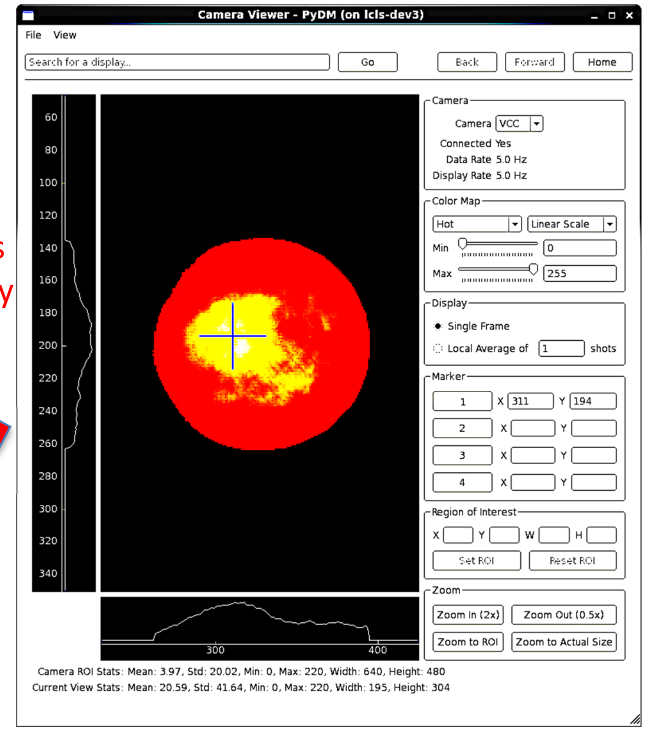


Figure: A screenshot of PyDM displaying a beam profile image.

B. Martins, BNL

The EPICS 7 “Normative Types”

The Normative Types Specification defines a standard for commonly used data types,
http://epics-pvdata.sourceforge.net/alpha/normativeTypes/normativeTypes.html

5. General Normative Types
    1. NTScalar
    2. NTScalarArray
    3. NTEnum
    4. NTMatrix
    5. NTURI
    6. NTNameValue
    7. NTTable
    8. NTAttribute
6. Specific Normative Types
    1. NTMultiChannel
    2. NTNDArray
    3. NTContinuum
    4. NTHistogram
    5. NTAggregate

```
$ eget XCOR:LI24:900:RMAT
     0.0727485     0.0289316             0             0     0.0652488     0.00125391
     0.0578214     0.0391775             0             0     -0.027185   -0.000192344
             0             0    0.00943029       1.14291             0               0
             0             0    -0.0013367    -0.0348832             0               0
  -0.000370971  -0.000283933             0             0    -0.0182387   -0.000198345
       0.10031      0.018722             0             0      -10.5721      -0.179568
```

```
$ eget pva://mccas0.slac.stanford.edu:39633/QUAD:LTU1:880:RMAT?type=design
```

```
$ eget LCLS:ELEMENTS
ELEMENT      ELEMENT_TYPE     EPICS_DEVICE_NAME    S_DISPLAY           OBSTRUCTION
CATHODE               MAD         CATH:IN20:111       2014.7                     N
 SOL1BK               MAD         SOLN:IN20:111       2014.7                     N
   CQ01               MAD         QUAD:IN20:121       2014.9                     N
   SOL1               MAD         SOLN:IN20:121       2014.9                     N
   XC00               MAD         XCOR:IN20:121       2014.9                     N
…
```

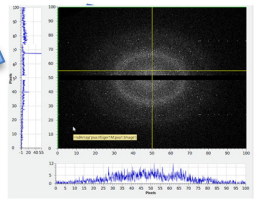
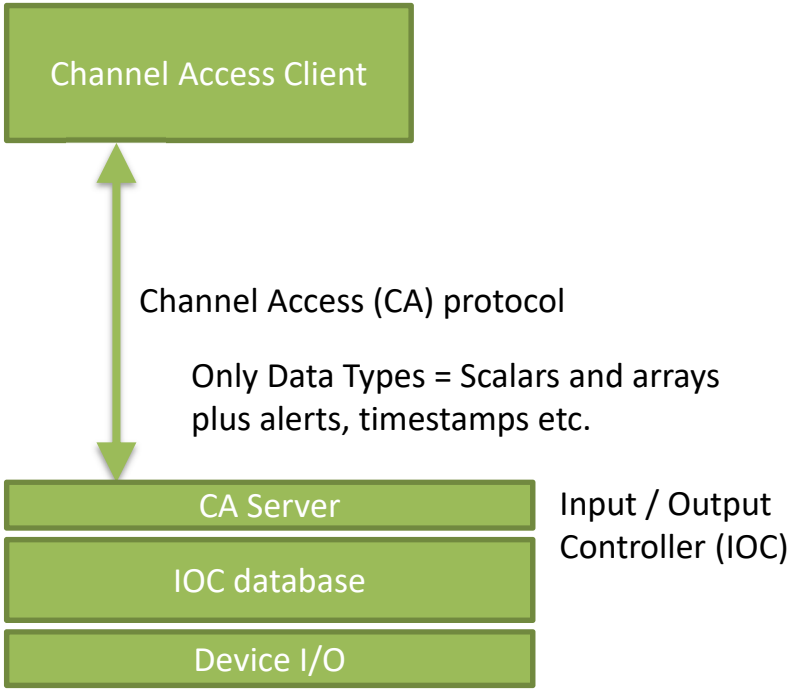


Figure: An extract of the Table of Contents of the Normative Types Specification document, together with examples of 4 selected types.

Examples from SLAC

EPICS Version 3 (legacy) basic block diagram

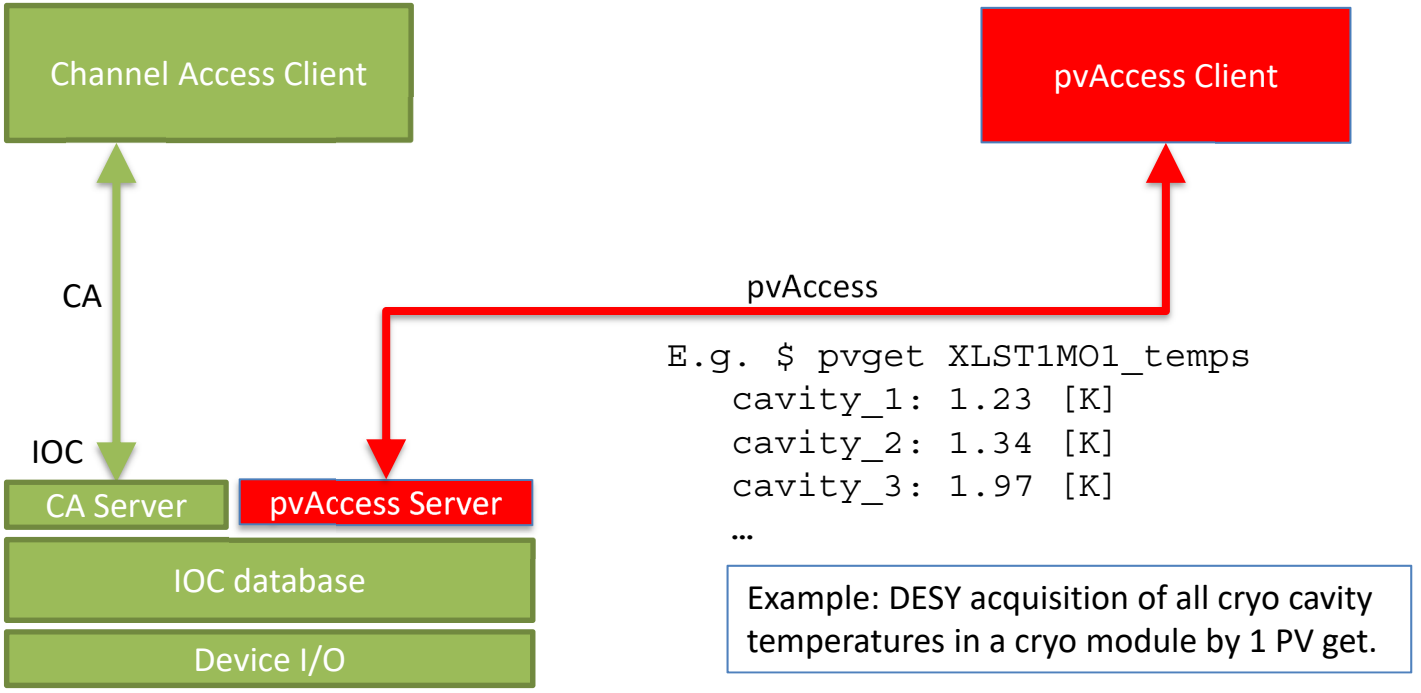
EPICS in the nominal usage: An EPICS client communicates over Channel Access (CA) protocol to an Input/Output Controller (IOC) Channel Access server (module rSrv in an IOC)



Examples: Dozens of accelerators, telescopes, and other installations worldwide. 47 listed in Wikipedia, but there are more.

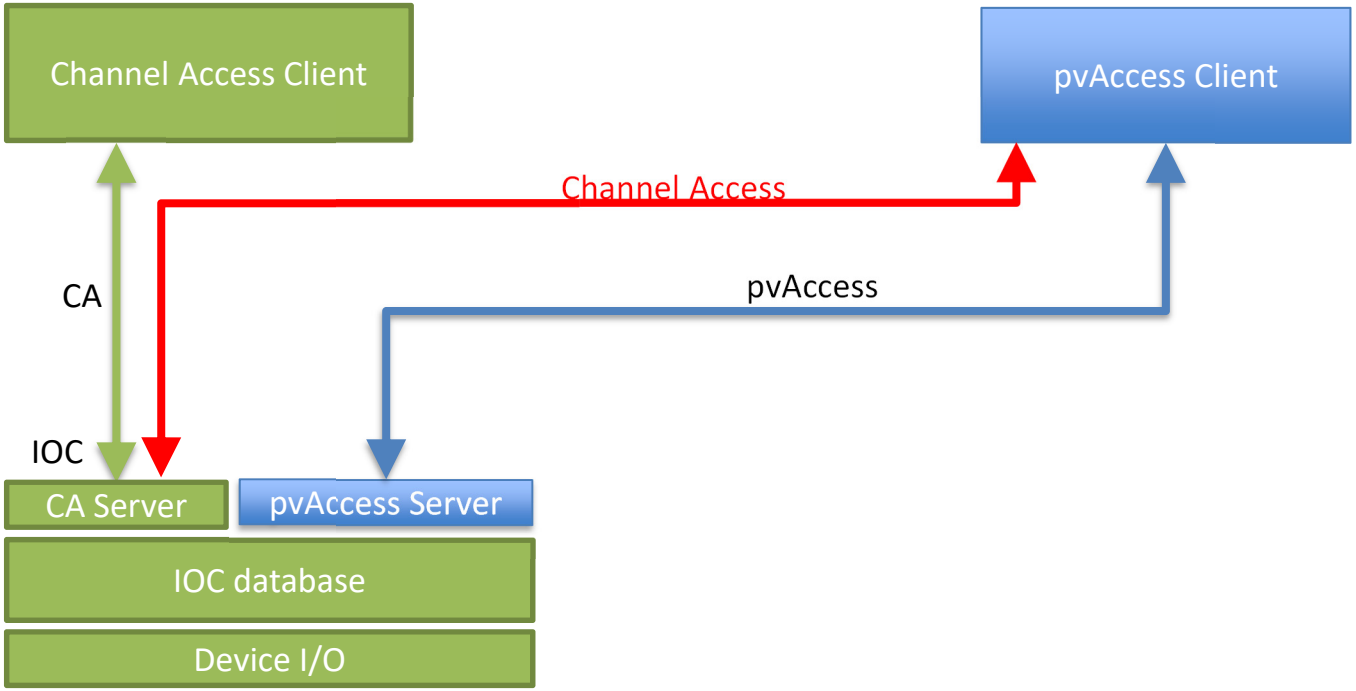
EPICS Version 7 = EPICS 3.16 + project called “Version 4”

Specifically: An EPICS 7 IOC ~= 3.16 IOC + pvAccess Server



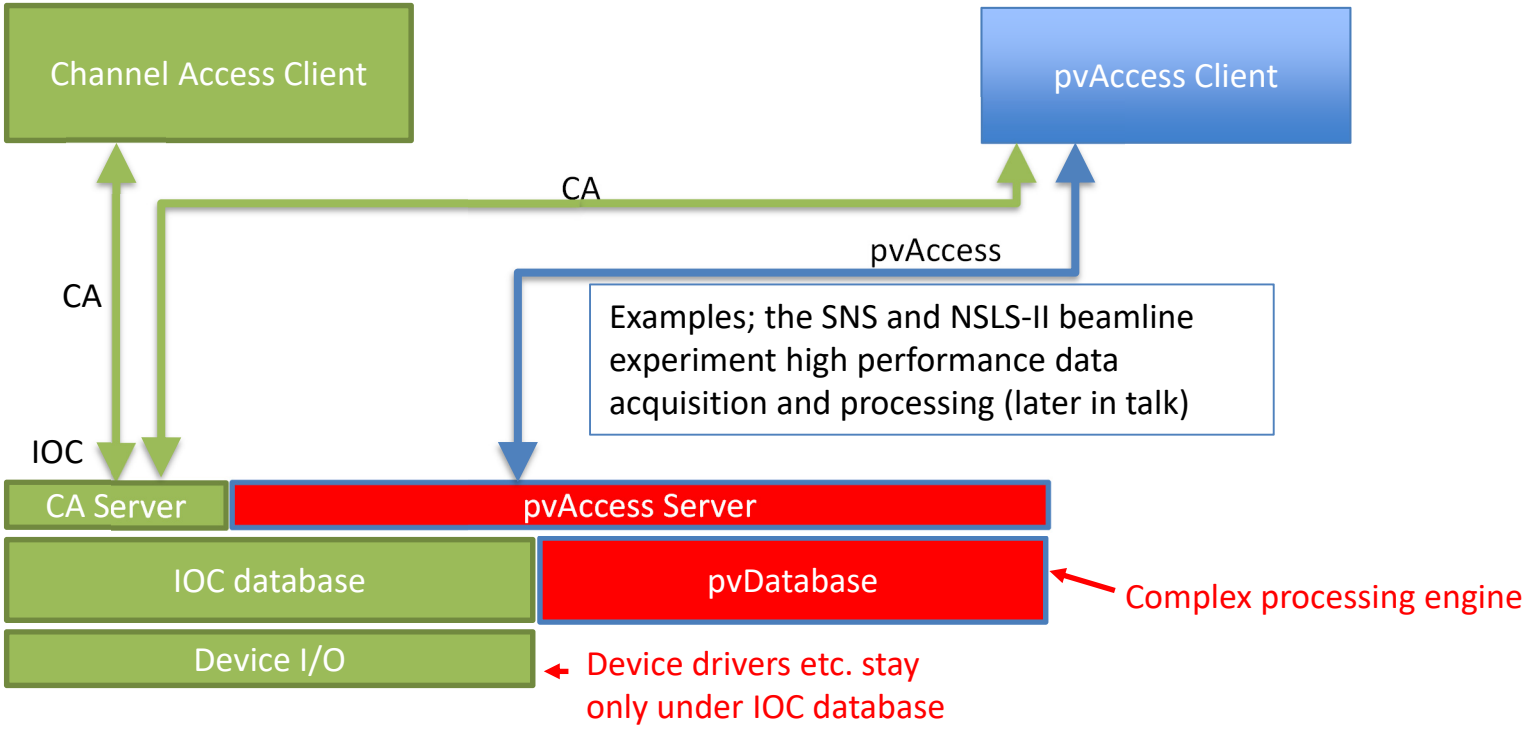
EPICS Version 7 Includes Channel Access

The pvAccess API includes Channel Access support, so one client lib does both



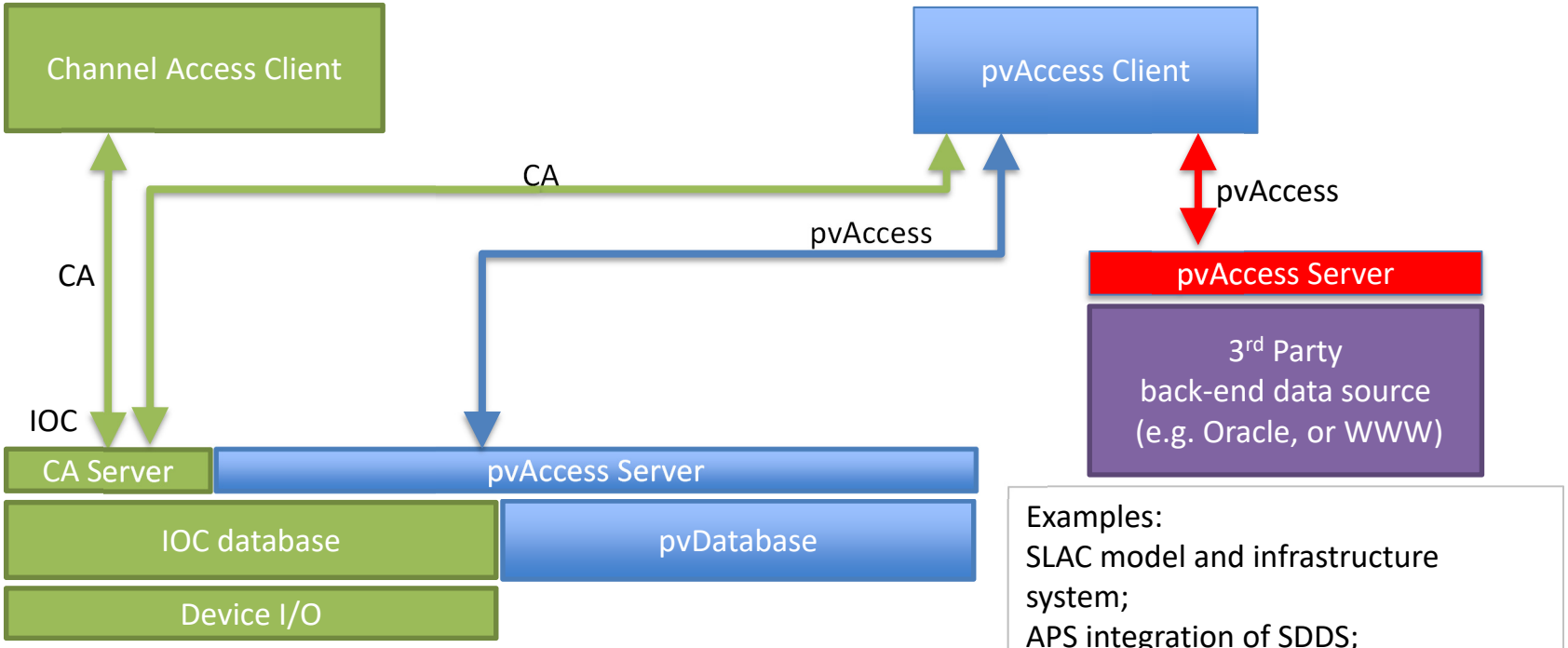
EPICS Version 7 new database

A new smart database, “pvDatabase” MAY be used for data assembly and processing



EPICS Version 7 Middleware Support

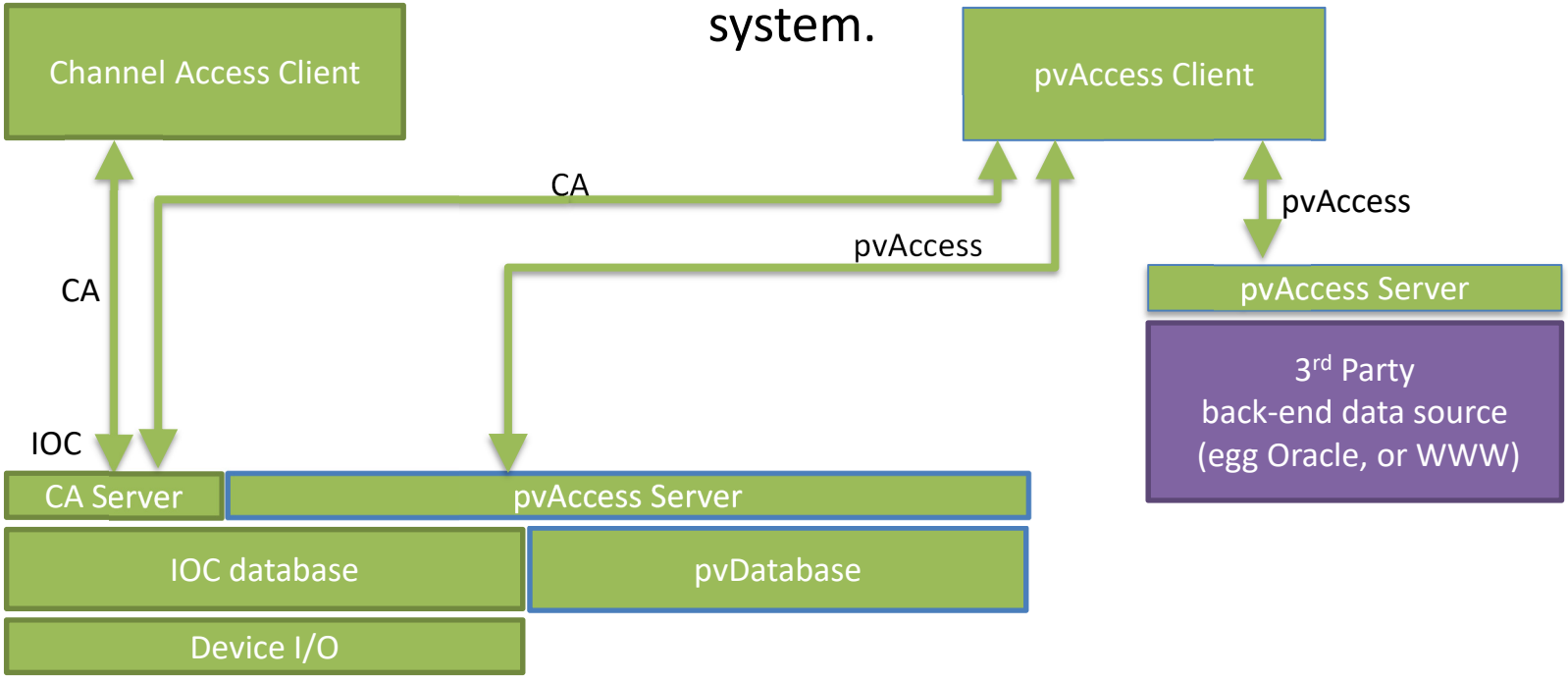
Process variables value subject to arguments ("Remote Procedure Call"), Scientific data services.



Examples:
SLAC model and infrastructure system;
APS integration of SDDS;
FRIB device configuration mgmt.

The New EPICS

So, EPICS 7 extends EPICS with new protocol, PVs of record groups, new (optional) processing database, and bringing 3rd party services into the control system.



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Argonne (APS) Deployment Plan Example

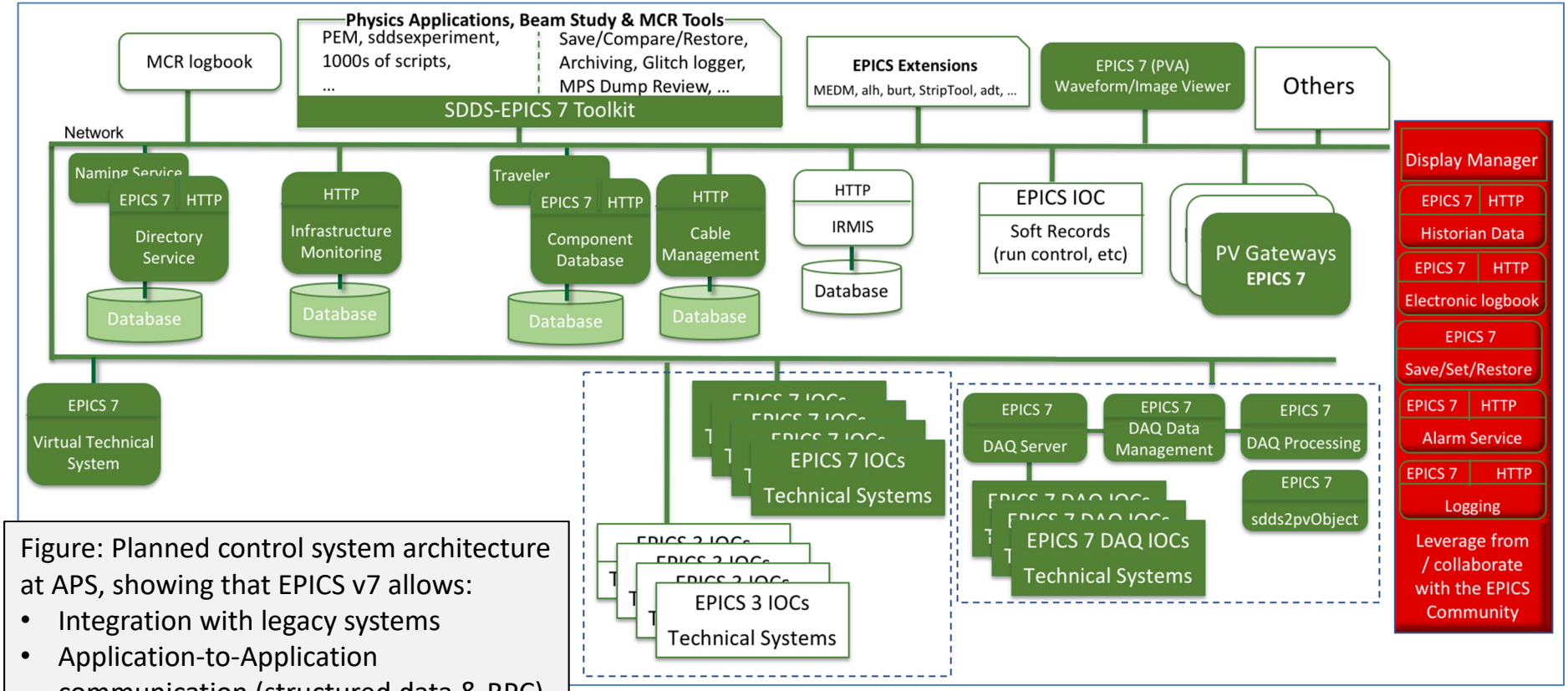


Figure: Planned control system architecture at APS, showing that EPICS v7 allows:

- Integration with legacy systems
- Application-to-Application communication (structured data & RPC).

Siniša Veseli, Andrew Johnson, Guobao Shen, ANL

Argonne (APS) Deployment Plan Example

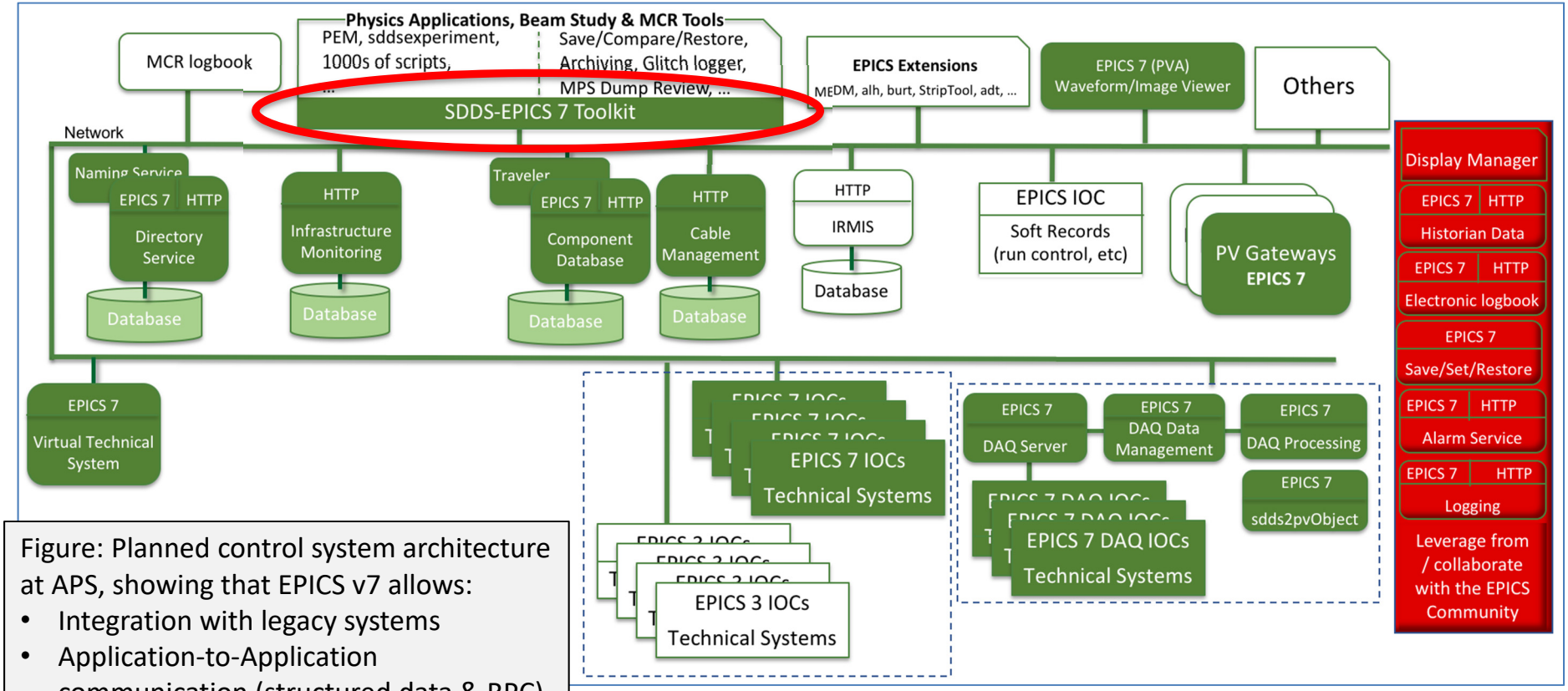


Figure: Planned control system architecture at APS, showing that EPICS v7 allows:

- Integration with legacy systems
- Application-to-Application communication (structured data & RPC).

Siniša Veseli, Andrew Johnson, Guobao Shen, ANL

SNS uses EPICS v7 for high throughput event readout, of structured PV data.

Neutron Detector

SNS SEQUOIA detector ray consisting of >800 ^{3}He tubes covering a solid angle of 0.8 steradian

nED

- pvAccess Server
- pvDatabase
- Classic EPICS IOC

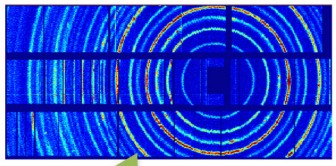
nED provides the driver interface to the detector electronics and streams experiment data using pvAccess

pvAccess streams event data at 80 Mbytes / sec

```
CHANNEL   : BL14B:Det:Neutrons
STATE     : CONNECTED
ADDRESS   : 10.111.29.150:57267
structure
    time_t timeStamp
        long secondsPastEpoch
        int nanoseconds
        int userTag
    epics:nt/NTScalar:1.0 proton_charge
        double value
    epics:nt/NTScalarArray:1.0 time_of_flight
        uint[] value
    epics:nt/NTScalarArray:1.0 pixel
        uint[] value
    epics:nt/NTScalarArray:1.0 sample_a1
        uint[] value
    epics:nt/NTScalarArray:1.0 sample_a2
        uint[] value
    epics:nt/NTScalarArray:1.0 sample_a8
        uint[] value
    epics:nt/NTScalarArray:1.0 sample_a19
        uint[] value
    epics:nt/NTScalarArray:1.0 sample_a48
        uint[] value
    epics:nt/NTScalarArray:1.0 sample_b1
        uint[] value
    epics:nt/NTScalarArray:1.0 sample_b8
        uint[] value
    epics:nt/NTScalarArray:1.0 sample_b12
        uint[] value
    epics:nt/NTScalarArray:1.0 position_index
        uint[] value
    epics:nt/NTScalarArray:1.0 position_x
        uint[] value
    epics:nt/NTScalarArray:1.0 position_y
        uint[] value
    epics:nt/NTScalarArray:1.0 photo_sum_x
        uint[] value
    epics:nt/NTScalarArray:1.0 photo_sum_y
        uint[] value
```

The EPICS 7 data structure includes an array of pixels and a corresponding array of times of flight for neutron event. Additional fields record accelerator metadata e.g. pulse information and detector diagnostic information.

CS-Studio



Diffraction rings of a powder sample at SEQUOIA

ADnED

- CA Server
- areaDetector data processing
- pvAccess Client

ADnED, a pvAccess client, generates online histograms and counting statistics from the nED data stream and serves them using the CA protocol to clients including CS-Studio

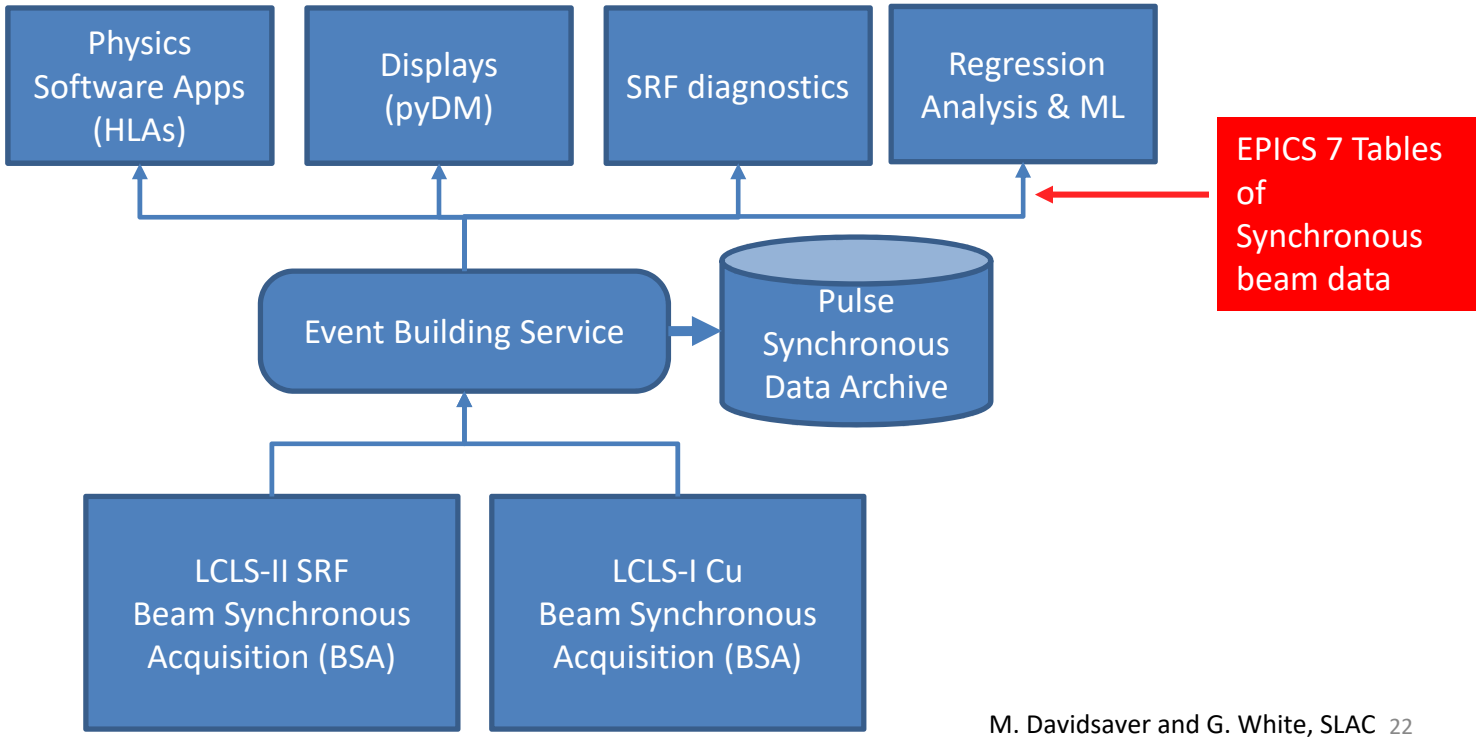
SNS/HFIR Outcomes:

1. v7 in use at 21 Beamlines
2. 10M events/s
3. Excellent reliability.

M. Pearson, K. Kasemir, S. Hartman, ORNL

All the data, all the time

Figure: Accelerator Event Building Service (of SLAC) collects all bunch-by-bunch data, lines up by bunch ID, tags with accelerator meta data, stream to clients, and archives for Machine Learning and diagnostics.



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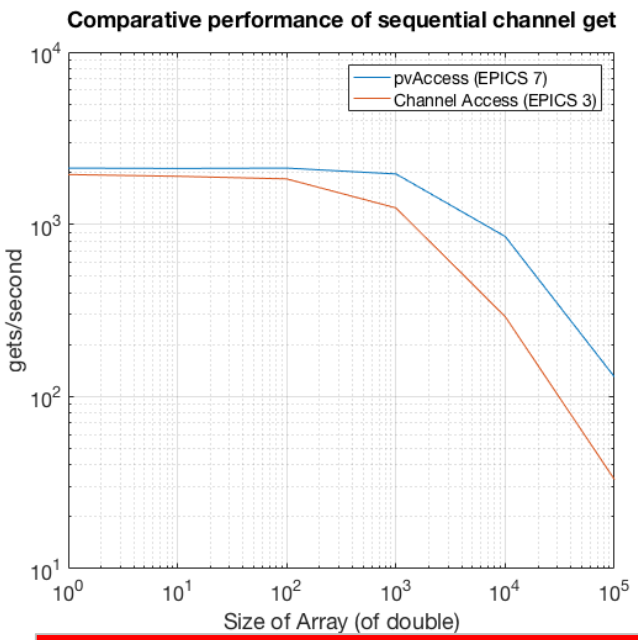
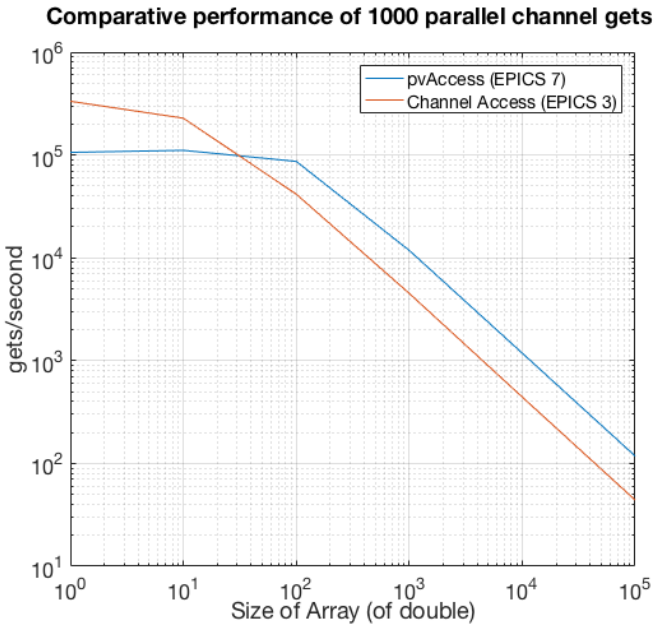
EPICS 7 network performance (pvAccess)

Comparison of new data protocol included in EPICS 7 compared to EPICS 3





pvAccess is significantly faster than EPICS 3 at big data. CA is faster at many small ops in parallel.

Use Cases Indication: Use pvAccess for machine beam synchronous accelerator data, experimental data, camera data, structured data or data & metadata. Use CA for very full synoptic displays and compatibility with legacy display mgr.

NSLS-II EPICS v7 areaDetector Performance Test

Problem – big images, network and processor limits:

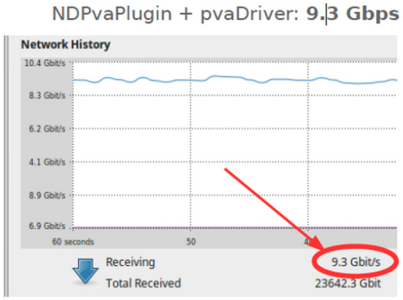
- Eiger 1M: 1030x1065 @ 3 kHz
- Eiger 4M: 2070x2167 @ 750 Hz
- Eiger 9M: 3110x3269 @ 238 Hz
- Eiger 16M: 4150x4371 @ 133 Hz

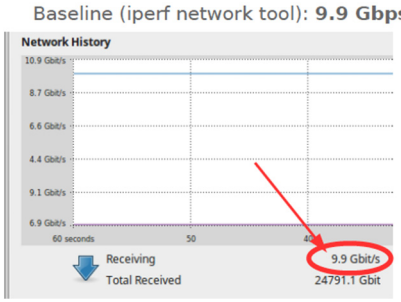
- All these detector configurations saturate a 10 Gbps link
- Other non-EPICS methods tried and failed (HTTP-chunking).

Solution test:

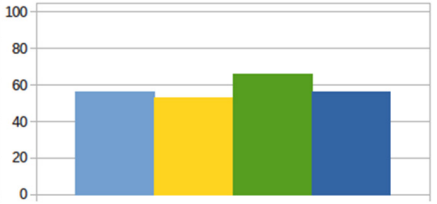
EPICS 7 server of an areaDetector plugin, NDPluginPva. EPICS 7 client areaDetector driver. Non-blocking callbacks
Test Data: 5K x 5K @ 50Hz ~= 10 Gb/s over 10Gig Ethernet. 10000 Images.

Results:





% Frames through – (more is better)



CPU usage (less is better)

Conclusions: EPICS 7 based areaDetector pipeline has high throughput, few frames lost, with no CPU saturation. Network bandwidth utilized is close the practical maximum.

Bruno Martins, BNL (following work by James Rowland and Dave Hickin at Diamond)

SLAC EPICS 7 Accelerator IOC Field Test Results

SubSystem	EPICS 7 Migration Status	Field Test Deployment Status	Test Results	Where
BPM	Full migration complete	Successful partial deployments running in production	Positive: running LCLS	LI27 and LI29
LLRF (VME-based)	Full migration complete	Successful partial deployments running in production	Positive: still early but integrated and running LCLS	LI24
Bunch Length	Full migration complete	Successful test and deployment	Positive: integrated and running LCLS	LI21 and LI24
Bunch Charge	Full migration complete	Successful test and deployment	Positive: integrated and running LCLS	LI21 and LI24
LINAC Upgrade (VME/CAMAC)	Not started	Not yet scheduled	None yet	LI20 - LI30

SLAC Conclusions: All lab and field tests successful. Planning full field IOC upgrade to EPICS 7

Thanks to E. Williams, S. Hoobler, and many others at SLAC

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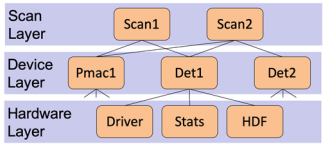
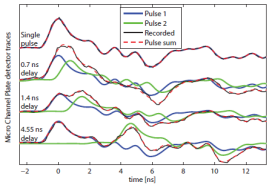
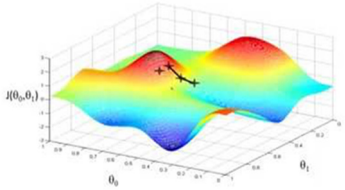
EPICS Technology Ecosystem Roles in Data Pipeline

Data Measurement & Transport	Device Abstraction / Modelling & Simulation	Collection & Event Building	Analysis & Tuning	Display & Physics Software
EPICS New network gateway. New network protocol pvAccess/pvData. Process Variables of Structured data	 OpenXAL (Java) - SNS Phantasy (Python) - FRIB Ophyd (Python) - BNL Malcolm (Python) - Diamond	Beam Synchronous Data Bunch resolved Archived data & meta data Bluesky experiment mgr. 	Bunch resolved regression analysis / ML 	High Level Apps' MATLAB and Python EPICS APIs PyDM / EPICS Qt / CSS "Display Managers" 

Community Feedback

- Performance is excellent
- Reliability needs have been met or exceeded
- Easy programming and scripting
- Successfully unifies controls and scientific systems
- Normative Types effectively enables interoperation and reuse
- Streaming supports big online data processing

- Getting started is (still) difficult due to scattered documentation.

Conclusion. Strategic Drivers Successfully Addressed

Driver	Requirements
Accelerator Physics	Emittance Minimization, Luminosity Optimization. Online Modelling. Online Accelerator Physics Software (HLAs). Machine Wide Beam Synchronous Diagnostics. ML and Regression Analysis. Automated tuning. Prognostics, downtime minimization ⇒ Structured data, RPC, MATLAB & Python APIs, Middleware esp. Python services, Bunch synchronous acq., Meta data in data, Data serialization to e.g. HDF5
Experiment / Detectors	Big Data – DAQ, Processing, Pipelining. Light Source Detector data size. Online Experiment Optimization ⇒ Fast. No CPU saturation, Native codec and compression support, HDF5, New process database, streaming, one protocol
Engineering	Control system + science data system integration. Faster, more effective development. EPICS control system version lab-wide standardization ⇒ Data Services, Python scripting, git sourced, integrated metadata, fast, reliable
Economic and organizational	Cost control, funding optimization. Lab resource utilization. Interlab collaboration and resource sharing. ⇒ Unified protocol, MATLAB & Python APIs, database driven display managers, Normative Types give interlab interoperability.

References

- The EPICS website, https://epics-controls.org
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- EPICS V4 EVALUATION FOR SNS NEUTRON DATA, K.U. Kasemir, G.S. Guyotte, M.R.Pearson, ORNL, Oak Ridge, TN37831, USA, contribution WEPGF105 of these proceedings
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