

# Exploration and Visualization of Oil Reservoir Simulation Data

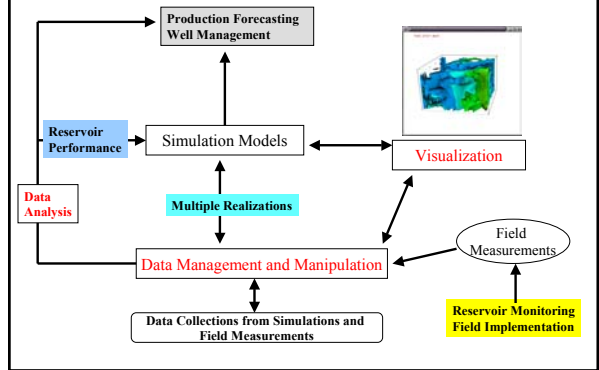
Joel Saltz, Umit Catalyurek, Tahsin Kurc  
 Biomedical Informatics Department  
 The Ohio State University  
<http://medicine.osu.edu/informatics>

Mary Wheeler, Steven Bryant,  
 Malgorzata Peszynska, Ryan Martino  
 Center for Subsurface Modeling  
 University of Texas at Austin  
<http://www.ticam.utexas.edu/CSM>

Alan Sussman, Michael Beynon  
 Department of Computer Science  
 University of Maryland  
<http://www.cs.umd.edu/projects/adr>

Don Stredney, Dennis Sessanna  
 Interface Laboratory  
 The Ohio Supercomputer Center  
<http://www.osc.edu>

# Economic Modeling and Well Management



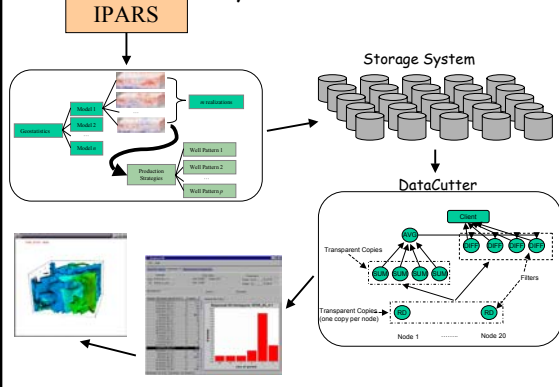
# Motivation and Challenges

- Implementing effective oil and gas production
  - Optimizing well placement
  - Efficient exploration of possible production strategies
- Challenges: Geologic uncertainty, operational flexibility, and large, detailed flow models
- Simulation: Small scale can be done
- geostatistical: Large scale exploration is not trivial
- Evaluation: Remote exploration capability
- Enable: Large storage space
  - Integration of a robust, Grid-based computational and data handling infrastructure

# Approach

- Combine leading-edge computational tools
  - IPARS for reservoir simulation
  - DataCutter/ADR for terascale data management/interrogation
  - DISCOVER for collaborative/interactive simulation
- Evaluate geologic uncertainty and production strategies simultaneously
  - Multiple realizations of multiple geostatistical models
  - Multiple production strategies (number, location of wells)

# System Architecture



# IPARS: Integrated Parallel Accurate Reservoir Simulator

- 8 individual physical models / algorithms for multiphase flow and transport
- Implemented in a common framework providing
  - memory management for general geometry grids
  - linear solvers with state-of-the-art preconditioners
  - portable parallel communication
  - keyword input and output with visualization
  - "hooks" for well management and other reservoir processes
- Code is portable across several serial and parallel platforms including Linux (clusters), SGI, RS6000, T3E, Windows (DOS)

## System Support for Exploration of Large Datasets

**DataCutter:** A suite of Middleware for subsetting and filtering multi-dimensional datasets stored in a distributed environment

- **Indexing Service**
  - Multilevel hierarchical indexes based on spatial indexing methods - e.g., R-trees
- **Filtering Service**
  - Distributed C++ component framework
  - Specialized components for processing data
  - **filters** - logical unit of computation, high level tasks,
    - `init`, `process`, `finalize` interface
  - **streams** - how filters communicate
    - unidirectional buffer pipes
    - uses fixed size buffers (min, good)
  - manually specify filter connectivity and filter-level characteristics
- **Active Data Repository (ADR):** C++ class library and runtime system for building parallel databases of multi-dimensional datasets

## Dataset

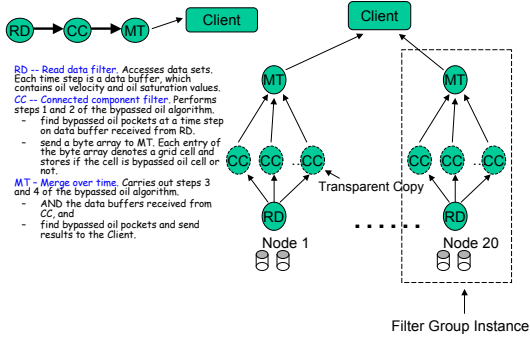
- Data size = ~1.5TB
- 207 simulations, selected from
  - 18 Geostatistics Models (GM)
  - 10 Realizations of each model (R)
  - 4 Well Patterns (WP)
- Each simulation is ~6.9GB
  - 10,000 time steps
  - 9,000 grid elements
  - 8 scalars + 3 vectors = 17 variables
- Stored on UMD Storage Cluster
  - 9TB disks on 50 nodes: PIII-650, 128MB, Switched Ethernet

## Economic Model

- Economic assessment
  - Net Present Value (NPV)
  - Return on Investment (ROI)
  - Sweep Efficiency (SE)
- Queries
  - return R-WP for given GM that has NPV > avg
  - return R-WP for all GM which has max NPV
  - ...

GM	R	WP	NPV	ROI	SE
GM1	R1	WP1	1000000	15%	80%
GM1	R2	WP1	1200000	18%	85%
GM1	R3	WP1	1100000	16%	82%
GM1	R4	WP1	1300000	20%	90%
GM1	R5	WP1	1400000	22%	95%
GM1	R6	WP1	1500000	24%	100%
GM1	R7	WP1	1600000	26%	105%
GM1	R8	WP1	1700000	28%	110%
GM1	R9	WP1	1800000	30%	115%
GM1	R10	WP1	1900000	32%	120%
GM1	R11	WP1	2000000	34%	125%
GM1	R12	WP1	2100000	36%	130%
GM1	R13	WP1	2200000	38%	135%
GM1	R14	WP1	2300000	40%	140%
GM1	R15	WP1	2400000	42%	145%
GM1	R16	WP1	2500000	44%	150%
GM1	R17	WP1	2600000	46%	155%
GM1	R18	WP1	2700000	48%	160%
GM1	R19	WP1	2800000	50%	165%
GM1	R20	WP1	2900000	52%	170%
GM1	R21	WP1	3000000	54%	175%
GM1	R22	WP1	3100000	56%	180%
GM1	R23	WP1	3200000	58%	185%
GM1	R24	WP1	3300000	60%	190%
GM1	R25	WP1	3400000	62%	195%
GM1	R26	WP1	3500000	64%	200%
GM1	R27	WP1	3600000	66%	205%
GM1	R28	WP1	3700000	68%	210%
GM1	R29	WP1	3800000	70%	215%
GM1	R30	WP1	3900000	72%	220%
GM1	R31	WP1	4000000	74%	225%
GM1	R32	WP1	4100000	76%	230%
GM1	R33	WP1	4200000	78%	235%
GM1	R34	WP1	4300000	80%	240%
GM1	R35	WP1	4400000	82%	245%
GM1	R36	WP1	4500000	84%	250%
GM1	R37	WP1	4600000	86%	255%
GM1	R38	WP1	4700000	88%	260%
GM1	R39	WP1	4800000	90%	265%
GM1	R40	WP1	4900000	92%	270%
GM1	R41	WP1	5000000	94%	275%
GM1	R42	WP1	5100000	96%	280%
GM1	R43	WP1	5200000	98%	285%
GM1	R44	WP1	5300000	100%	290%
GM1	R45	WP1	5400000	102%	295%
GM1	R46	WP1	5500000	104%	300%
GM1	R47	WP1	5600000	106%	305%
GM1	R48	WP1	5700000	108%	310%
GM1	R49	WP1	5800000	110%	315%
GM1	R50	WP1	5900000	112%	320%
GM1	R51	WP1	6000000	114%	325%
GM1	R52	WP1	6100000	116%	330%
GM1	R53	WP1	6200000	118%	335%
GM1	R54	WP1	6300000	120%	340%
GM1	R55	WP1	6400000	122%	345%
GM1	R56	WP1	6500000	124%	350%
GM1	R57	WP1	6600000	126%	355%
GM1	R58	WP1	6700000	128%	360%
GM1	R59	WP1	6800000	130%	365%
GM1	R60	WP1	6900000	132%	370%
GM1	R61	WP1	7000000	134%	375%
GM1	R62	WP1	7100000	136%	380%
GM1	R63	WP1	7200000	138%	385%
GM1	R64	WP1	7300000	140%	390%
GM1	R65	WP1	7400000	142%	395%
GM1	R66	WP1	7500000	144%	400%
GM1	R67	WP1	7600000	146%	405%
GM1	R68	WP1	7700000	148%	410%
GM1	R69	WP1	7800000	150%	415%
GM1	R70	WP1	7900000	152%	420%
GM1	R71	WP1	8000000	154%	425%
GM1	R72	WP1	8100000	156%	430%
GM1	R73	WP1	8200000	158%	435%
GM1	R74	WP1	8300000	160%	440%
GM1	R75	WP1	8400000	162%	445%
GM1	R76	WP1	8500000	164%	450%
GM1	R77	WP1	8600000	166%	455%
GM1	R78	WP1	8700000	168%	460%
GM1	R79	WP1	8800000	170%	465%
GM1	R80	WP1	8900000	172%	470%
GM1	R81	WP1	9000000	174%	475%
GM1	R82	WP1	9100000	176%	480%
GM1	R83	WP1	9200000	178%	485%
GM1	R84	WP1	9300000	180%	490%
GM1	R85	WP1	9400000	182%	495%
GM1	R86	WP1	9500000	184%	500%
GM1	R87	WP1	9600000	186%	505%
GM1	R88	WP1	9700000	188%	510%
GM1	R89	WP1	9800000	190%	515%
GM1	R90	WP1	9900000	192%	520%
GM1	R91	WP1	10000000	194%	525%
GM1	R92	WP1	10100000	196%	530%
GM1	R93	WP1	10200000	198%	535%
GM1	R94	WP1	10300000	200%	540%
GM1	R95	WP1	10400000	202%	545%
GM1	R96	WP1	10500000	204%	550%
GM1	R97	WP1	10600000	206%	555%
GM1	R98	WP1	10700000	208%	560%
GM1	R99	WP1	10800000	210%	565%
GM1	R100	WP1	10900000	212%	570%
GM1	R101	WP1	11000000	214%	575%
GM1	R102	WP1	11100000	216%	580%
GM1	R103	WP1	11200000	218%	585%
GM1	R104	WP1	11300000	220%	590%
GM1	R105	WP1	11400000	222%	595%
GM1	R106	WP1	11500000	224%	600%
GM1	R107	WP1	11600000	226%	605%
GM1	R108	WP1	11700000	228%	610%
GM1	R109	WP1	11800000	230%	615%
GM1	R110	WP1	11900000	232%	620%
GM1	R111	WP1	12000000	234%	625%
GM1	R112	WP1	12100000	236%	630%
GM1	R113	WP1	12200000	238%	635%
GM1	R114	WP1	12300000	240%	640%
GM1	R115	WP1	12400000	242%	645%
GM1	R116	WP1	12500000	244%	650%
GM1	R117	WP1	12600000	246%	655%
GM1	R118	WP1	12700000	248%	660%
GM1	R119	WP1	12800000	250%	665%
GM1	R120	WP1	12900000	252%	670%
GM1	R121	WP1	13000000	254%	675%
GM1	R122	WP1	13100000	256%	680%
GM1	R123	WP1	13200000	258%	685%
GM1	R124	WP1	13300000	260%	690%
GM1	R125	WP1	13400000	262%	695%
GM1	R126	WP1	13500000	264%	700%
GM1	R127	WP1	13600000	266%	705%
GM1	R128	WP1	13700000	268%	710%
GM1	R129	WP1	13800000	270%	715%
GM1	R130	WP1	13900000	272%	720%
GM1	R131	WP1	14000000	274%	725%
GM1	R132	WP1	14100000	276%	730%
GM1	R133	WP1	14200000	278%	735%
GM1	R134	WP1	14300000	280%	740%
GM1	R135	WP1	14400000	282%	745%
GM1	R136	WP1	14500000	284%	750%
GM1	R137	WP1	14600000	286%	755%
GM1	R138	WP1	14700000	288%	760%
GM1	R139	WP1	14800000	290%	765%
GM1	R140	WP1	14900000	292%	770%
GM1	R141	WP1	15000000	294%	775%
GM1	R142	WP1	15100000	296%	780%
GM1	R143	WP1	15200000	298%	785%
GM1	R144	WP1	15300000	300%	790%
GM1	R145	WP1	15400000	302%	795%
GM1	R146	WP1	15500000	304%	800%
GM1	R147	WP1	15600000	306%	805%
GM1	R148	WP1	15700000	308%	810%
GM1	R149	WP1	15800000	310%	815%
GM1	R150	WP1	15900000	312%	820%
GM1	R151	WP1	16000000	314%	825%
GM1	R152	WP1	16100000	316%	830%
GM1	R153	WP1	16200000	318%	835%
GM1	R154	WP1	16300000	320%	840%
GM1	R155	WP1	16400000	322%	845%
GM1	R156	WP1	16500000	324%	850%
GM1	R157	WP1	16600000	326%	855%
GM1	R158	WP1	16700000	328%	860%
GM1	R159	WP1	16800000	330%	865%
GM1	R160	WP1	16900000	332%	870%
GM1	R161	WP1	17000000	334%	875%
GM1	R162	WP1	17100000	336%	880%
GM1	R163	WP1	17200000	338%	885%
GM1	R164	WP1	17300000	340%	890%
GM1	R165	WP1	17400000	342%	895%
GM1	R166	WP1	17500000	344%	900%
GM1	R167	WP1	17600000	346%	905%
GM1	R168	WP1	17700000	348%	910%
GM1	R169	WP1	17800000	350%	915%
GM1	R170	WP1	17900000	352%	920%
GM1	R171	WP1	18000000	354%	925%
GM1	R172	WP1	18100000	356%	930%
GM1	R173	WP1	18200000	358%	935%
GM1	R174	WP1	18300000	360%	940%
GM1	R175	WP1	18400000	362%	945%
GM1	R176	WP1	18500000	364%	950%
GM1	R177	WP1	18600000	366%	955%
GM1	R178	WP1	18700000	368%	960%
GM1	R179	WP1	18800000	370%	965%
GM1	R180	WP1	18900000	372%	970%
GM1	R181	WP1	19000000	374%	975%
GM1	R182	WP1	19100000	376%	980%
GM1	R183	WP1	19200000	378%	985%
GM1	R184	WP1	19300000	380%	990%
GM1	R185	WP1	19400000	382%	995%
GM1	R186	WP1	19500000	384%	1000%
GM1	R187	WP1	19600000	386%	1005%
GM1	R188	WP1	19700000	388%	1010%
GM1	R189	WP1	19800000	390%	1015%
GM1	R190	WP1	19900000	392%	1020%
GM1	R191	WP1	20000000	394%	1025%
GM1	R192	WP1	20100000	396%	1030%
GM1	R193	WP1	20200000	398%	1035%
GM1	R194	WP1	20300000	400%	1040%
GM1	R195	WP1	20400000	402%	1045%
GM1	R196	WP1	20500000	404%	1050%
GM1	R197	WP1	20600000	406%	1055%
GM1	R198	WP1	20700000	408%	1060%
GM1	R199	WP1	20800000	410%	1065%
GM1	R200	WP1	20900000	412%	1070%
GM1	R201	WP1	21000000	414%	1075%
GM1	R202	WP1	21100000	416%	1080%
GM1	R203	WP1	21200000	418%	1085%
GM1	R204	WP1	21300000	420%	1090%
GM1	R205	WP1	21400000	422%	1095%
GM1	R206	WP1	21500000	424%	1100%
GM1	R207	WP1	21600000	426%	1

## BPO using DataCutter

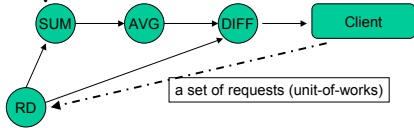


- RD - Read data filter:** Accesses data sets. Each time step is a data buffer, which contains oil velocity and oil saturation values.
- CC - Connected component filter:** Performs steps 1 and 2 of the bypassed oil algorithm.
  - Find bypassed oil pockets at a time step on data buffer received from RD.
  - send a byte array to MT. Each entry of the byte array denotes a grid cell and stores if the cell is bypassed oil cell or not.
- MT - Merge over time:** Carries out steps 3 and 4 of the bypassed oil algorithm.
  - AND the data buffers received from CC and
  - find bypassed oil pockets and send results to the Client.

## Representative Realization

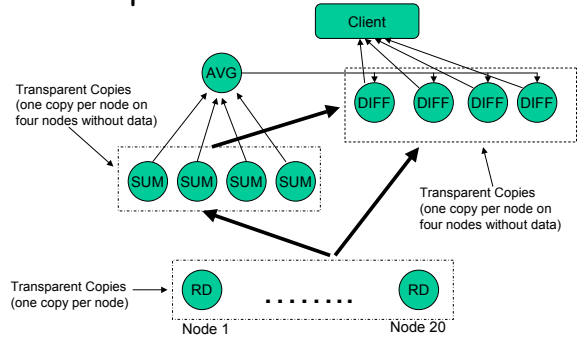
- Select the simulation/realization that has values closest to a user-defined criteria.
  - analyze that simulation or use its initial conditions for further simulation studies.
- Find the dataset among a set of datasets
  - values of oil concentration, water pressure, and gas pressure are closest to the average of these values across the set of datasets
- User selects
  - A set of datasets (D) and a set of time steps ( $T_1, T_2, \dots, T_N$ ).
- Query:** Find the dataset that is closest to the average.
 
$$\min \sum_{\text{all grid points}} |O_c - O_{\text{avg}}| + |W_p - W_{\text{avg}}| + |G_p - G_{\text{avg}}|$$

## Representative Realization



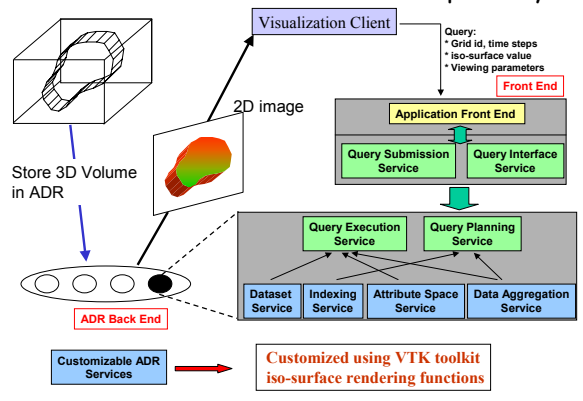
- RD - Read filter:** Accesses data sets. A data buffer is one time step. Read filter sends data from each dataset to SUM and DIFF.
- SUM - Sum filter:** Performs sum of  $C_o$ ,  $W_p$ , and  $G_p$  at each grid point across datasets.
- AVG - Average filter:** Carries out average operation on  $C_o$ ,  $W_p$ , and  $G_p$  values. AVG and SUM together execute step 1 of the average algorithm.
- DIFF - Difference filter:** Finds the sum of differences between grid values and average values for each dataset (Step 2). Sends the difference to the Client.
- Client:** Keeps track of differences for each time step, carries out average over all time steps for each dataset (Step 3). Note this could be another filter.

## Representative Realization

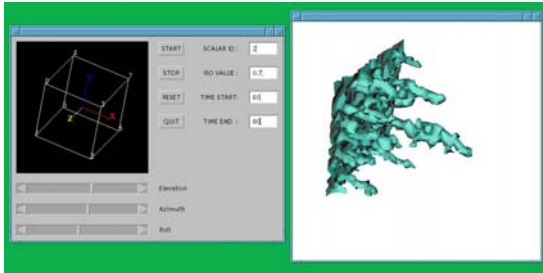


- Interactive**
- Collaborative**
- Real time monitoring**
- Real time steering**

## Visualization with Active Data Repository



## Visualization with Active Data Repository



Iso-surface rendering of output (e.g., oil saturation)

## Experimental Results

Query Type	# of Realizations	Time Steps (start:end:stride)	Execution Time (secs)
ECO	206	0:10000:1	136.97
BPO	206	1000:9000:1000	1.07
RR	206	1000:9000:1000	12.37

Economic model (ECO) uses ASCII text files, whereas for BPO and RR input files are binary files. For ECO most of the time is spent in parsing text files