Papers we will be covering today:

- “Shear buckling and dynamic bending in cloth simulation” (CASA 2008) by Chuan Zhou, Xiaogang Jin, and Charlie C. L. Wang from Zhejiang University, Hangzhou, China

- “Simulating Knitted Cloth at the Yarn Level” (SIGGRAPH 2008) by Jonathan M. Kaldor, Doug L. James, Steve Marschner, Cornell University
Why simulate at a yarn level?

- Most cloth simulations deal in an elastic sheet model
- This yields results which behave similar to leather rather than a woven or knit material
- The yarn-yarn interactions on the micro level are key to getting accurate results on the macro level
Knit vs. woven materials

- Knits
  - Non-linear 3-D looping structure
  - Consists only of one continuous yarn
  - Highly stretchable

- Weaves
  - Linear weft and warp structure
  - Consists of hundreds of yarns
  - Stress causes buckling rather than stretching
Shear buckling and dynamic bending in cloth simulation

- Structural bending is caused by compressive in-plane deformation.
- Shear buckling occurs when the woven material has been stretched to the point where it resists further shearing of the fibers.
- Weaves are anisotropic, meaning they have different characteristics during stretching, shearing, and bending.
The Contribution

• They have developed a new physical model considering the micro-interweaved structure in woven fabrics with more accurate shear buckling model

• They decouple the buckling deformation into shearing and structural bucklings

• A new dynamic bending model is derived from the thin-shell theory
Shear Buckling on Woven Structure

- Shearing stress is related to angle variation between yarns rather than length variation.
- Elastic sheet models with simple mass-spring systems can only handle length variations.
Weft and Warp gaps

• The hole between weft and warp is filled by shearing

• Resistance to further weft/warp rotation under greater stress is what causes the shear buckling
Resistance to compression

- In diagonal stretching the compression forces between yarns are perpendicular to the external load force
- In diagonal compression, the internal forces are opposite the external
Relation between diagonal forces

• $\alpha$ represents the resistance to diagonal extension
• $\beta$ represents the resistance to diagonal compression

$$\alpha + \beta \equiv 1 \quad (0 \leq \alpha, \beta \leq 1)$$

• In most cases the stiffness of shearing springs should be much larger than the values of other springs in the system
Dynamic Bending Method

- Linear beam theory model

\[ M_x = k^b \kappa = (EI_x) \frac{d\theta}{dx} \]

- In the dynamic model, \( k^b \) changes depending on the current shape
Simplified model with dynamic stiffness

• Bending force:

\[ f_A = \frac{e_A \times M_C}{l_A} \]

• Where

\[ M_C = k^b \frac{\theta_A + \theta_B}{l_A + l_B} n \]

• From
Implementation on a Particle System

• Shearing springs are only reacted when they are under compression

• Very large stiffness coefficients will be assigned to those compressed shearing springs
Results

- Two shearing tests:
  - One with diagonal shear load at a 45 degree angle from weft and warp
  - One with simple stretching along the direction of the yarn
Results

• Their model provides a realistic shear buckling result which is visually similar to real woven materials
Simulating Knitted Cloth at the Yarn Level

• Few works have focused on knit simulation
• Knits behave very differently from elastic sheet models and even from woven fabrics
Multiphasic deformations

- There are layers to the deformation of knits materials
- Unrolling of the sheet
- Deformation of woven or knit structure
- Additional load causes the yarns themselves to stretch
Knit and Purl loops

- The yarn is organized in loops along horizontal rows
- "Knit" stitches come up through the previous loop
- "Purl" stitches come down through the previous loop
Types of knits

- Stockinette – all “knit” stitches
- Garter – alternating “knit” and “purl” stitches
- 2-2 rib – two rows of “knits” followed by two rows of “purls”
The Yarn-Level Cloth Model

- Yarns are modeled as one continuous open cubic b-spline of radius \( r \)
- Indices \( i, j \) range over spline segments while \( k, l \) range over the control points
- Equation of curve position: \( y(s) = \sum b_k(s)q_k, \ s \in [0, N] \)
- And velocity: \( v(s) = \sum b_k(s)\dot{q}_k \)
Yarn constraints

- Mass:

\[ M \ddot{q} = -\nabla_q E(q) - \nabla_q D(\dot{q}) + f \]

\[ C(q) = 0, \]
Intra-Yarn Properties

• A bending energy function which is quadratic in nature

\[ E_i^{\text{bend}} = k_i \ell_i \int_0^1 \kappa_i(s)^2 \, ds, \]

• Inextensibility where the total curve length is a hard constraint but mass can move around

\[ C_i^{\text{len}} = 1 - \frac{1}{\ell_i} \int_0^1 \| y_i'(s) \| \, ds. \]
Yarn-Yarn Collisions

• Yarn collision forces are handled with an energy term:

\[ E_{\text{contact}}^{(i,j)} = k_{\text{contact}} \ell_i \ell_j \int_0^1 \int_0^1 f \left( \frac{\|y_j(s') - y_i(s)\|}{2r} \right) ds\, ds' \]

• Where \( f(d) \) is defined as

\[ f(d) = \begin{cases} 
\frac{1}{d^2} + d^2 - 2, & d < 1 \\
0, & \text{otherwise}
\end{cases} \]
Damping and Friction

• Mass-proportional damping:

\[ D_i^{\text{global}} = k_{\text{global}} \int_0^1 v_i(s)^T v_i(s) ds \]

• Contact damping:

\[ \ell_i \ell_j \int_0^1 \int_0^1 \left( k_{di} \| \Delta v_{ij} \|^2 - (k_{dt} - k_{dn}) (\hat{n}_{ij}^T \Delta v_{ij})^2 \right) ds \, ds' \]

• Non-rigid motion damping (fuzz):

\[ \frac{\alpha}{r(s)} (v_{\text{rigid}}(s) - v(s)) \]

Small rigid damping region (repeat every row / column)

Large rigid damping region (repeat every 2 rows / 2 columns)
Additional Constraints

• Gluing the end of the yarn:

\[ C_{\text{glue}} = y(s_1) - y(s_2) \]

• Contact with objects of implicit surfaces:

\[ E_{i_{\text{obj}}} = k_{\text{obj}} \int_0^1 \left\{ \begin{array}{ll} (f(y_i(s)) - f_0)^2, & f(y_i(s)) < f_0 \\ 0, & \text{otherwise} \end{array} \right\} ds \]

• With distance fields (plane) they employ a velocity filter along with the appropriate frictional impulse
Integrating Yarn Dynamics

• Use an implicit-explicit integration method
• The bottleneck for the integration is usually in the collision detection, so they use spatial culling
• Static bounding spheres limit the collision checking to close neighbors
• AABB tree traversal and contact force evaluation is highly parallelizable
Initial Yarn Configuration

• Input: a knit pattern, spline segments (k per stitch), a set of curves to describe the various kinds of stitches

• Goal: to obtain a properly interconnected configuration which can be relaxed to a rest state
Results

• Code written in Java and run on machines with 4-core Intel Xeon processors at 2.66 GHz
• Rendering time ranged from 4 to 15 mpf
• The model handles constant low-stiffness contact and transient stiff contact between two colliding yarns, but is not as stable in handling constant high-stiffness contact
• Realistic results can be a basis for future approximation models